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The Effect of Comparative Differences in Composition of Oil Palm Empty Fruit Bunches (OP-EFB) and HDPE Plastics: Physical and Mechanical Properties of Wood Plastic Composite (WPCs)

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***Abstract**. Conventional wood composites face significant challenges such as moisture absorption, low durability, and susceptibility to termite attacks, limiting their application in outdoor and structural environments. Wood Plastic Composites (WPCs) offer a more durable and sustainable alternative by combining lignocellulosic fibers with thermoplastics, enhancing mechanical strength, water resistance, and longevity. This study's Wood Plastic Composite (WPC) is developed using oil palm empty fruit bunches (OP-EFB) as fillers and plastic as the matrix. This research aims to evaluate the impact of varying compositions of OP-EFB and HDPE plastic on the physical and mechanical properties of WPCs. The composition ratios of OP-EFB to plastic examined in this study include 60:40, 55:45, 50:50, 45:55, and 40:60, with the addition of maleic anhydride (MAH) as a coupling agent and benzoyl peroxide (BPO) as an initiator. The board manufacturing process was conducted at 170°C with a pressing duration of 10 minutes. The findings indicate that variations in the OP-EFB and HDPE plastic ratios significantly influence the properties of the resulting WPCs. The optimal composition was determined to be a 45:55 ratio of OP-EFB to HDPE plastic, yielding a density of 0.83 g/cm³, water absorption of 0.21%, modulus of rupture (MOR) of 180.86 kg/cm², parallel surface compressive strength of 200.48 kg/cm², and perpendicular surface compressive strength of 47.13 kg/cm². Overall, the physical and mechanical properties of the WPC meet the requirements of SNI 8154-2015 standards for wood-plastic composites.*
***Keywords:** WPCs; OP-EFB; HDPE plastic; MAH.*

Type of the Paper: Regular Article.

1. Introduction

Wood Plastic Composites (WPCs) have emerged as an innovative and sustainable alternative to traditional wood composites due to the numerous limitations associated with the latter. Conventional wood composites, such as plywood and particleboard, are highly susceptible to moisture absorption, leading to swelling, warping, and decay. Additionally, they are prone to termite attacks and fungal growth, which significantly reduces their durability and lifespan. The mechanical strength of wood composites is also relatively low, limiting their applications in

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structural and outdoor environments. Furthermore, the production of wood composites relies heavily on virgin timber, contributing to deforestation and environmental degradation. These challenges have driven the development of WPCs, which combine lignocellulosic fibers with thermoplastic matrices such as high-density polyethylene (HDPE) or polyvinyl chloride (PVC). By incorporating recycled plastics and agricultural waste, such as oil palm empty fruit bunches (OP-EFB), WPCs not only offer improved mechanical properties but also enhance water resistance, termite resistance, and weather durability. The integration of thermoplastics acts as a protective barrier, preventing moisture penetration and increasing the lifespan of the material. Additionally, WPCs require minimal maintenance and provide better aesthetic flexibility compared to traditional wood composites. Therefore, the development of WPCs presents a more durable, eco-friendly, and cost-effective solution for various applications, including construction, furniture, and outdoor structures. However, further research is needed to optimize the composition and processing parameters to enhance the mechanical performance and sustainability of WPCs.

Wood Plastic Composites (WPCs) are innovative materials combining wood fibers with thermoplastics, offering advantages such as durability, low maintenance, and environmental sustainability. The selection of filler materials and polymer matrices significantly influences the physical and mechanical properties of WPCs [1]. The wood-plastic composite (WPCs) consisted of lignocellulose, lignin, recycled thermoplastic plastic (PVC), mineral powder, a plasticizer such as triethyl phosphate, an impact modifier (including chlorinated polyethylene, high-elasticity acrylate-type modifier, or acrylonitrile-butadiene-styrene copolymer), along with other processing additives [2]. Wood polymer composites (WPCs) have been developed as alternative materials by combining synthetic thermoplastic polymers as the matrix with lignocellulosic fibers as the dispersed phase [2,3].

Indonesia ranks among the world's top palm oil producers, with oil palm plantations covering 15.38 million hectares in 2022 and yielding 48.23 million tons of production [4]. Oil Palm Empty Fruit Bunches (OP-EFB), a byproduct of the palm oil industry, have emerged as a promising filler material due to their abundance and lignocellulosic composition. Oil palm empty fruit bunches (OP-EFB) are a type of lignocellulosic agricultural waste that can negatively impact the environment [5,6]. OP-EFB is a potential raw material for reinforcing material in composites without being continuously developed, so research innovations on OP-EFB composites are needed [7]. Oil palm empty fruit bunches (OP-EFB) can be converted into composite boards with greater market value by utilizing their cellulose as fiber [8]. Studies have demonstrated that OP-EFB fibers can enhance the mechanical properties of composites. For instance, hybridizing OP-EFB with ramie fibers in an epoxy–carbon nanotube matrix improved tensile strength by up to 127% compared to non-hybrid composites [8]. The findings indicate that the ratio of empty fruit bunches

(EFB) to crude palm oil (CPO) produced by palm oil mills is approximately 27:23. On average, manufacturers generate around 3,558.8 tons of EFB per month. Most palm oil mills manage their EFB waste through mulching treatment. This suggests that palm oil mills in Indonesia have not yet widely adopted the advanced technologies developed by researchers [9].

Polymer composites are a key focus of contemporary research in material science [10]. High-density polyethylene (HDPE) is commonly used as a matrix in WPCs because of its high strength-to-density ratio, chemical resistance, and recyclability. The density of HDPE ranges from 930 to 970 kg/m³, and it exhibits a tensile strength of approximately 38 MPa. Studies show that WPCs utilizing HDPE matrices possess excellent mechanical properties. For instance, research on plastic composite boards composed of OP-EFB and HDPE found that the optimal modulus of rupture (MOR) reached 134.40 kg/cm² when subjected to a pressing temperature of 170°C [11].

The composition and processing parameters of WPCs, such as the ratio of filler to polymer and pressing temperature, play crucial roles in determining their final properties. Optimizing these factors can lead to composites with enhanced mechanical strength and water resistance, making them suitable for various applications, including construction and furniture manufacturing [2]. In summary, the integration of OP-EFB fibers and HDPE in WPCs presents a sustainable approach to producing materials with improved physical and mechanical properties. Further research into the comparative effects of different compositions and processing conditions will contribute to the development of high-performance WPCs.

This study presents a novel approach to optimizing the composition of Oil Palm Empty Fruit Bunches (OP-EFB) and High-Density Polyethylene (HDPE) plastic in Wood Plastic Composites (WPCs), focusing on both physical and mechanical properties. Unlike previous research that primarily explores the use of OP-EFB in composites without detailed composition optimization, this study systematically investigates the effects of varying OP-EFB-to-HDPE ratios. The inclusion of maleic anhydride (MAH) as a coupling agent and benzoyl peroxide (BPO) as an initiator further enhances interfacial adhesion, leading to improved mechanical performance.

2. Materials and methods

2.1. Materials

The material utilized in this study consisted of oil palm empty fruit bunches (OP-EBF), which were sourced from PTPN (Perseroan Terbatas Perkebunan Nusantara) VI, located in West Pasaman Regency, West Sumatra which had been chopped and compressed, plastic seeds, coupling agents MAH (maleic anhydride) was acquired from Merck, and BPO (benzoyl peroxide) initiator. The tools used are electric heater, sieve (40 and 60 mesh), oven, measuring cup, goblet, bucket, scale, material mold, aluminum plate, cutting saw, cutter, chopping machine, cold felts, hot felts, and testing machine for physical and mechanical properties of WPC boards.

2.2 Preparation of Wood Plastic Composite (WPCs)

OP-EBF that has undergone compression is broken down to produce fiber. Then the fibers are pulverized and sieved until the particles pass the 60 mesh sieve. Then dried to 10% moisture content. HDPE plastic seeds that will be tested are mashed using a disk mill. Then 5 containers were prepared according to the number of test samples carried out. Then each container is filled with plastic according to the percentage of plastic used. The plastic is pulverized with particles passing 10 mesh. The material calculations carried out in the WPCs manufacturing process are as follows:

1) The produced panels have the following dimensions 20 x 20 x 1 cm^3
2) Desired board density (ρ) is 1.0 g/cm^3
3) Weight of OP-EFB for one panel according to the treatment tested
4) Calculation of the weight of one board is done by formula $\rho = \frac{m}{v}$, so that it is obtained 400 g
5) The weight of MAH used is 5% of the total weight of the material so that 12 g are obtained.
6) The weight of BPO used is 15% of the total weight of MAH so that 1.8 g are obtained

2.3 Manufacturing of Wood Plastic Composite (WPCs)

The process of manufacturing wood plastic composite (WPCs) are as follows: (1) Blending of OP-EFB fiber particles with plastic at 60:40; 55:45; 50:50; 45:55 and 40:60 w/w. (2) Addition of MAH as coupling agent and BPO as initiator to the plastic and fiber mixture. (3) Pouring the mixture into a mold measuring 20 cm x 20 cm x 1 cm which is placed on an aluminum plate evenly. (4) Covering the candidate board with another aluminum plate. (5) Forging with cold felts is carried out for 20 minutes until a board sheet with a thickness of approximately 2 cm is formed. (6) Cold forging for 20 minutes until a board sheet with a thickness of approximately 2 cm is formed. (7) Hot forging with a temperature of 170 ^{o}C for 10 minutes.

2.4 Research Observations of Wood Plastic Composite (WPCs)

The analysis carried out on oil palm empty fruit bunches (OP-EFB) included moisture content [12], hemicellulose, cellulose and, lignin [13]. Observations of the physical properties of composite boards are density, water absorption [14], while observations of the mechanical properties of composite boards are fracture firmness, surface parallel compressive, and surface perpendicular compressive firmness [14].

3. Results and Discussion

3.1 Chemical Analysis of Oil Palm Empty Fruit Bunches (OP-EFB)

Before making WPC, the first thing to do is to analyze the chemistry of OP-EFB fibers. The chemical composition of the OP-EFB fiber is obtained in the following Fig. 1.

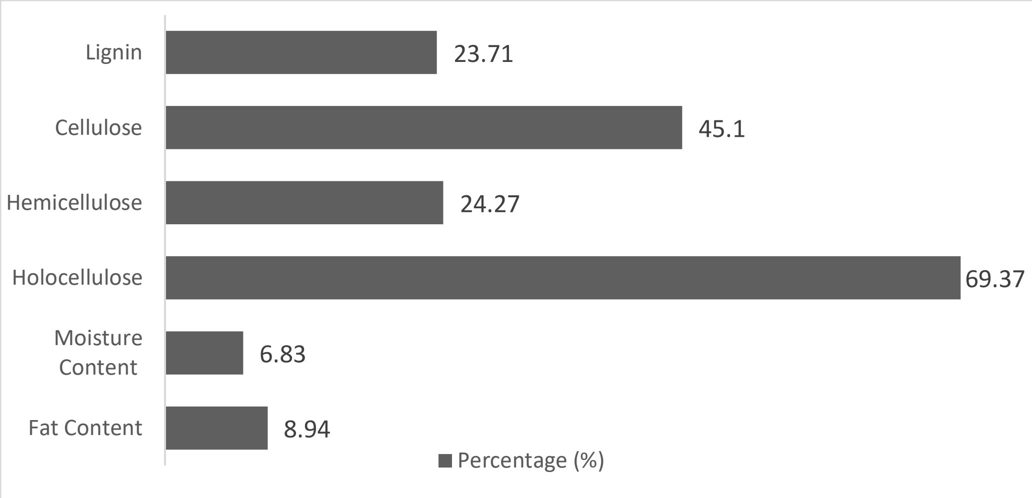


Fig. 1. Chemical Component of OP-EFB Fiber

Based on the results of the analysis carried out as described in Fig. 1, the composition of OP-EFB fiber is obtained with a moisture content of 6.83%, fat content of 8.94%, holocellulose 69.37%, hemicellulose 24.27%, cellulose 45.10% and lignin 23.71%. Cellulose content is very necessary in making WPC. The components contained in OP-EFB consist of cellulose 47.81%, holocellulose 64.29%, lignin 23.13%, hexane soluble component 2.36%, water 12.25% [15]. Testing the composition of the fibers in OP-EFB of PT Kharisma Alam Persada South Borneo produces data on cellulose, lignin and hemicellulose content, respectively at 55.75%; 28.93% and 15.32% [16]. Various factors including climate, variety, and region of the palm plant cause the difference in analysis results.

3.2 Physical and Mechanical Properties of Wood Plastic Composite (WPCs)

Density is one of the physical properties that affect the strength of WPCs. Density is the ratio between the mass of wood and its volume during dry conditions. The density also affects the strength of the board produced. The impact of density and surface layer properties on particle board quality was analyzed, and a comparison was made with recent studies [17]. The higher the density, the higher and stronger the mass of the board will be. The adhesion between the boards will affect the density of the boards produced. The stronger the adhesion between the particles, the stronger the board will be. The average density values can be seen in Fig. 2.

Based on Fig. 2, the resulting WPCs density values range from 0.76 g/cm^3 to 0.94 g/cm^3. The highest density value was obtained in treatment C with an average density of 0.94 g/cm^3 and the lowest density level in treatment E with a density of 0.74 g/cm^3. The average value of composite board density ranged from 0.52 gr/cm^3- 0.73 gr/cm^3 of composite boards from oil palm trunks (elaeis guineensis jacq) and polypropylene plastic waste in some variation of the ratio and addition of maleic anhydrid [18]. The density of WPCs is affected by the distribution of particles between OP-EFB and HDPE plastic which is evenly mixed so that the filler is bonded to a denser matrix. The composition of OP-EFB that is too high causes the adhesion between the particles to each other is not optimal so that the density of the resulting WPCs is reduced. This happens because the matrix cannot accommodate all the filler, so the resulting WPCs' density is reduced. Meanwhile, the composition of HDPE that is too high causes the formation of pores in the matrix that cannot be fully filled by the filler so that the density of composite board/WPCs is reduced.

Low density arises when the filler does not fill the pores [19], for matrices that are not filled by fillers, they cause pores that cause a lack of density in WPCs [20]. To produce the best WPCs density value, it is necessary to evenly distribute the composition of the matrix and filler in a balanced manner. In addition, a coupling agent (polymer binder) is also added to improve the bond between the matrix and the filler. The density is also affected by the moisture content of the OP-EFB used [21]. High moisture content can decrease the density value of the resulting WPCs. According to the SNI 8154–2015 standard, the density value of the composite board/WPCs produced must be following the minimum density limit of ≥ 0.60 g/cm³.

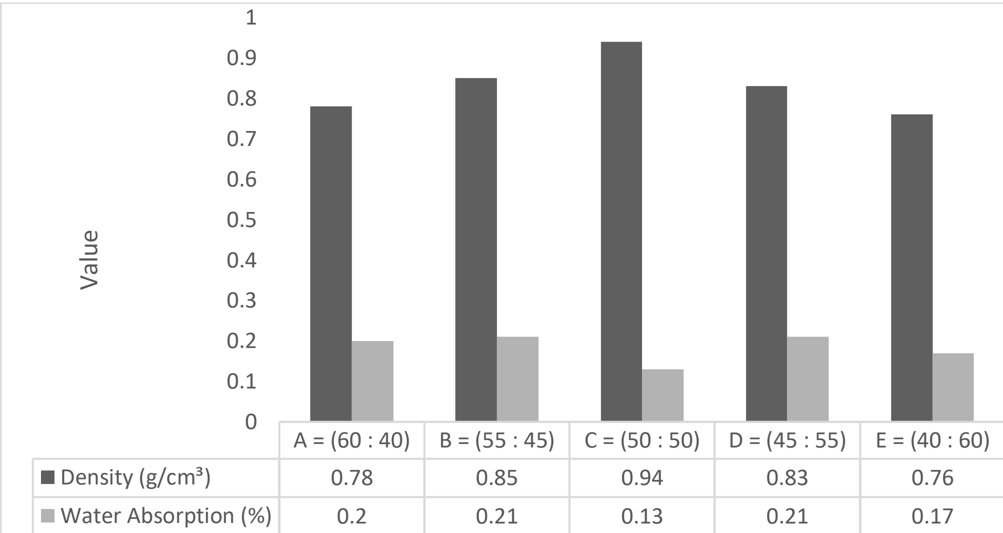


Fig. 2. Density and Water Absorption of Wood Plastic Composite (WPCs)

Water absorption is the amount of water that WPCs can absorb in percent of the initial weight of WPC after soaking at room temperature for 24 hours. Based on the method of absorption, water absorption is distinguished into two types, namely water entering through the empty cavity between the fibers and the matrix and water entering the filler that forms WPCs [21]. Based on Fig. 2, the water absorption value of WPCs produced ranges from 0.13% to 0.21%. The highest water absorption value was found in treatment B (0.21%), while the lowest absorption value was in treatment C (0.13%). The Indonesian National Standard (SNI) does not require a water absorption value, but the water absorption test can be used as a consideration in applying WPCs as an exterior or interior material.

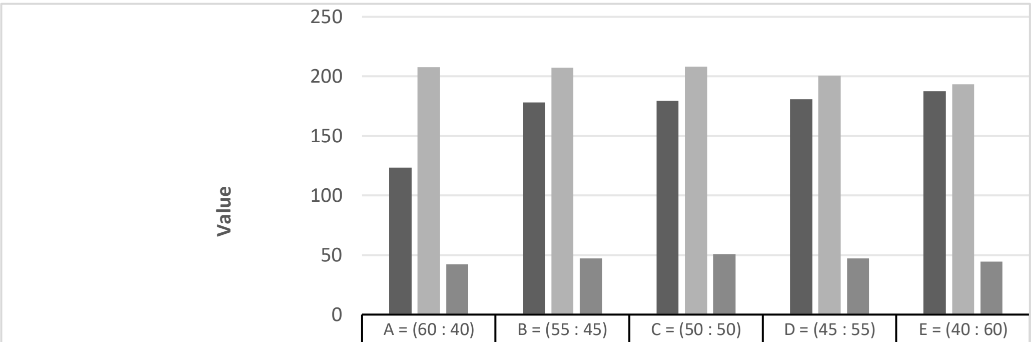
Fracture Strength / Modulus of Rupture (MOR) is the bending strength of the board in withstanding the accepted load up to the point of the maximum acceptable load capacity. MOR is like a three-point bend test. MOR measures the bond strength of the test specimen [22]. Fracture strength is directly proportional to WPCs quality. Fracture strength refers to a material's capacity to withstand failure, which is defined based on the type of applied load, including tensile, compressive, or bending forces [23]. The higher the value of WPCs fracture strength, the stronger the WPCs is in bearing the load. Based on Fig. 3. The resulting WPCs fracture strength value ranges from 123.33 kg/cm² to 187.76 kg/cm². The highest fracture strength value was in treatment E (187.76 kg/cm²) and fracture fastness in treatment A (123.33 kg/cm²). Converting these to megapascals (MPa), the range is approximately 12.1 MPa to 18.4 MPa. The average value of WPCs fracture strength increased with the high concentration of plastic seeds. The higher the concentration of plastic used 33 kg/cm², the higher the WPCs fracture strength produced. Another study investigated the fracture toughness of WPCs, estimating it to be 1.79 MPa using a four-point bending test [24].

Research findings showed that the composite board's average MOR value ranged from 139.58 kg/cm² to 233.52 kg/cm². The composite board with a plastic ratio of 40:60 and 2.5% MAH had the highest fracture consistency, while the board with a plastic ratio of 60:40 and 0% MAH had the lowest. The results indicate that the MOR value can increase with a higher concentration of plastic used. The increase in MOR value is attributed to plastic properties, which enhance WPCs flexibility, making the board more resistant and raising the MOR value. According to SNI 8154-2015, the WPCs fracture strength must meet a minimum 180 kg/cm² standard. The average results of the research that complied with SNI 8154-2015 were treatment D (180.96 kg/cm²) and treatment E (187.76 kg/cm²). Meanwhile, treatments A, B, and C did not comply with the SNI 8154-2015 standards.

Surface parallel press strength refers to the ability of WPC to withstand applied loads until they become damaged and can no longer support the received load. Surface alignment is evaluated when the sample is aligned, followed by applying pressure until the sample is damaged or destroyed [25]. Based on Fig. 3, the resulting WPCs surface parallel compressive strength value ranges from 193.49 kg/cm² to 208.38 kg/cm². WPCs highest surface alignment fastness value was in treatment C (208.38 kg/cm²), and the lowest was in treatment E (193.49 kg/cm²). The surface alignment of treatment E (193.49 kg/cm²) does not meet the minimum requirement of 200 kg/cm² as specified by the SNI 8154-2015 standard. In contrast, treatments A, B, C, and D have successfully met this standard. The compressive strength parallel to the surface is influenced by the composition of the OP-EFB material and the type of plastic used. Additionally, the compressive strength parallel to the surface is directly related to the board's density—higher density results in greater compressive strength [26].

Surface Perpendicular Press Firmness refers to the strength of WPCs in withstanding the load applied until they are damaged and cannot handle the force exerted by load [27]. The perpendicular robustness of the surface is tested when the sample is in a perpendicular state, which is then pressed until the sample is damaged and destroyed and based on Fig. 3. The resulting WPCs surface perpendicular compressive strength value ranges from 42.3 kg/cm² to 50.83 kg/cm². The highest surface perpendicular compressive strength value was obtained in treatment C (50.83kg/cm²) and the lowest surface perpendicular compressive strength was obtained in treatment A (42.3 kg/cm²). A balanced comparison between the composition of OP-EFB and the plastic used influences the average perpendicular fastness value of the installation. The further the comparison of the composition of OP-EFB and the plastic used, the lower the value of perpendicular compressive strength of the resulting surface.

The fiber and plastic composition ratio is too high in WPCs, causing the filler not to be completely dissipated in the matrix so that cavities are formed on the resulting board. Increasing cavities can lower WPCs' surface perpendicular compressive strength value [27]. Based on SNI 8154-2015, the surface perpendicular compressive strength value in the resulting WPCs must meet the minimum 50 kg/cm² standard. From the research that has been carried out, the average value of perpendicular compressive strength of the surface that meets the standard is treatment C, with a value of 50.83 kg/cm². Meanwhile, treatment A, B, D, and E still do not meet SNI 8154-2015. The physical and mechanical properties of wood plastic composite (WPCs) can be seen in Fig. 3.



	A = (60 : 40)	B = (55 : 45)	C = (50 : 50)	D = (45 : 55)	E = (40 : 60)
Modulus of Rupture (MOR) (kg/cm²)	123.33	178.16	179.6	180.96	187.76
Surface Parallel Press Strength (kg/cm²)	207.93	207.36	208.38	200.48	193.49
Surface Perpendicular Press Firmness (kg/cm²)	42.3	47.16	50.83	47.13	44.33

Fig. 3. Physical and Mechanical Properties of Wood Plastic Composite (WPCs)

3.3 Recapitulation of Properties – Properties of WPC from TKKS and HDPE Plastic with Differential Treatment of Material Composition Comparison

Based on Table 1, it can be seen that the difference in the comparison of the composition of OP-EFB and HDPE plastic to the physical and mechanical properties of WPCs includes density, water absorption, MOR, surface parallel compressive strength, surface perpendicular compressive strength. The WPCs density obtained has met SNI 8154-2015, while the MOR that meets the SNI 8154-2015 standard is D and E treatment, for the surface parallel compressive strength that meets the SNI 8154-2015 standard is the A treatment,B, C, and D. Meanwhile, the perpendicular pressure strength of the surface following the SNI 8154-2015 standard is treatment C. Table 1 presents a summary of the recapitulated data on the physical and mechanical properties of WPC made from oil palm empty fruit bunches and plastic, considering variations in material composition. Water absorption is not part of the SNI 8154-2015 standard assessment criteria.

Table 1. Recapitulation of Physical and Mechanical Properties of WPCs from OP-EFB and HDPE plastic with Different Material Composition Treatments Compared to SNI 8154-2015.

Composition OP-EFB: Plastic	Density (g/cm³)	Water Absorption (%)	Modulus of Rupture (MOR) (kg/cm²)	Surface Parallel Press Strength (kg/cm²)	Surface Perpendicular Press Firmness (kg/cm²)
SNI 8154 - 2015	**≥ 0,60**	**-**	**≥ 180**	**≥ 200**	**≥ 50**
A (60:40)	0.78	0.20	1233.33	207.93	42.3
B (55:45)	0.85	0.21	178.16	207.36	47.16
C (50:50)	0.94	0.13	179.6	208.38	50.83
D (45:55)	0.83	0.21	180.96	200.48	47.13
E (40:60)	0.76	0.17	187.76	193.49	44.33

To determine the optimal composition OP-EFB and HDPE plastic in WPCs, a Multi-Attribute Decision Making (MADM) method using the Simple Additive Weighting (SAW) approach was employed. This method objectively assesses various material compositions by assigning weighted scores to key physical and mechanical properties, including density, water absorption, modulus of rupture (MOR), surface parallel compressive strength, and surface perpendicular compressive strength. The evaluation process involved ranking different composition treatments based on their overall performance in meeting the standards set by SNI 8154-2015. This systematic approach identified the most effective composition for achieving high-quality WPCs.

Table 2. Assessment Criteria of Physical and Mechanical Properties of WPC from OP-EFB and HDPE Plastic by MADM-SAW Method

Parameters	Grade 1	Grade 2	Grade 3
Density (g/cm³)	< 0.6 g/cm³	0.6 g/cm³ – 0.7 g/cm³	> 0.7 g/cm³
Water Absorption (%)	>10 %	5% - 10%	< 5%
Modulus of Rupture (MOR) (kg/cm²)	<180 kg/cm²	>183 kg/cm²	180 -183 kg/cm²
Surface Parallel Press Strength (kg/cm²)	<200 kg/cm²	>205 kg/cm²	200 – 205 kg/cm²
Surface Perpendicular Press Firmness (kg/cm²)	<50 kg/cm²	>52 kg/cm²	50 - 52kg/cm²

Based on data processing with MADM-SAW, the optimum results were obtained in treatment D with an average value of 2.6. The following values are density 0.83 kg/cm², water absorption 0.21%, fracture firmness 180.96 kg/cm², surface parallel compressive firmness 200.48

kg/cm², and surface perpendicular compressive firmness 47.13 kg/cm²

4. Conclusions

In conclusion, the study demonstrates that varying the composition of OP-EFB and HDPE plastic significantly influences the mechanical properties of wood plastic composites, notably enhancing fracture toughness and both surface parallel and perpendicular compressive toughness, while leaving density and water absorption largely unaffected. Utilizing the MADM-SAW method, the optimal formulation was identified as treatment D (45:55), which yielded a density of 0.83 kg/cm², water absorption of 0.21%, fracture toughness of 180.96 kg/cm², surface parallel compressive toughness of 200.48 kg/cm², and surface perpendicular compressive toughness of 47.13 kg/cm². These results underscore the critical role of filler-to-matrix ratios in optimizing composite performance and highlight the potential of OP-EFB reinforced WPCs for advanced, durable applications. Further research and technological advancements could enhance the properties and applications of WPCs in various industries.

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