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Techno-economic Study of Recycled Plastic Waste Boards (RPB) as Sustainable Shell Construction Material for Fishing Vessels in Indonesia

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Abstract

The extreme increase in plastic waste over the past few decades has significantly impacted environmental challenges, especially in marine ecosystems. Despite numerous attempts, the use of recycled plastic waste remains restricted to specific applications. This paper experimentally investigates the potential of using Recycled Plastic-Waste Boards (RPB) as a shell hull construction material for fishing vessels in Indonesia. The study technically investigated the performance of RPB works compared to regular materials like wood and fiberglass-reinforced plastic (FRP) for fishing vessels in terms of mechanical properties, and it's cost-effective. The RPB was made from mixed plastic waste, which was collected, chopped into small pieces, and then heated using a special design heating pot which then poured into special mold. The RPB was then mechanically tested using the ASTM D638 standard for tensile strength and the ASTM D790 standard for flexural strength. The results indicate that the RPB′s tensile and flexural strength are 9.4 MPa and 17.22 MPa, respectively, which meets the required mechanical strength standards for marine applications. In addition, the economic analysis shows that using RPB material can lower the construction costs of a 4-GT-sized boat shell hull by 57.79% and 17.09% compared with wood and FRP materials. Based on technical and economic views, the RPB materials have potential as alternative materials for boat shell construction and are more economical. These findings suggest that RPB provides a sustainable alternative to conventional materials and promotes the development of a circular economy within Indonesia's fishing sector. Overall, this research highlights the potential of RPB to contribute to both environmental sustainability and economic feasibility in the construction of small fishing vessels.

1. Introduction

One of the most urgent environmental problems of our day has been plastic garbage. Estimated at 8 million metric tonnes, plastic enters the waters each year [1], [2] this issue has far-reaching effects for coastal residents and marine ecosystems. Inadequate waste management practices and heavy plastic use in Southeast Asia, notably Indonesia, greatly exacerbate this worldwide catastrophe. Every year, Indonesia's plastic output rises consistently by 4.65% [3]. The management of plastic garbage, meanwhile, has not been sufficiently handled. With 18.9% of terrestrial garbage and 35.41% of ocean waste—equivalent to 9.36 million tons—comprising plastic [3], [4], this issue has caused plastic waste to be a major contaminant.

The end-up plastic waste to the sea has directly harmed the marine fishing industry [5]. Plastic pollution, particularly microplastics (MP), has been found in 926 seafood species, including finfish and crustaceans [6], [7]. This reduces fish growth and fitness, decreasing fish production [5], [6], [7]. The seafood contamination threatens fisheries' economic viability, affecting local communities that rely on fishing for income and sustenance [5], [8]. This problem is a significant threat to Indonesia, with over 17,000 islands and a coastline spanning more than 54,000 kilometers, home to one of the world's largest artisanal and small-scale fishing sectors [9]. In 2022, it was recorded that 7,392,029 heads of families were fishermen, meaning that 11.19% of heads of families in Indonesia depend on their livelihoods as fishermen [9]. In addition, the country has around 625,000 registered small fishing vessels [10], most of which are made using traditional materials like wood or more modern materials like fiberglass-reinforced plastic (FRP). Despite their widespread use, FRP-based boats raise significant sustainability concerns due to the non-recyclable nature of fiberglass and its adverse environmental impact during disposal [11]. FRP contributes to marine debris, with studies showing high concentrations of fiberglass particles in marine bivalves, indicating ingestion and potential health impacts on these organisms [12]. Furthermore, the production of

FRP involves hazardous materials such as PVC and polyester resin, which have been identified as harmful to human and environmental health [13].

Efforts to utilize recycled plastic waste for construction materials in general have received quite a lot of attention both nationally and internationally. Literature studies still dominate the study's scope, with few studies using an experimental approach. Awoyera and Adesina [14] reviewed various approaches to converting recycled plastic into new products. This research also addresses the limitations of using plastic waste for construction applications. This research also explores various approaches to recycle plastic waste into new products. In addition, a literature review related to the recycling of plastic waste materials for building and construction materials has been reviewed by Nyika and Dinka [15] and Tsuchimoto and Kajikawa [16], which generally examines the potential for recycling plastic waste, the types of plastic used, and the potential and limitations in the field of building and construction in general. Da Silva et al. [17] conducted a literature review related to the application of plastic waste for construction materials with a life-cycle assessment approach in the context of current research and future potential. Meanwhile, Uvarajan et al. [18] studied the use of plastic waste for use as building bricks and paving blocks with a literature review approach. The use of plastic waste to make paving blocks has been experimentally carried out by Sudarno et al. [19], by combining recycled plastic waste with gravel, where the compressive strength test results were 50.97 MPa and the flexural strength was 1.73. Studies related to the technological approach to converting plastic waste into structural materials are also quite limited, as has been done by Kalali et al. [20]. Kalali et al. [20] discuss various types of approaches to converting plastic waste into new products to improve environmental sustainability. The article describes plastic waste recycling facilities that use a mechanical approach and a chemical process, along with their application in construction. However, the scope of this research remains restricted to a review of some existing literature.

On the other hand, the utilization of recycled plastic waste for ship construction materials is still very limited, especially with an experimental approach. Such as the utilization of used HDPE plastic drum material for ship hull skin carried out by Amiruddin et al. [21]. The approach used is to make a ship frame from wood and a ship shell from used HDPE drum material, which are connected with special glue. The type of used HDPE drum waste is not reprocessed (melted) to be molded into new construction boards, and mechanical strength and ship skin thickness testing is not carried out. Kadhafi et al. [22] utilized HDPE plastic material for ship construction with a length of 10 meters. With the approach of the mechanical strength value of the material based on the literature, the thickness of the ship skin was obtained. A comparison of the complexity of the production method between molding and welding joint methods technically and economically was carried out, where facilities with molding were pricier than the welding joint method. Dinata et al. [23] investigated several types of plastic combined with several natural fibers for ship construction materials using a literature study approach. The test results require further experimental investigation to prove the mechanical strength value of the material as a material for ships. Dwikurniawan [24] attempt to conduct mechanical testing of construction boards made from recycled LDPE (Low Density Polyethylene) waste conversion combined with Ori and Betung bamboo. Tensile and bending tests based on ASTM D638 and ASTM D790 produced average strength values of 32.2 MPa and 58.526 MPa. However, the experimental results seem to be not validated and need to be investigated further.

Based on the description, it can be seen that the utilization of recycling is still focused on literature studies, and its application is still limited to buildings and general construction. While its utilization for ship construction is still very few. Recycled plastic waste materials are not yet used in shipbuilding, neither in the manufacturing process nor in testing or determining construction sizes for fishing vessels. Using recycled plastic waste boards as a substitute material for building small fishing boats has enormous promise as a creative idea. It contributes to the development of a circular economy, offers a cost-effective alternative to FRP, and simultaneously reduces the environmental impact of plastic waste. Especially in a high-demand, high-usage environment like Indonesia's fishing sector, the move toward recycled plastic materials calls for a comprehensive scientific and economic study to guarantee the viability. This paper is to evaluate the technical performance and the economic consequences of recycled plastic waste boards for small fishing vessels in Indonesia in comparison to conventional materials such as wood and FRP.

2. Method

In this study, a specific technique was utilized to create a board material out of waste plastic that had been reprocessed. Following that, the material was put through a series of mechanical testing, notably tensile and flexural tests, to determine whether or not it could be utilized in the construction of ships [25], [26]. The results of the mechanical tests were utilized to determine the size of the ship's shell construction, which is necessary to estimate the costs of constructing a fishing boat constructed from this material. In addition, the prices of construction were compared with those of standard materials such as wood and fiberglass-reinforced plastic (FRP) to evaluate whether or not the utilization of recovered plastic waste for the production of boats is economically viable [27]. The following paragraph outlines the detailed steps of the methodology for conducting either the manufacturing of the recycled plastic board, preparing the specimen for the mechanical test, and then performing the mechanical test.

2.1. The Manufacturing of Recycled Plastic Boards

Raw material preparation starts the process of producing recycled plastic waste boards. This step includes sorting and cleaning several varieties of plastic trash, including low-density polyethylene (LDPE), medium-density polyethylene (MDPE), high-density polyethylene (HDPE), and polypropylene (PP). While cleaning eliminates impurities that can compromise the quality of the final product, thorough sorting guarantees that polymers with comparable qualities are blended. Ensuring homogeneity and structural integrity of the recycled plastic boards depends on this first stage [28], [29]. Once separated, the plastic trash was shredded into smaller bits (Figure 1.a). Increasing the surface area of the plastic helps it melt and mix easier, so this step helps the following melting process. During the melting phase, the shredded material enables more effective heat transport, therefore assuring an even and complete melting process [30], [31], [32]. A specially designed heated pot set apparatus (Figure 1.b) produces recycled plastic waste boards. This equipment set includes a large stainless-steel pot (Figure 1.c) for melting plastic trash. An iron mold was then used to pour the melted material, shaping the plastic waste mix into a board. Before it cools, a roller rolls the cast and pushes it along a rail.

Figure 1. (a) Shredded plastic waste, (b) Jig-set for Recycled Plastic Waste Board Manufacture, (c) stainless steel heating pot.

As shown in Figure 2.a, all the plastic types were melted in a big stainless-steel pot during the melting stage. Starting with PP, the plastics were added in a particular sequence: HDPE, MDPE, and LDPE. Each kind of plastic has a different melting point and behavior [34]; hence, this sequence guarantees appropriate blending. A uniform combination, which produced boards with consistent qualities. The next step is to cast plastic ingots into boards by pouring molten plastic into molds. Slack is removed throughout this time, hence reducing 2-5% of the plastic content. This stage guarantees that the end product was dense and concentrated [30], [31] by removing air pockets or impurities possibly left in the mixture. Any leftover porosity was removed by rolling and pressing the still-warm material after casting. This stage compresses the material to get rid of any air bubbles possibly created during the casting, hence improving the structural integrity and strength of the board [31], [32]. Figure 2.b and Figure 2.c show the casting and rolling processes.

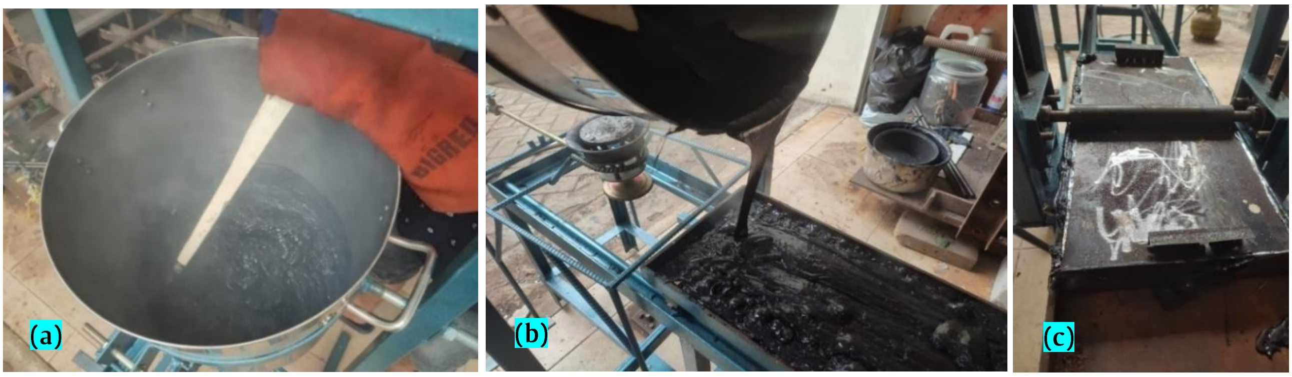


Figure 2. (a) Melting stage, (b) Casting process and (c) rolling process.

Thereafter, the board was placed in cold water, chilling, which assists in the material cooling more quickly and uniformly. When the board was properly cooled, it helped to prevent warping or breaking that can be caused by uneven temperature distribution [28], [31]. This technique is especially important when it comes to ensuring that the board solidifies consistently. Once the board has reached the desired level of curing, it can be removed from the mold. Finally, the board received thorough finishing process. This includes trimming excess material, smoothing rough edges, and conducting rigorous quality checks to ensure the board meets the desired specifications. This final step is very important to ensure the end-product of the board is durable and proper. Figure 3 depicts the final product of the board made from recycled plastic trash.

Figure 3. The Recycled Plastic Waste Board manufactured using heating pot and molds.

In summary, the manufacturing process of Recycled Plastic Waste Boards (RPB) follows a systematic sequence (Figure 4) comprising plastic sorting, shredding, melting, casting, rolling, cooling, and finishing. Initially, selected types of plastic waste—such as LDPE, MDPE, HDPE, and PP—are cleaned and sorted to ensure material compatibility. The plastics are then shredded into smaller fragments to facilitate uniform melting. In the melting stage, plastics are processed in a specific order to ensure optimal blending, after which the molten material is poured into molds and subsequently rolled to eliminate internal voids. The boards are then cooled using water to ensure dimensional stability before undergoing final finishing steps, including trimming and quality inspection. This multi-stage process is designed to produce recycled plastic boards with consistent structural and mechanical properties suitable for marine construction applications.

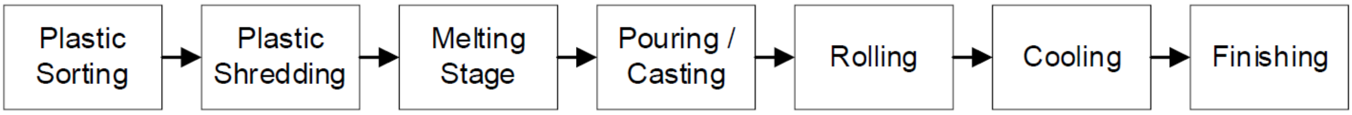


Figure 4. Recycled Plastic Waste Board Material Manufacturing Process.

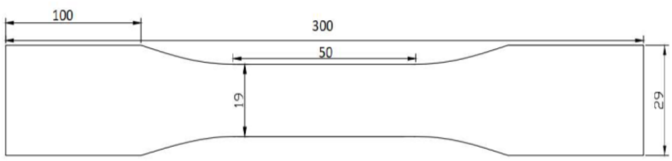
The Recycled Plastic Waste Board (RPB) produced in this study was composed solely of mixed polyolefin plastic waste (LDPE, MDPE, HDPE, and PP) without any added reinforcement such as fibers or fillers. This approach was intended to assess the feasibility of pure recycled plastic boards without enhancement, focusing on maximizing the recyclability and sustainability aspects. However, this choice may also contribute to variability in mechanical properties, which is further analyzed in the results section.

In terms of production challenges, one practical issue encountered was in the joining of boards to form larger hull panels. Mechanical fastening using stainless bolts and marine-grade adhesives was used, but further development in seamless lamination or welding techniques is needed for improved structural integrity and waterproofing.

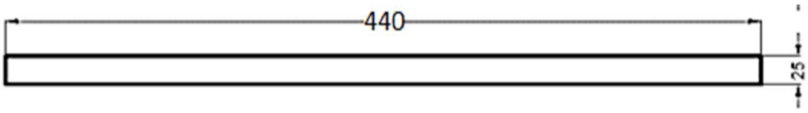
2.2. Mechanical Testing

After completing the manufacturing of the recycled plastic-waste board, the investigators shaped it into a specimen size for the testing process. A Universal Testing Machine (UTM) was used to conduct a tensile strength test as per the ASTM D-638 standard [33] and a flexure strength test as per the ASTM D-790 standard [34]. The results were then examined and compared to the building classification rules based on DNVGL-ST-0342 [35] and Turk Loydu 2014 Tentative Rules for Polyethylene Crafts [36].

The procedure of tensile strength testing involves subjecting a specimen to a controlled tensile load until it breaks. The specimen was subjected to a tensile load during the experiments. Five distinct specimen measurements are specified in the ASTM D-638 standard [33]. In this study, a type 3 specimen size was employed for the tensile test, as the required thickness exceeded 14 mm. Figure 6a illustrates the specimen's tensile strength test conducted with universal testing equipment, while Figure 5a illustrates the specimen's design in accordance with the ASTM D-638 standard. Flexural testing is the process of applying compressive stress to the center point of a specimen that is supported at both extremities. The specimen is distorted because of the conflicting forces acting on it. The ASTM D-790 standard delineates four flexural testing techniques; however, this investigation exclusively employs category "A" testing. Figure 6b illustrates the flexural strength test conducted on the sample using universal testing equipment, while Figure 5b illustrates the sample design in accordance with the ASTM D-790 standard [34].



(a)



(b)

Figure 5. (a) Specimen design for tensile strength test, (b) Specimen design for flexural strength test.

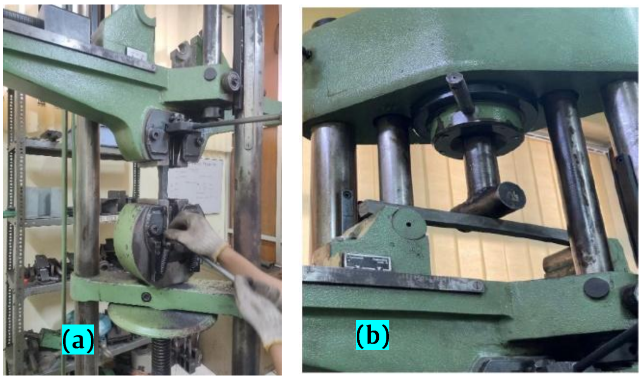


Figure 6. Tensile test (a) & flexural test (b) of the specimen using Universal Testing Machine.

According to ASTM D-638 [33], tensile strengths and strain values can be calculated using Eq. 1 and 2. These two values can then be used to determine the Tensile Modulus of Elasticity (MoE) using Eq. 3. The resulting MoE value can be compared against the ship classification standard criteria.

$$\sigma = \frac{P}{A_0} \tag{1}$$

$$\varepsilon = \frac{\Delta L}{L_0} \tag{2}$$

$$MoE = \sigma/\varepsilon \tag{3}$$

Tensile strength (σ) is expressed in N/mm² or MPa. As indicated in Eq. 1, it was determined by dividing the cross-sectional area (A_0) of the specimen by the load applied (P). Using Eq. 2, one may find the strain value (ε) by first calculating strain by dividing the change in length following testing (ΔL) by the initial length (L_0). Known values of strain (ε) and stress (σ) allow one to derive the modulus of elasticity (MoE), which is the ratio of stress to strain (according to Eq. 3).

Based on test results, the material's flexural strength value (Modulus of Rupture or MoR) is calculated using Eq. 4 from the ASTM D790 standard [34]. Data on the load (P), support distance (L), specimen thickness (d), and specimen width (b) is needed for this calculation. The flexure modulus of elasticity (MoE) value is obtained using Eq. 5, which requires data on the support distance (L), specimen width (b), specimen thickness (d), and slope of the load-deflection curve (m).

$$MoR = \frac{3PL}{2bd^2} \tag{4}$$

$$MoE = \frac{mL^3}{4bd^3} \tag{5}$$

Impact testing, although recognized as an important measure of material toughness, was not included in this phase due to its limited direct correlation with static structural demands experienced by small-scale fishing vessel hulls under normal operational loads. The predominant stresses in such applications are static in nature—stemming from hydrostatic pressure, buoyancy variation, and distributed loads from equipment and personnel—where tensile and bending performance are more critical in determining material suitability. In addition, given the laminated assembly technique used in this study, impact behavior is better interpreted at the full-structure scale, which was beyond the scope of this investigation. Therefore, tensile and flexural tests were prioritized and aligned with recognized standards (ASTM D638 and D790) and serve as reliable parameters to benchmark the RPB material against established marine construction criteria.

2.3. Scantling Calculation

The choice of construction regulations for ships is typically determined by the ship's size, the materials used in its construction, and the classification society. This study focuses on innovative materials related to plastic materials, fishing vessels, and ships with a length not exceeding 24 meters. To ensure safety, compliance, and material performance, this study refers to two regulations from different classification societies: DNV-GL [35] and Turk Loydu [36]. After comparing the regulations issued by the two classification societies, there are differences and similarities between the DNVGL-ST-0342 Craft 2016 Standard and the Turk Loydu 2014 Tentative Rules for Polyethylene Crafts. The main difference between the two regulations lies in describing the properties that plastic must possess to be used as shipbuilding material. The Turk Loydu 2014 Tentative Rules for Polyethylene Crafts include LDPE, MDPE, and HDPE, while the DNVGL-ST-0342 regulation only explains LDPE and MDPE. On the other hand, the similarities between the two regulations are found in calculating the load on the hull and determining the minimum thickness of the hull shell. After determining the load's size and identifying the ship's specific loads, one can calculate the construction size. Both regulations require the initial calculation of two loads: the sea pressure on the hull bottom and the sea pressure on the hull side. These load values will serve as the basis for the later calculation of the scantlings.

2.3.1. Sea Pressure on Hull Bottom

The sea pressure on the hull bottom (Pb) is a load that affects the lower part of the ship's hull. It is calculated using an empirical formula, which is then multiplied by various factor values and coefficients obtained from specific graphs. The empirical formula for determining the load value at the bottom of the hull can be found in Eq. 6.

$$P_b = PF_b \,.\, k_{lb} \,.\, k_\beta \,.\, k_a \qquad (6)$$

where

P_b = Sea pressure on hull bottom [kN/m^2]

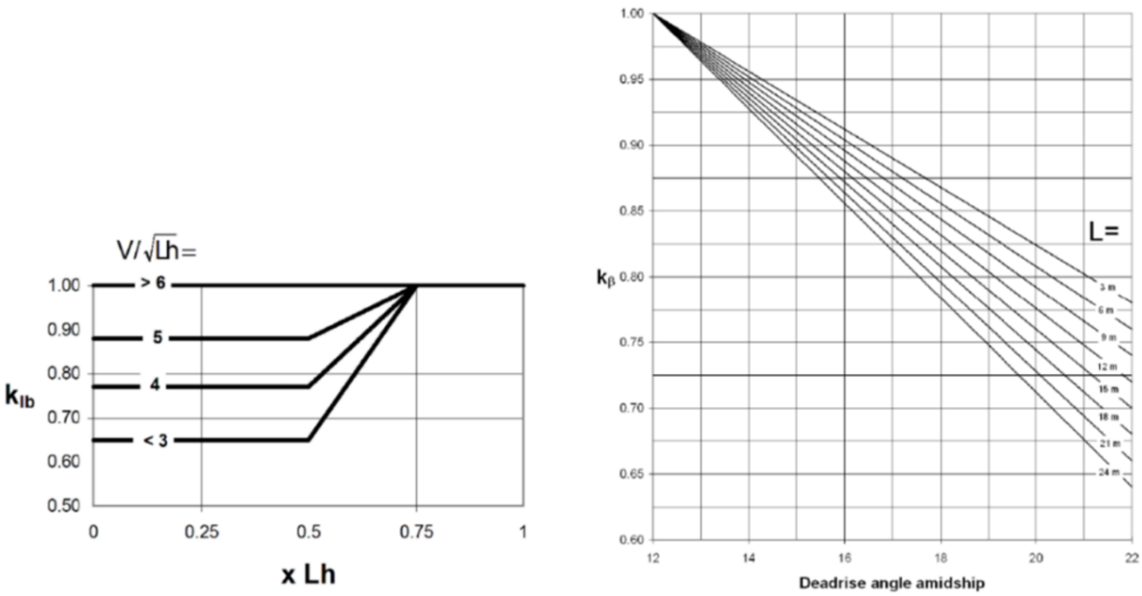
PF_b = The pressure factor taken from Figure 11

k_{lb} = Longitudinal load distribution factor

k_β = Deadrise angle correction factor if V > and L > 9 m

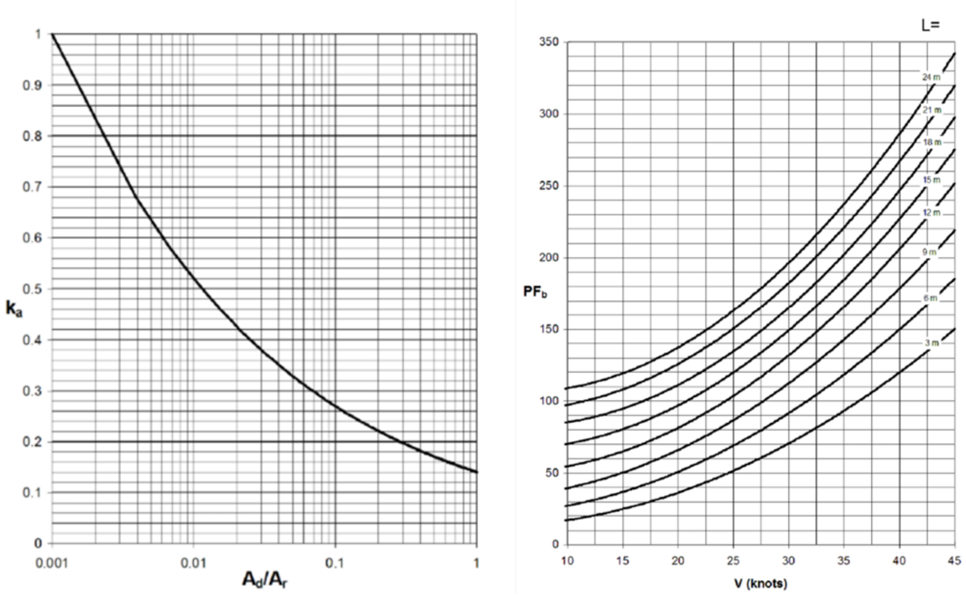
k_a = Area reduction factor

The longitudinal load distribution factor is determined using the graph in Figure 7a. The values of x/Lh and $V\sqrt{L_h}$ are used to find this graph's longitudinal load distribution factor. The deadrise angle correction factor value is determined when the ship's speed exceeds 3√L and its length exceeds 9 m, where the determination utilizes the graph shown in Figure 7b.



(a) (b)

Figure 7. (a) Longitudinal Load Distribution Factor of Pb, (b) Deadrise Correction Angle Factor Graph.



(a) (b)

Figure 8. (a) Area Reduction Factor Graph, (b) Pb Pressure Factor Graph.

Calculating the area reduction factor value using the graph in Figure 8a requires the Ad coefficient values. To determine the thickness of the plate, the Ad coefficient used is the square of the plate width (s2). The pressure factor value is determined by using the graph in Figure 8b to calculate the load on the ship's lower hull. In Figure 11, ship length and speed data are necessary to determine the pressure factor value and where the speed line intersects the ship length curve.

2.3.2. Sea Pressure on Hull Side

Sea Pressure on Hull Side (Ps) is a load that occurs on the side area of the ship's hull. The calculation of Ps is similar to that of Pb, which involves multiplying several factor values and coefficients obtained from specific graphs. The empirical formula for calculating the load value on the side of the hull can be seen in Eq. 7.

$$Ps = PF_s \, . \, kl_s \, . \, k_v \, . \, k_a \tag{7}$$

where:

P_s = Sea pressure on hull side [kN/m2]
PF_s = The pressure factor taken from Figure 11
kl_s = Longitudinal load distribution factor
k_v = Vertical distribution factors
k_a = Area reduction factor

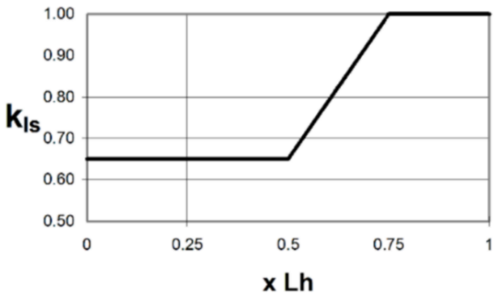
The longitudinal load distribution factor value is obtained from the graph in Figure 9a. In this graph, the value is determined based on the x/Lh value. The vertical distribution factor value is determined by calculation using empirical methods. Eq. 8 is an empirical formula for calculating vertical distribution value, where two components, Fv and h, are needed to perform the calculation.

$$kv = \frac{F_v - h}{F_v} \tag{8}$$

where:

h = Distance from the center of load to the side of the ship [m]
Fv = 4.5Δ/100LB

Determination of the pressure factor value used to calculate the load on the side of the ship's hull using the graph in Figure 9b. Figure 9b shows that ship length and ship speed data are required to determine the pressure factor value, which will later be used to find the point where the speed line and the ship's length curve intersect.



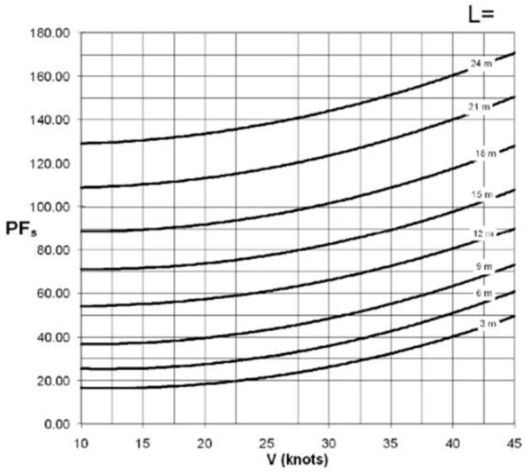


Figure 9. (a) Longitudinal Load Distribution Factor of Ps, (b) Ps Pressure Factor Graph

2.3.3. Minimum Thickness of Boat Shell

Eq. 9 can be used to calculate the thickness of the boat shell after the coefficient of sea pressure on the hull bottom and hull side has been determined. This equation takes into account the coefficient for material, frame spacing, the load on the hull, and the length of the ship. The minimum thickness of the hull is directly proportional to the amount of pressure that is applied, including the frame spacing and the type of material.

$$ty = k\,.\,s\,.\sqrt{\frac{PF}{L\,.6{,}7}}.\,(14\;+\;3{,}6L) \tag{9}$$

where:
ty = minimum shell thickness
k = 1.0 for LDPE
s = frame spacing
PF = Load on the hull
L = Ship length

2.4. Cost Calculation

Examining the economic viability of employing recycled plastic waste boards as a raw material for ship construction needs a methodical approach to cost calculation and comparison. The process in this work was evaluating the whole cost of constructing a ship with recycled plastic waste boards and contrasting it with conventional materials, including wood and fiberglass-reinforced plastic (FRP). The overall cost of shipbuilding covered material cost, labor, and overhead. The material cost was approximated from the previously computed scantling findings and the material needs. Labor costs were determined using the productivity method of the work stages and necessary workloads. An estimate of the length of the production process was used to determine overhead. Once the overall cost was determined, it was contrasted with the entire cost of shipbuilding utilizing wood and FRP components. This comparison, which included material and construction expenses, directly compared the overall cost of building the ship using recycled plastic waste boards versus wood and FRP. This comparison helps to show which material produced the lowest initial cost for constructing a vessel of comparable size and function.

3. Results and Discussion

The results of the material testing of recycled plastic waste board (RPB) provide substantial insights on its appropriateness as a hull construction material for fishing vessels. The mechanical performance of RPB samples was evaluated by tensile and flexural strength tests. The findings were subsequently compared with the minimum strength criteria established for materials used in constructing fishing boats. A financial analysis was undertaken to compare the total construction costs of a fishing vessel fabricated with RPB to those constructed from solid wood (Teak) and fiberglass-reinforced plastic (FRP).

3.1. Technical Analysis

The technical analysis in this paper examines the mechanical properties of the RPB by means of a tensile test and a flexural test following ASTM D-638 and ASTM D-730, respectively, as described in the methodology. Before conducting the tensile test, the thickness of the specimen was recorded and tabulated. Tensile testing uses a tensile load on the specimen until it fails or breaks to determine the breaking load. The tensile test findings were recorded as load and stretching values and then displayed in a graph with the x-axis representing stretching and the y-axis the load on the specimen.

Table 1 summarizes the data, including the computed values for stress, strain, and modulus of elasticity using Eq. 1, 2, and 3. The data in Table 1 suggests that the specimen with the greatest cross-sectional area (CSA) was Tensile 3, measuring 21.45 millimeters wide and 20.45 millimeters thick. A bigger cross-sectional area does not automatically link to better tensile performance, either. With a maximum force of 4.98 kN, the Tensile 2 specimen showed the greatest tensile load capacity despite its smaller CSA. Moreover, Tensile 2 showed the elongation at 4.98 millimeters, thereby suggesting its better ductility and mechanical reaction under tensile stress.

Regarding the tensile strength of the RPB, the RPB material's maximum tensile stress ranges from 8.16 MPa to 11.96 MPa. With a strain of 14.76%, the Tensile 2 specimen has the highest maximum tensile stress of 11.96 MPa. The recorded greatest modulus of elasticity (MoE) is 2.11 GPa, corresponding to the Tensile 1 specimen. The MoE value varies with the stress and strain of every specimen; a higher stress value coupled with a lower strain value produces a bigger MoE. RPB material averages 9.6 MPa tensile strength, 12.86% strain, and 1.81 GPa modulus of elasticity. Apart from the test findings, RPB material shows a clear correlation between stress and strain. The stress-strain graph in Figure 10a–which depicts tensile specimen 2 with a maximum tensile stress value of 11.96 MPa and a strain of 14.76%–shows this relationship.

The tensile strength results of the RPB specimens showed moderate consistency across the three samples tested. The calculated average tensile strength was 9.6 MPa, with a standard deviation of ±1.93 MPa. The observed variability is within an acceptable range for recycled thermoplastic materials and can be attributed to minor differences in board composition and processing conditions. Similarly, the average strain was 12.86% with a standard deviation of ±2.41%, and the average modulus of elasticity (MoE) was 1.81 ± 0.38 GPa. These values indicate that the RPB material exhibits a balance between ductility and stiffness, suitable for accommodating the typical loads encountered by small fishing vessel hulls.

Table 1. Summary of Tensile Test Result

Specimen Code	L_0 (mm)	Width (mm)	Thickness (mm)	Area (mm^2)	Breaking Load (kN)	Elongation (mm)	Tensile Strength (MPa)	Strain (%)	MoE (GPa)
Tensile 1	50	19.20	21.00	403.20	3.45	5.03	8.58	10.07	2.11
Tensile 2	50	20.00	20.75	415.00	4.98	7.38	11.96	14.76	1.95
Tensile 3	50	21.45	20.45	438.65	2.57	6.86	8.16	13.74	1.35
						Average	**9.6**	**12.86**	**1.81**

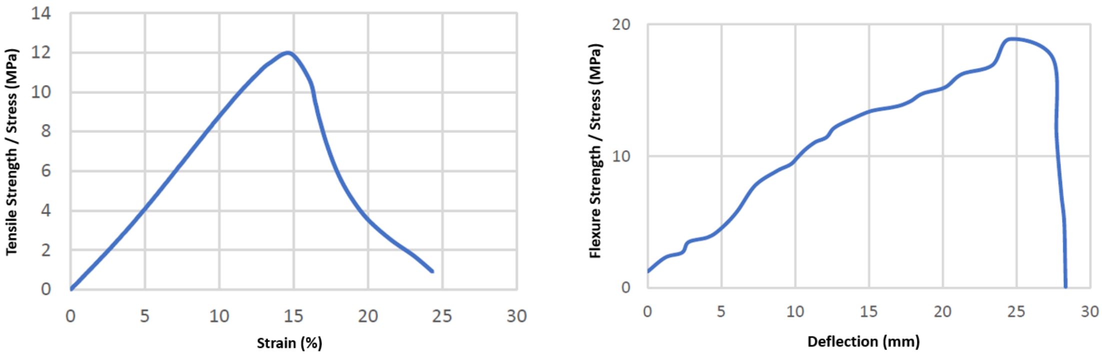
On the other hand, the flexural test examines a material's ability to resist bending by applying a load until structural failure occurs or the material can no longer sustain the applied force. The data from the test is usually shown on a load-deflection curve, which shows how the applied force relates to the bending of the material. Table 2 provides a summary of the flexural test outcomes, including the calculated flexural strength values. As seen in Table 2, the Flexure 1 specimen had the highest maximum load, 0.346 kN. Nonetheless, the difference in maximum load across all specimens was minimal. Flexure 2 had the largest cross-sectional area (CSA) (447.70 mm²), while Flexure 1 had the highest deflection (27.47 mm). These findings imply that, despite geometric changes across the specimens, their flexural responses remained within a similar range.

The maximum bending stress the RPB material can withstand ranges from 15.75 to 18.89 MPa. The highest bending stress recorded is 18.89 MPa in the Flexure 1 specimen. The Flexure 3 specimen has the highest modulus of elasticity at 0.801 GPa. Additionally, based on Table 2, the RPB material shows an average bending stress value of 17.22 MPa, a deflection of 21.39 mm, and a modulus of elasticity of 0.664 GPa. A stress-deflection graph illustrates the relationship between stress and deflection. Figure 10b shows an example of a stress-deflection graph for a Flexure 1 specimen. This specimen has a flexural strength of 18.89 MPa and a deflection of 27.47 mm.

For the flexural tests, the RPB specimens demonstrated an average Modulus of Rupture (MoR) of 17.22 MPa, with a standard deviation of ±1.57 MPa. This suggests that the material offers adequate resistance to bending loads with relatively low variation among specimens. The average deflection at break was 21.39 ± 4.12 mm, and the average modulus of elasticity was 0.664 ± 0.123 GPa. These values reflect good flexibility and energy absorption capacity, which are beneficial for marine hull applications subjected to continuous wave-induced stress cycles.

Table 2. Summary of Flexure Test Result

Specimen Code	L_{span} (mm)	Width (mm)	Thicknes s (mm)	Area (mm^2)	Breaking Load (kN)	Flexure Strength/MOR (MPa)	Deflection (mm)	MoE (GPa)
Flexure 1	320	20.90	20.10	420.09	0.346	18.89	27.47	0.561
Flexure 2	320	22.00	20.35	447.70	0.323	15.75	19.37	0.631
Flexure 3	320	20.95	20.80	435.76	0.324	17.02	17.32	0.801
					Average	**17.22**	**21.39**	**0.664**



(a) (b)

Figure 10. (a) Stress-Strain Graphic, (b) Stress-Deflection Graph.

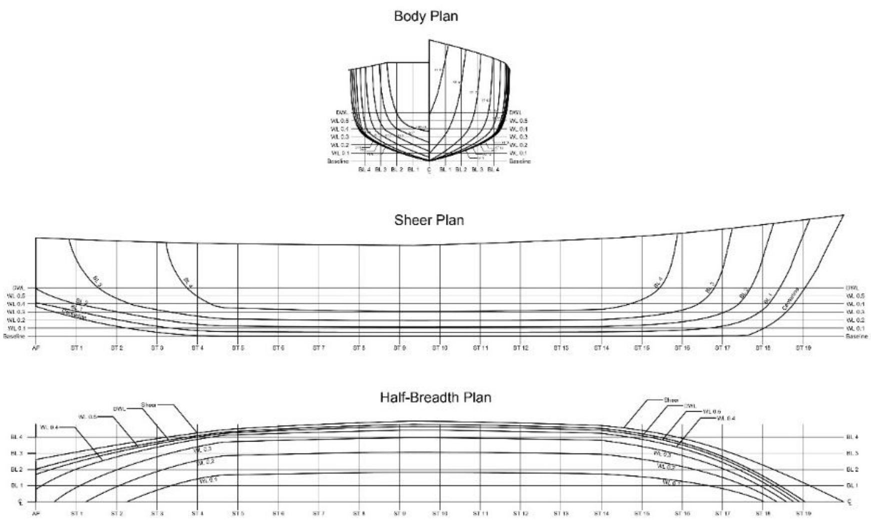
The tensile and flexural test results show noticeable variation between specimens, particularly in ultimate strength and elongation values. This deviation is primarily attributed to the inherent variability in the recycled plastic mixture used to manufacture the boards. As the RPB consists of heterogeneous waste plastics (LDPE, HDPE, MDPE, PP), slight inconsistencies in composition, melting behavior, or cooling rate may cause differences in polymer bonding and density. These factors affect the microstructure, resulting in localized stiffness or weakness within each board. Additionally, manual processes such as pressing and rolling might contribute to differences in void content and thickness uniformity, further influencing mechanical performance.

Despite this variability, based on the test results, RPB exhibits mechanical strength values—both tensile and flexural strength—that surpass the minimum strength requirements set by DNV-GL and Turk Loydu standards. The minimum permitted tensile strength for plastic materials used in ship construction is 6.7 MPa. According to Table 1, the tensile strength of all RPB material specimens exceeds this minimum standard, and the overall average tensile strength is also above the required level.

Furthermore, RPB material meets the minimum flexural strength standards as well. The minimum flexural strength requirement is 15 MPa. While specimen Flexure 2 only slightly exceeds the minimum standard by about 0.75 MPa, the average flexural strength of RPB clearly surpasses this requirement, as demonstrated in Table 2. This indicates that RPB material is technically feasible for use in ship hull shell construction.

3.2. Scantling Calculation Results

The ship design examined in this study is a 4 GT fishing vessel operating in the Bangka Belitung Islands. This vessel's design data and main dimensions are utilized for calculating the hull construction dimensions, adhering to the DNVGL-ST-0342 Craft 2016 Standard and the Turk Loydu 2014 Tentative Rules for Polyethylene Crafts. As shown in the line plan drawing (Figure 11), this ship has a slender shape and resembles a traditional Jukung-type vessel but does not feature an outrigger. The primary dimensions of the ship, along with any additional pertinent measurements, are shown in Figure 11. In terms of length, the vessel measures 10 meters in length overall (LoA), while its draft (T) measures 0.6 meters. Two and a half meters are the frame spacing that was utilized in the construction. In addition, the pace at which this vessel completes its operations is ten knots.



Main Dimensions	Notation	Value
Length Overall	L_{OA}	10 (m)
Length at the waterline	L_{WL}	9.52 (m)
Length Between Perpendicular	L_{BP}	9.52 (m)
Breadth	W	2 (m)
Height	H	1.5 (m)
Draft	D	0.6 (m)
Service Speed	V_S	10 Knot
Block Coefficient	C_B	0.546
Gross Tonnage	GT	4

Figure 11. Fishing Vessel' s Lines Plan 4 GT size and its main dimensions

Calculating the hull for a fishing vessel involves two key stages: determining the load on the hull and calculating the minimum thickness of the hull. According to the method outlined in Section 2.3, the side load acting on the vessel is measured at 42.32 kN/m². However, the base load is recorded at 44.56 kN/m². Given that the recycled plastic waste board product used in manufacturing provides an equivalent thickness, it is assumed that the vessel's construction will utilize the same thickness for the hull on both sides and the base. Therefore, in the subsequent calculations, the maximum load–44.56 kN/m² (base load)–will be used as the main load.

The minimum thickness of the hull shell is calculated using Eq. 9. Based on these calculations, the hull shell minimum thickness is 21 mm. This assessment is not limited to recycled plastic sandwich panel materials but includes calculations using FRP and solid teak wood. The minimum hull shell thickness for FRP and solid wood is calculated according to the BKI Volume VII Rule for Small Vessels up to 24 m [37]. This analysis compares each material's construction sizes, subsequently influencing each option's economic analysis. The overall calculation results of the minimum thickness calculation of the ship's hull can be seen in Table 3.

Table 3. Comparison of Minimum Ship′s hull shell thickness

Material	**Minimum Thickness (mm)**	
	DNV-GL & Turk Loydu	BKI
Recycled plastic Waste Board (RPB)	21	-
Fiberglass-Reinforced Plastic (FRP)	-	7.4
Solid Wood (Teak)	-	25

The comparison of the shell thickness of RPB, FRP, and teak wood was then applied to a fishing vessel of the same size and weight, which was a-4 Gross Tonnage (GT) fishing vessel, to determine the volumetric material required and the economic comparison involved in the construction of fishing vessels using them.

3.3. Economic Analysis

Economic analysis aims to determine the costs associated with the hull construction process using different materials. This analysis directly compares building costs for recycled plastic waste boards, fiberglass-reinforced plastic (FRP), and solid wood. The cost calculation is divided into material, labor, and overhead. This assessment seeks to evaluate the feasibility of recycled plastic sandwich panel material as a competitive alternative to traditional hull materials like teak and fiberglass. To calculate the hull construction costs, we will simulate the building of a ship using data outlined in Section 3.2. The work area, specifically the hull and transom areas, must be determined before performing the construction cost calculations. The hull shell area of the vessel is 31.76 m^2 and the transom is 0.74 m^2. The total area required for hull construction based on the line plan data is 32.5 m^2. This area is then multiplied with hull thickness to ascertain the material and labor needed to construct the ship for each type of material.

3.3.1. Material Cost

The amount and cost of materials used in hull building decide material costs. Recycled Plastic-Waste Board (RPB) ship building contains three key material elements: RPB, adhesive, and coating (paint). Given the hull is made utilizing a lamination technique, the material needs were determined from the hull area to be built. Measuring 1000 mm x 80 mm x 12 mm, the RPB has a surface area of 0.08 m². The glue also spreads at 0.3 kg/m². Table 4 compiles the number and cost of materials required to build a ship using RPB using this data. Building a ship's shell with RPB material will cost IDR 19,812,500 altogether. Of this whole cost, the RPB material makes up 69.72%, or IDR 13,812,500.

Table 4. Summary of Material Cost using RPB

Material Component	**Quantity**	**Unit**	**Cost per Unit (IDR)**	**Total Cost (IDR)**
RPB	1,625	Board	8,500	13,812,500
Adhesive	30	Kg	150,000	4,500,000
Finishing Coat	3	L	500,000	1,500,000
			Total Material Cost	**19,812,500**

Furthermore, the materials used to construct FRP (Fiberglass Reinforced Plastic) ships include fiberglass, resin, aerosol, catalysts, and color pigments. For the ship's hull shell, three types of fiberglass are utilized: Chopped Strain Mat (CSM) 300, CSM 450, and Woven Roving (WR) 600. The quantities of fiberglass and resin required are based on the lamination area and the number of layers needed. Additionally, CSM fiberglass has a resin ratio 30:70, meaning that for every 30 grams of fiberglass, 70 grams of resin are required. In contrast, WR fiberglass has a resin ratio of 45:55. The hull skin of this ship comprises ten layers: one layer of gelcoat, three layers of CSM 300, four layers of CSM 450, and two layers of WR 600. The total material costs and requirements for building an FRP ship are outlined in Table 5. The total material cost amounts to IDR 30,581,000, with the most significant expense being resin procurement, which costs IDR 14,785,000. Additionally, the procurement of CSM 450 fiberglass incurs the highest cost compared to other fiberglass types, totaling IDR 3,250,000.

Table 5. Summary of Material Cost using FRP

Material Component	Quantity	Unit	Cost per Unit (IDR)	Total Cost (IDR)
Resin	287	Kg	55,000	14,785,000
Aerosol	33	Kg	156,000	5,148,000
Catalyst	3	Kg	67,000	201,000
Color pigment	2	Kg	86,000	172,000
Wax	1	Can	140,000	140,000
CSM300	98	m^2	20,000	1,960,000
CSM450	130	m^2	25,000	3,250,000
WR600	65	m^2	35,000	2,275,000
Finishing Coat	3	L	550,000	1,650,000
			Total Material Cost	**30,581,000**

On the other hand, the fishing vessel made of solid wood needs the teak wood itself, the adhesive, the bark of wood (for tightness on the between woods joint), and the coatings (paint) as the main materials. Purchasing teak wood is typically based on cubic capacity, with pricing calculated per cubic meter (m^3). To determine the required amount of teak wood, the surface area of the ship's skin can be multiplied by the wood's thickness to find the total volume needed. The usage rates for adhesive and finishing paint estimate at around 0.6 kg/m^2 and 0.25 kg/m^2, respectively. Table 6 provides a comprehensive breakdown of the total costs and material requirements for shipbuilding with solid wood. The overall cost amounts to IDR 49,470,000, making it the most expensive option compared to RPB and FRP. The primary expense is the procurement of teak wood, which alone requires IDR 46,000,000 for one m^3.

Table 6. Summary of Material Cost using Solid Wood

Material Component	Quantity	Unit	Cost per Unit (IDR)	Total Cost (IDR)
Teak Wood	1	m^3	46,000,000	46,000,000
Adhesive	4	Kg	180,000	720,000
Finishing Coat	24	L	110,000	2,750,000
			Total Material Cost	**49.470.000**

3.3.2. Labor Cost

Labor cost analysis for ship hull construction involves calculating and directly comparing the labor costs associated with three different materials: RPB (Recycled Plastic Board), FRP (Fiberglass Reinforced Plastic), and solid wood. The process entails detailing the work required for each material and estimating the labor requirements (man-hours) necessary to complete the tasks. A summary of the labor costs is presented in Table 7, which calculates using different tasks since the building process of these three types of material boats has different components and processes.

Table 7. Summary of Labor Cost

Material Type	Tasks/Processes	Productivity (MH/m^2)*	Total Work Area (m^2)*	Total Workers	Duration (Days)	Cost (IDR)	Total Cost (IDR)
RPB	1st layer assembly	5.56	32.50	6	4	2,800,000	13,600,000
	2nd-4th layer assembly (3 layers)	6.11	97.50	6	14	9,800,000	
	Finishing	2.00	32.50	2	4	1,000,000	
FRP	1st layer (wax, gelcoat, CSM300)	1.50	32.50	4	1	600,000	9,600,000
	2nd layer (CSM300)	1.25	65.00	4	3	1,800,000	
	3rd layer (CSM450)	1.25	130.00	4	5	3,000,000	
	4th layer (WR600)	1.75	65.00	4	4	2,400,000	
	Finishing	2.50	32.50	4	3	1,800,000	
Solid Wood	Fabrication	175	0.81	3	7	4,550,000	29,250,000
	Assembly	725	0.81	6	15	19,500,000	
	Finishing	200	0.81	3	8	5,200,000	

*For solid wood, productivity and total work area go with (MH/m^3) and m^3

For constructing the hull shell with RPB, six workers are needed: two craftsmen and four helpers. In the finishing phase, only one craftsman and one helper are required. Labor costs depend on the duration of the work and the daily labor rates. The daily costs for craftsmen and helpers using RPB materials are set at IDR 150,000 and IDR 100,000, respectively. RPB is generally a more economical option due to its straightforward construction process, which does not necessitate specialized skills. Consequently, the total labor cost for construction with RPB amounts to IDR 13,600,000.

In contrast, using FRP results in the lowest labor cost, totaling IDR 9,600,000. Despite having the cheapest labor cost, FRP involves the highest number of tasks (five types of process) due to its quicker processing time and higher worker productivity. Only four workers are required: two craftsmen and two helpers. The daily rate for craftsmen is IDR 200,000, while helpers earn IDR 150,000 per day. Although the labor cost for craftsmen in FRP is slightly higher than for RPB, this is justified by the necessity for greater skill.

The highest labor cost is associated with constructing the hull shell from solid wood, reaching IDR 29,250,000. While FRP requires lower labor costs despite involving more tasks, solid wood construction features only three processes but demands significantly more time. Additionally, woodworking calls for skilled labor, resulting in increased daily rates. The cost for a craftsman working with solid wood is IDR 250,000 per day, while helpers earn IDR 200,000.

3.3.3. Overhead Cost

Overhead costs are those incurred by building a fishing vessel's hull, excluding material and labor charges. These expenses are classified as indirect ones connected to the building process. The simulation for determining the cost of constructing a fishing vessel hull shows overhead such as power and consumables. Table 8 lists the overhead expenses related to building a hull utilizing three distinct materials: Recycled plastic waste Board (RPB), fiberglass reinforced plastic (FRP), and solid wood (teak). It indicates that, when compared to teak wood, the overhead expenses for constructing a hull using RPB and FRP reveal that the material with the most overhead cost is teak wood, totaling IDR 1,674,500. Teak wood also has the highest electricity costs–IDR 747,000–because of the large and energy-consuming machinery needed for its preparation.

Table 8. Summary of Overhead Cost

Material Type	Cost Component	Cost (IDR)	Total Cost (IDR)
RPB	Consumables	169,500	517,500
	Electricity	348,000	
FRP	Consumables	595,000	746,000
	Electricity	51,000	
Solid Wood	Consumables	927,500	1,674,500
	Electricity	747,000	

3.3.4. Comparison of Building Cost

The construction of the hull of a fishing boat with different materials requires different production methods and material requirements. These variations affect the cost of building the hull for each material. Table 9 compares building costs between the three materials (RPB, FRP, and solid wood). Based on Table 9, the hull of a boat made of teak wood requires the highest construction cost, IDR 80,394,500. The following material has the second highest cost: fiberglass, with a construction cost of IDR 40,927,000. The cheapest total building cost is RPB, with a total cost of IDR 33,930,000. This advantage is reflected in the material cost and overhead cost, where the use of RPB is cheaper than the others.

Table 9. Comparison of Building Cost (all in IDR)

Cost	RPB	FRP	Solid Wood
Material Cost	19,812,500	30,581,000	49,470,000
Labor Cost	13,600,000	9,600,000	29,250,000
Overhead Cost	517,500	746,000	1,674,500
Total Cost	**33,930,000**	**40,927,000**	**80,394,500**

Although RPB has the lowest total construction cost, it is essential to keep in mind that FRP has a considerably lower labor cost. When compared to the labor cost of RPB, which is IDR 13,600,000, the labor cost for FRP is IDR 9,600,000. The result is a 29.42% reduction. This difference in cost is a result of the smaller thickness of the FRP skin, which makes the process of craftsmanship more productive and less time-consuming. On the other hand, the labor cost for teak wood is the highest, reaching IDR 29,250,000. This is because the production of teak wood requires more highly skilled workers. The results of this calculation suggest that the use of RPB (Recycled Polymer Building) is not only feasible but also advantageous from a financial standpoint when it is used to construct the hulls of fishing vessels. In addition to its favorable impact on cost-effectiveness, RPB makes a positive contribution to environmental sustainability by limiting the ecological footprint associated with traditional materials and reducing the amount of trash produced. The environmental benefit contributes to the creation of a ripple effect, which improves economic prospects and ensures that future generations will continue to benefit from these advantages.

4. Conclusion

In conclusion, this study demonstrates that using Recycled Plastic Waste Boards (RPB) as a construction material for fishing vessel hulls is technically and economically viable. The mechanical testing conducted shows that RPB possesses sufficient tensile and flexural strength, complying with the standards established by ship construction classification. This result indicates that the RPB has potential to be operated in the marine environment, making it an alternative material to substitute solid wood and fiberglass-reinforced plastic (FRP) for fishing vessels. From an economic standpoint, the analysis indicates that utilizing RPB lowers material costs and addresses the urgent issue of plastic waste management. Transforming plastic waste into a durable construction material supports the principles of a circular economy, offering a sustainable solution that benefits both the fishing industry and the environment. The adoption of RPB in fishing vessel construction presents significant benefits, including increased durability, reduced environmental impact, and cost savings. As Indonesia faces considerable plastic pollution and relies heavily on its fishing sector, shifting to RPB for hull construction provides an innovative opportunity to alleviate environmental challenges while supporting local economies. Therefore, integrating recycled materials like RPB into maritime applications represents a promising step toward sustainable development in Indonesia's fishing industry.

Future studies should investigate a wider spectrum of mechanical tests to better understand the structural behavior of Recycled Plastic Board (RPB) in maritime uses. In particular, studies on long-term durability in saltwater conditions, macro- and microstructural features, and impact resistance would offer insightful analysis of the appropriateness of the material for prolonged use in shipbuilding. The creation of hybrid materials–combining RPB with other low-cost, high-strength materials–also offers interesting possibilities for improving mechanical performance while preserving economic viability. From an economic standpoint, more research might expand the cost modeling to cover bigger fishing boats or other vessel kinds, therefore allowing the discovery of pricing patterns and cost-efficiency across different ship sizes and configurations. This would help to strengthen RPB's feasibility as a sustainable material in more general maritime environments.

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