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Exploration of a mixture of HMR (high moisture resistant) and HDPE (high-density polyethylene) as an environmentally friendly furniture board alternative

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ABSTRACT

Waste management remains a significant obstacle to sustainable living, particularly due to the accumulation of plastic waste at disposal sites and the furniture industry's growing reliance on unsustainable plywood materials. Annually, over 300 million tons of plastic waste are generated. High-Density Polyethylene (HDPE) plastic waste, often containing formaldehyde resin, and moisture-resistant (HMR) board waste are frequently discarded without proper processing, posing environmental concerns. Despite their valuable properties—HMR offers moisture resistance, while HDPE provides strength and recyclability—limited research exists on their synergistic application in sustainable composite materials. This study explores the integration of HDPE and HMR as an environmentally responsible alternative to conventional furniture boards. Employing a qualitative approach, including observation, expert interviews, and literature analysis, combined with a thermopressing methodology, the study identifies optimal mixing techniques for producing boards resistant to heat, humidity, and substantial loads. Three composition ratios were tested: 200:50, 190:60, and 180:70 (HDPE to HMR). Results demonstrate that the 200:50 composition achieved optimal performance, withstanding 23 kg loads without failure, exhibiting excellent water resistance over 24 hours, and showing superior fire resistance compared to conventional plywood. This research contributes to waste valorization and sustainable material innovation for furniture manufacturing.

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1. Introduction

Waste management is a critical aspect of environmental responsibility and represents one of the greatest challenges in sustainable living, particularly in reducing waste in final disposal sites. Research by Hanifah and Arumsari indicates that plastic bottles, despite their recyclable potential, are often unsuitable for recycling [1]. A typical plastic bottle consists of two types of plastic: PET (Polyethylene Terephthalate) for the body and HDPE (High-

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Density Polyethylene) for components such as bottle caps. These materials have distinct characteristics, and recycling typically targets the bottle body, which is easier to process, as bottle caps are harder to recycle [2].

Numerous innovations have emerged in HDPE waste management. For instance, research by Berliana and Artayasa demonstrates that HDPE plastic waste can be repurposed to create furniture with sufficient strength and durability to withstand loads [3]. Other studies have shown that recycled HDPE boards exhibit competitive mechanical performance when processed under appropriate thermal conditions [4]. Building on these findings, Dolza's study highlights that HDPE's high tensile strength, water resistance, and moldability make it an ideal material for composite products [5]. Furthermore, research by Bolong et al. indicates that recycled HDPE boards are suitable for outdoor furniture due to their adequate tensile and flexural strength and low water absorption [6].

Building upon these findings, extensive research has demonstrated HDPE's versatility in composite applications. Studies investigating the incorporation of natural fibers into HDPE matrices have shown promising results, with tensile and flexural strengths increasing by up to 25% and impact strength enhanced by up to 38% when properly processed [7]. The integration of recycled plastics in wood-plastic composites (WPCs) has been extensively studied, with Rahman et al.'s comprehensive review demonstrating successful applications across various industrial sectors. Their study emphasizes the importance of pre-processing treatments and advanced manufacturing techniques in enhancing WPC recyclability and eco-friendliness. It also highlights the transition toward circular economy principles in composite manufacturing. This focus aligns with current industry trends toward sustainable materials development, where waste valorization and end-of-life considerations are increasingly critical for achieving environmental sustainability goals. Research on textile waste utilization in HDPE composites revealed improved structural properties through effective bonding of textile fibers with the matrix. Furthermore, investigations into multi-material recycling have successfully produced furniture components from mixed HDPE materials, demonstrating the material's adaptability in various composite configurations.

Recent developments in green composites have demonstrated the viability of utilizing agricultural and forest industry waste in natural fiber-polymer composites, with studies showing promising mechanical properties when processed under optimal conditions [7]. Research by Jomboh et al. has established that natural fiber-reinforced hybrid composites offer sustainable alternatives to conventional materials while maintaining competitive performance characteristics [7]. These hybrid composites, combining natural and synthetic reinforcements, address environmental challenges associated with non-biodegradable synthetic fibers. They also overcome limitations such as high water absorption and low thermal stability inherent in purely natural fiber composites. Additionally, the development of hybrid composites represents a significant advancement in addressing the limitations of individual fiber types, as environmental challenges like non-biodegradability and poor recyclability of synthetic reinforcements necessitate exploring natural materials to fully or partially replace them. Investigations into bio-based composites from waste agricultural residues have shown successful applications in the construction and furniture industries [8]. While HDPE research has progressed significantly, High Moisture Resistant (HMR) materials represent another critical area of focus. HMR boards are engineered wood products designed to resist moisture better than conventional MDF through special resin formulations. These materials typically have a density of 750-800 kg/m³ and are widely used in high-humidity applications such as kitchen cupboards, bathroom vanities, and laundry facilities. Research by Fadilla et al. demonstrated that HMR offers superior mechanical properties and moisture resistance compared to regular MDF, making it suitable for water-exposed environments [9].

Studies on WPCs have established that component composition ratios significantly impact final properties, with wood flour content affecting flexural strength, tensile strength, and dimensional stability. Additionally, processing technologies have evolved to include various manufacturing methods such as extrusion, injection molding, and compression, each offering specific advantages for different applications.

Kertabumi Recycling Center processes HDPE waste into boards for various products, such as tables, chairs, accessories, and plaques. In its manufacturing process, Kertabumi partners with PT Trimitra Abadi Kreasindo, which specializes in fabrication and manufacturing services using precision cutting technology, including laser cutting from 3D designs. After eight years of operation, the company has found it challenging to process one of its most significant waste streams, HMR. HMR waste containing formaldehyde resin is often discarded without processing.

Despite the benefits of both HDPE and HMR, there is a lack of research investigating their synergistic application, particularly in fabricating moisture-resistant composite materials. This gap underscores the need for further studies to examine the mechanical and processing aspects of integrating HDPE and HMR to develop sustainable, high-performance composites. While the individual properties of HMR and HDPE are well-documented, no studies have systematically investigated their combination for composite board applications or evaluated their load resistance, fire resistance, and water resistance under standardized testing conditions, leaving critical performance questions unanswered. Current WPC research predominantly focuses on conventional wood fibers rather than engineered wood waste like HMR. Despite extensive HDPE recycling research, the challenge of processing HMR waste containing formaldehyde resin remains inadequately addressed. The literature lacks comprehensive studies on converting HMR waste into valuable composite materials or guidance on optimal HMR-HDPE mixing ratios for composite board production.

Previous research on wood-plastic composites has predominantly employed conventional methods, including extrusion [10], injection molding [5], and compression [11]. While these methods are effective for traditional wood fiber-HDPE combinations, they present limitations when processing HMR waste containing formaldehyde resin. Extrusion, commonly used in WPC manufacturing, requires high shear forces that may compromise the integrity of engineered wood particles. Injection molding, though suitable for small components, is unsuitable for producing large boards required in furniture applications. Song's research demonstrates that hot pressing is the most effective technique for melting HDPE when conducted within the appropriate temperature range of 170°C to 200°C [10]. This hot pressing approach was selected for this study due to its precise control over temperature, pressure, and processing time compared to conventional methods. Unlike extrusion or injection molding, hot pressing allows precise control of the consolidation process, essential when working with HMR particles that require careful handling to prevent resin degradation. Amarasinghe et al. showed that incorporating wood waste into composite panels can improve the physical and mechanical properties of the final product, particularly in terms of dimensional stability and water absorption capacity [11]. Nevertheless, the specific examination of this combination for modular furniture boards remains insufficiently investigated. Moreover, studies indicate that increasing the wood powder content within the HDPE matrix can enhance the composite's mechanical strength, provided the HDPE matrix is sufficient to effectively bind the wood filler [12].

This study investigates the feasibility of combining HMR and HDPE waste as a sustainable alternative to plywood, a material widely used in the furniture industry due to its cost-effectiveness compared to solid wood. However, plywood's overuse may lead to sustainability challenges due to raw material scarcity and environmental impacts. This research was conducted independently, without laboratory resources, with the primary aim of determining the optimal HDPE-HMR mixing ratio. This study can be advanced through expert testing, including technical evaluations of load strength, fire resistance, and moisture content, to verify the quality and durability of the resulting product.

To address these identified gaps, this study employs a qualitative research methodology incorporating direct observation, expert interviews, and comprehensive literature analysis. The research utilizes a hot pressing approach, systematically investigating three specific HMR-HDPE mixing ratios (by weight): 200:50, 190:60, and 180:70. Performance evaluation includes load resistance testing (up to 23 kg), fire resistance assessment, and water resistance analysis over 24-hour exposure periods.

The contributions of this research are threefold: theoretically, it provides the first systematic investigation of HMR-HDPE waste combinations, expanding the understanding of engineered wood waste valorization in composite materials; practically, it offers the furniture industry a sustainable alternative to conventional plywood while addressing the challenge of HMR waste disposal; and methodologically, it demonstrates the feasibility of sustainable materials development using accessible hot pressing techniques in resource-constrained environments.

This research distinguishes itself by being the first to thoroughly explore HMR-HDPE waste combinations for furniture board applications. Unlike conventional WPC research focusing on virgin wood fibers, this study specifically addresses the valorization of HMR waste containing formaldehyde resin—a material often discarded unprocessed. The independent research approach, conducted without extensive laboratory resources, demonstrates the feasibility of sustainable materials development in resource-constrained environments.

2. Literature review

High Moisture Resistant (HMR) is a Medium Density Fiberboard (MDF) specially treated to resist Moisture. Fhadilla et al. stated that HMR offers greater mechanical properties and moisture resistance than regular MDF. This makes HMR a common choice for locations with high water exposure, such as kitchens and bathrooms [9]. However, combining HMR with other materials, such as thermoplastics, has not been widely studied in the literature, especially regarding developing composite materials.

High-density polyethylene (HDPE) falls into the category of thermoplastic materials. It is known for its strength, light weight, water resistance, and recyclability. Sun and Qin noted that HDPE is increasingly favored for modern furniture and fixtures due to its sustainable nature and ability to withstand various weather conditions [13]. From a sustainable design perspective, HDPE can effectively replace traditional materials, such as wood and wood-based products. Its strength and recyclability make HDPE ideal for outdoor products and environmentally friendly goods.

An important aspect of HDPE-based research is the application of recycled plastics in an economical and ecologically beneficial manner. Syafiqri et al. emphasized the need for environmentally friendly materials in furniture design to help the circular economy [14]. Sutiharni provided an example of implementing a community workshop on using waste materials as raw materials for new value-added products [15]. Based on what Kusnaedi shared, plastic waste could also be converted to valuable new products using the heating method [16].

Research on HDPE composites with cotton fibers from textile waste shows that adding natural fibers to HDPE can increase tensile strength and reduce material density. This approach can be used as a model in utilizing HMR waste as a filler in HDPE [17]. Although the moisture resistance properties of HDPE and its composites have been widely studied, combining HDPE and HMR, especially for developing moisture-resistant composite materials, is still minimal and has not been widely reported in the scientific literature [18]. These findings further strengthen the urgency to develop materials with environmentally friendly designs, focusing on integrating HDPE and HMR as an alternative to recycled materials.

Although the uses of HDPE and HMR are the subject of more and more research, no research has been done on including these two materials in composite compositions. This dearth of studies offers a great chance to investigate the viability of mixing various materials, evaluate their mechanical characteristics, including tensile strength, and examine their fit for environmental use, including furniture and building. The results of this work will improve the present body of knowledge by offering an understanding of how HDPE and HMR can be effectively mixed to generate composite materials with moisture resistance.

The integration of recycled plastics in wood plastic composites has been extensively studied, with Rahman et al.'s comprehensive review demonstrating successful applications across various industrial sectors. Their study emphasizes the importance of pre-processing treatments and advanced manufacturing techniques in enhancing the recyclability and eco-friendliness of wood-plastic composites, highlighting the transition toward circular economy principles in composite manufacturing [19]. Studies on natural fiber reinforced composites have shown that surface modification techniques can significantly enhance mechanical performance, with improvements of up to 40% in tensile strength reported in jute fiber reinforced biopol composites [8]. Additionally, research on PLA composites with cellulose and abaca fibers has revealed optimal processing parameters for achieving superior mechanical properties.

3. Material and method

This research uses a qualitative method, namely, in this design, the author needs data collection and validation to produce material exploration. It is hoped that HMR waste and HDPE plastic can later become new materials in furniture manufacturing to reduce furniture waste. According to Rusmana et al, aualitative research methods emphasize the in-depth understanding of a problem rather than looking at the problem to be generalized and more towards the nature and analysis of the data more deeply [20].

3.1. Data collection

Daruhadi and Sopiati explain that data collection techniques are the methods researchers employ to gather information or data for their studies, serving as critical components of research methodology [21]. In this study, the main data collection method was observation, supplemented by interviews and documentation involving individuals engaged in HDPE and HMR waste management. These approaches facilitated a literature review, providing comprehensive insights and valuable information for the research.

Laia, E., describes an observation report as a written document that records details about a subject, collected through systematic fieldwork or observation [22]. Sarita and Imawati note that such reports offer a broad summary or narrative based on observation results [23]. In this research, both direct and indirect observation methods were used, with tools like recordings, notes, and documentation to gather data.

Fadilla and Wulandari highlight that interviews enable researchers to obtain detailed information directly from HDPE management and HMR production experts through face-to-face interactions, with or without structured guidelines [24]. Snyder, H., defines a literature study as a research method involving the search, identification, and analysis of documents relevant to the research problem [25]. In this study, the literature review was used to collect supporting data on various aspects, including the properties of HDPE and HMR and techniques for developing new materials.

3.2. Exploration

The research process of this material exploration uses the thermopressing (hot pressing) method, which is the process of heating and pressing to form recycled materials into solid sheets. This method uses heat and pressure by heating HDPE and HMR using an extruder and oven machine, which is then flattened using a press machine. One of the hallmarks of thermopressing is that it uses heat and pressure to form a solid sheet.

A board mold measuring 27 × 19 × 1 cm was used to test this material. Experiments and feedback from HDPE technicians at the Kertabumi Recycling Center indicate that approximately 250 kg of HDPE is required to produce one 0.5-cm-thick board. The HMR-to-HDPE ratios were set at 200:50, 190:60, and 180:70 based on initial testing. At the 180:70 ratio, the board showed reduced flatness compared to the other ratios. Consequently, the 180:70 ratio was established as the upper limit to ensure the board's structural integrity and flatness while maintaining HMR functionality. This research also aims to transform poorly managed HMR waste into usable board material. The 190:60 and 200:50 ratios were selected not only for their superior physical properties but also for practical measurement considerations, as these ratios, being multiples of 10 g, are easier to replicate.

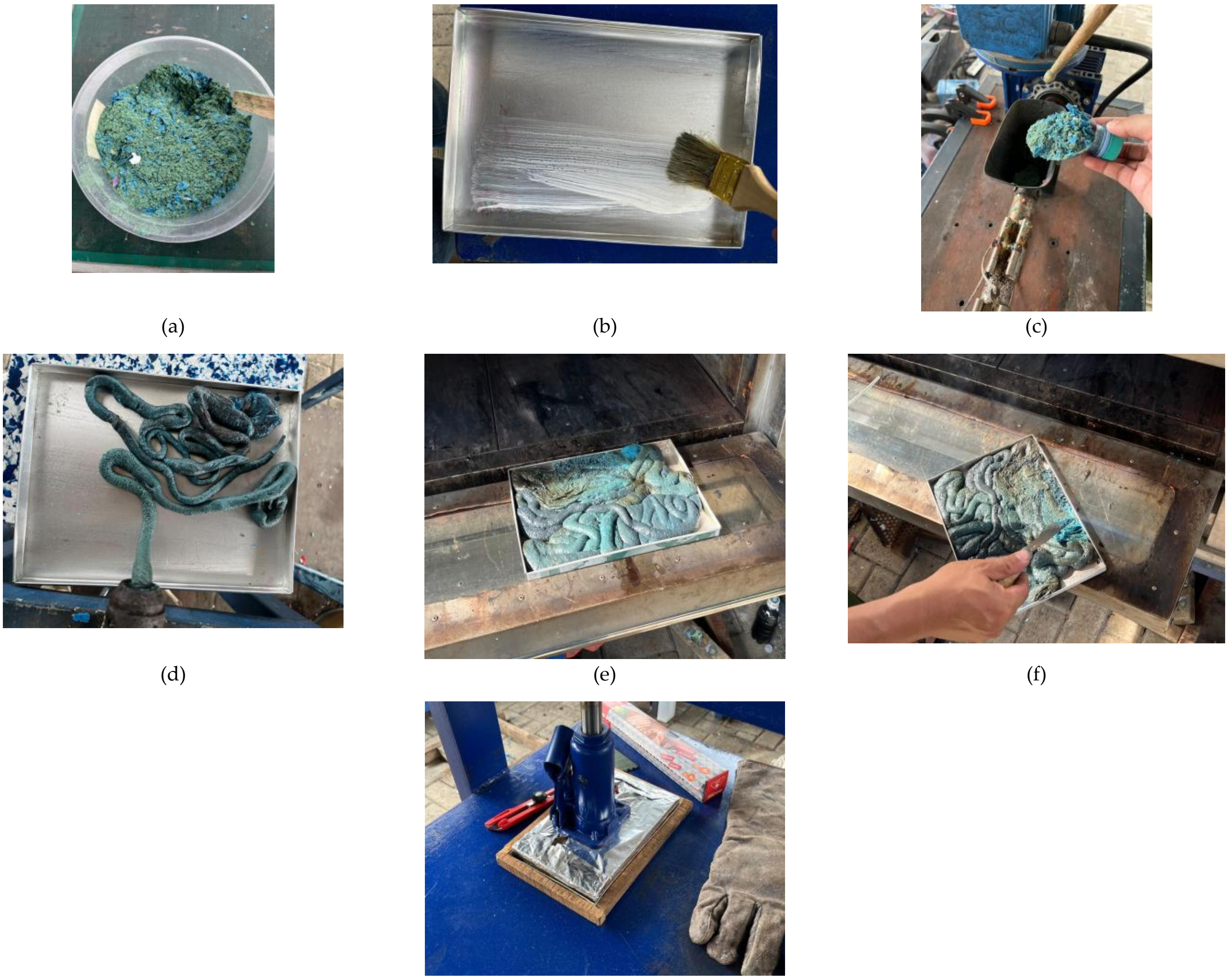
The rationale for selecting these three ratios stems from technical and practical considerations. Preliminary experiments at Kertabumi Recycling Center showed that approximately 250g of material is needed to produce a 0.5 cm thick board in a 27×19×1 cm mold, providing the basis for determining material proportions. HMR content was varied from 20% (50g of 250g total) to 28% (70g of 250g total) to maximize HMR waste incorporation while maintaining board integrity. This balanced waste valorization with performance requirements. Initial tests showed that compositions exceeding the 180:70 ratio produced boards with poor flatness and compromised structural properties, thus setting 180:70 as the upper limit to ensure quality while maximizing HMR waste use. The ratios progress in 10-gram increments, enabling accurate measurement and replication in manufacturing while identifying optimal composition ranges. The ratios were designed to increase HMR content gradually, converting HMR waste with formaldehyde resin into valuable composites. Each ratio represents a different level of waste integration for performance comparison.

This study acknowledges significant methodological limitations in sample replication. Due to resource constraints, only one sample was produced for each mixing ratio (200:50, 190:60, 180:70), yielding a 27×19×1 cm board divided into three sections for performance evaluations. According to established composite testing protocols, a minimum of five replicates per composition is recommended for proper statistical analysis and confidence interval determination [25]. This single-sample approach is a major constraint, precluding statistical validation of performance characteristics.

The testing protocol used one 10×23 cm board section for load resistance, one 4.5×11.5 cm section for fire resistance, and one 4.5×11.5 cm section for water resistance per ratio. The single-sample approach limits this study, precluding statistical analysis or confidence interval determination, so results are preliminary, demonstrating proof-of-concept rather than validated performance. This limitation arises from resource constraints in this exploratory study, designed to establish preliminary evidence of HMR-HDPE composite viability and identify promising ratios for future studies. Future studies should use at least three replicates per ratio for statistical analysis and confidence in performance measurements, with larger samples enabling comprehensive mechanical testing and validation of compositional differences.

The thermopressing methodology follows an 11-step process detailed in **Fig. 1**, **Fig. 2**, and **Fig. 3**, covering HDPE processing, material mixing, and final board production through controlled heating and pressing, respectively.

Fig. 1. The exploration begins with shredding HDPE using a machine, then washing and drying.



(a) (b) (c) (d) (e) (f) (g)

Fig. 2. Material processing: (a) Mixing HDPE with HMR with a ratio of 200 g HDPE : 50 g HMR, 190 g HDPE : 60 g HMR, and 180 g HDPE : 70 g HMR, (b) apply silicone rubber tires to the mold so the material does not stick, (c) Feeding the material mixture into the extruder machine at 200°C heat, (d) HDPE and HMR mixtures will harden immediately while waiting for all the mixtures to enter the extruder, (e) The hardened result is put in the oven to melt and become a flat board (at 250°C), (f) after 20 minutes, the board is removed and leveled using an oiled spatula, and (h) The board is pressed to have an even thickness, and then it is allowed to sit for 3 hours in an open room.

(a) (b) (c)

Fig. 3. Results of the board made with: (a) ratio of 200 g HDPE and 50 g HMR and the weighs is 245 g, (b) ratio of 190 g HDPE and 60 g HMR and the weighs is 239 g, and (c) ratio of 180 g HDPE and 70 g HMR and weighs is 227 g.

In the experiment with a ratio of 200 g HDPE and 50 g HMR, a board weighing 245 g was produced. This board has the smoothest surface compared to other experimental results, indicating optimal heating and pressing. This board has a little original color from the HDPE plastic used, the presence of the remaining color from the plastic shows that the color mixing process is not entirely even, but it does not have an impact on the function or overall final appearance of the board so that the color of the board is not entirely black. The resulting board is uneven in width, but the thickness remains at 0.5 cm.

(a) (b)

Fig. 4. Strength test: (a) exploration board that has been cut into three parts and (b) how to take load strength test results.

Table 1
Strength test results

Quantity of water (liters)	Ratio of HDPE (gr) and HMR (gr)			Plywood
	200:50	190:60	180:70	
5	✓	✓	✓	✓
10	✓	✓	✓	✓
15	✓	✓	 The board has a crack	-
20	✓	✓	-	✓
23	 The board is most curved between plywood and a ratio of 190 g HDPE + 60 g HMR	 The board is only curved		 The board is only curved

In the second experiment, a ratio of 190 g HDPE and 60 g HMR was produced with a weight of 239 g. The board has a relatively flat surface and has a predominantly black color with little color left from HDPE plastic, but not as much as in the first experiment. The resulting board is uneven in width, but the thickness remains at 0.5cm. In the third experiment with a ratio of 180 g HDPE and 70 g HMR, a board weighing 227 g was produced. This board has the roughest surface among the three experiments conducted, a paste-textured board from the extruder machine. It is deep black and tends to be flat. A less smooth surface is likely due to the shorter heating time in the oven. However, the thickness of the board remained consistent at 0.5 cm.

In addition to HMR, ACP waste is also a waste that is difficult to recycle at PT Trimitra Abadi Kreasindo. Previously, researchers had explored ACP and HDPE waste, but the results made the extruder machine black because the ACP base material, made of rubber, melted in the machine due to the heat. Based on these results, HMR was chosen as the blending material due to its moisture-resistant properties, while HDPE excelled in material strength. By combining these two materials, an alternative to furniture boards that is strong, waterproof, and more environmentally friendly will be found. During the thermopressing process, material loss occurs through moisture evaporation and thermal degradation. Analysis shows progressive mass loss correlating with HMR content: 200:50 ratio yielded 245 g (2% loss), 190:60 ratio produced 239 g (4.4% loss), and 180:70 ratio resulted in 227g (9.2% loss) from 250 g initial material. Higher HMR content contributes more significantly to mass loss due to moisture evaporation and organic compound volatilization during heating at 200-250°C. Production planning should account for 2-10% material loss depending on HMR content ratio.

The three board results above have different textures, shapes, and weights. This difference is caused by the various amounts of HMR and HDPE, which also make the melting point of each material different. So, texture with a lot of HDPE HDPE has a smooth texture. In addition, this significant difference in weight is also caused by its burning in the melting process. Undeniably, HMR is also processed from wood, so it has properties that are easily flammable/burnable compared to HDPE.

4. Results and discussion

4.1. Strength test

Based on field data from the experiment, a board measuring 27 cm × 19 cm with a thickness of 0.5 cm was divided into three sections: one section of 10 cm × 23 cm for strength testing, and two sections of 4.5 cm × 11.5 cm each for water and heat resistance tests. For the strength test (see **Fig. 4**), the setup required two chairs and a bucket, all equal height, to act as supports. The board was placed across the chairs with each end positioned 2 cm above the chair surfaces. A 33 g bucket was placed at the board’s center, and water was added incrementally in 500 ml portions until the bucket, with a capacity of 23 liters (equivalent to 23 kg), was full. This load resistance test aimed to assess the board’s weight-bearing capacity for potential use in furniture manufacturing.

Load resistance testing evaluated the structural integrity and weight-bearing capacity of HMR-HDPE composite boards. Three different mixing ratios were tested alongside a conventional plywood control sample. The testing protocol involved incrementally increasing the load using water-filled containers, starting at 5 liters and progressing to 23 liters (23 kg), to determine the maximum load capacity before failure. Performance was assessed based on structural deformation, crack formation, and overall board integrity. The detailed results of the load testing are presented in **Table 1**.

The board, of 200 g HDPE and 50 g HMR, showed increased elasticity performance and better material capability at a load of 23 liters of water (23 kg). In this case, load failure did not occur. On the contrary, in the composition of 180 g HDPE and 70 g HMR, there was a crack when the applied load was 15 kg (15 liters), which was strong compared to the sum of the tested endurance. These two results show different behaviors from each other; therefore, 200 g HDPE + 50 g HMR is more focused on implementing high load endurance. It can be concluded that because the mixing procedure is controlled, the maximum loading received by the board influences load endurance.

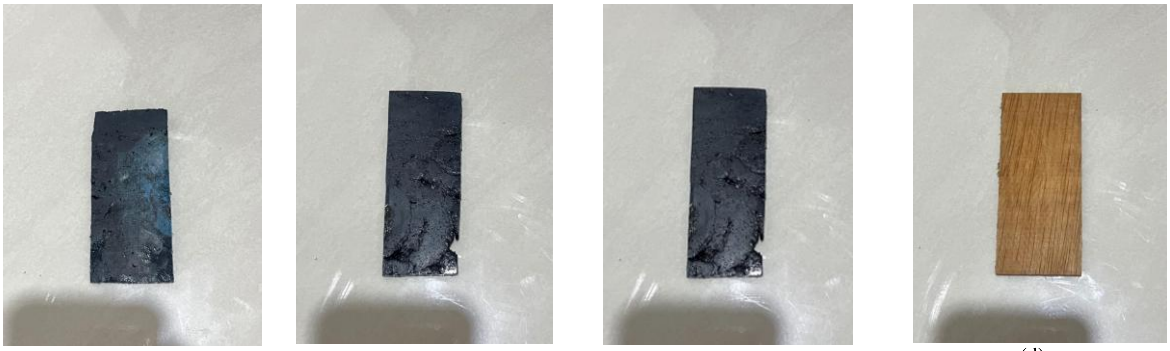
4.2. Fire resistance test

Furniture is an essential component of the home that improves the activities and comfort of its occupants. However, furniture might present a risk beyond its functionality if made from flammable materials. Berthet et al. demonstrate that optimizing thermopressing conditions is essential for achieving both mechanical performance and fire safety requirements in sustainable construction materials. Their research on bio-based fiberboards shows that controlled molding parameters significantly influence flammability characteristics, with restrictive thermopressing conditions producing materials with enhanced fire resistance properties essential for building occupant safety [26]. The optimization of thermopressing parameters observed in this study aligns with recent findings on sustainable material processing, where controlled temperature and pressure conditions not only enhance mechanical properties but also influence fire resistance characteristics crucial for building material applications. Therefore, assessing the fire resistance of furniture materials is crucial to inhibit the quick spread of fire through the furniture components during an occurrence. A direct combustion test was conducted to assess the fire resistance of the board material, utilizing a torch with a temperature exceeding 300°C on four types of boards: three variants of HDPE and HMR compositions, and one variety of plywood for comparison.

Fig. 5. Fire resistant test.

(a) (b) (c) (d)

Fig. 6. Fire resistant test results for: (a) 200 g HDPE and 50 g HMR, this board has relatively good resistance to fire, only a slight burn with black spots that do not damage the structure, (b) 190 g HDPE and 60 g HMR, the board burns and becomes brittle and the surface is charred and easy to press—low fire resistance, (c) 180 g HDPE and 70 g HMR, the board has the best resistance to fire and it does not melt, it only leaves black spots, and the texture remains intact, and (d) plywood, the board burns, turns black to the touch, and the coating splits, indicating low resistance to fire.



(a) (b) (c) (d)

Fig. 7. Water resistant test results for: (a) 200 g HDPE and 50 g HMR, this board has good water resistance, (b) 190 g HDPE and 60 g HMR, this board has good water resistance, (c) 180 g HDPE and 70 g HMR, this board has good water resistance, and (d) plywood, board becomes wet and most water-soaked.

Fire resistance evaluation (see **Fig. 5**) was performed to assess the thermal stability and combustion behavior of the HMR-HDPE composite boards when exposed to direct flame. Each board sample was subjected to controlled flame exposure using a torch maintaining temperatures exceeding 300°C for a duration of one minute. The testing methodology ensured consistent heat application at a standardized distance of 20 cm from the board surface. Post-combustion analysis focused on surface texture changes, structural integrity, color alterations, and overall fire damage assessment. The comparative fire resistance performance of all tested compositions is summarized in **Fig. 6**.

The board, composed of 180 grams of HDPE and 70 grams of HMR among the four tested samples, exhibited the superior fire resistance. This board did not combust; it altered its form, developing black blotches without exhibiting a brittle feel. Simultaneously, the board, composed of 190 grams of HDPE and 60 grams of HMR, ignited and softened under pressure, signifying inadequate resistance. The board, including 200 g HDPE and 50 g HMR, exhibited minimal combustion, with peak temperatures reported at 300°C, whereas plywood demonstrated elevated temperatures and sustained more significant damage. Plywood exhibited the least resistance, ignited readily, was easily compromised, and its layers delaminated post-combustion.

4.3. Water resistance test

To determine the ability of the board to withstand water exposure, a test was carried out by soaking each board sample in water for 24 hours. This test looks at the changes to the board after being exposed to water for a considerable period, including its shape, surface texture, and structural strength. This test is important to assess how much the board material can be used in a humid or water-sensitive environment. The following photo and table present the results of the observations and instructions on taking the test after immersion.

Water resistance testing was implemented to determine the moisture absorption characteristics and dimensional stability of the composite boards when exposed to prolonged water immersion. The evaluation protocol involved complete submersion of board samples in water for 24 hours, followed by comprehensive assessment of physical and structural changes. Key performance indicators included surface texture modification, dimensional changes, water absorption levels, and structural integrity maintenance. Comparative water resistance analysis demonstrates the superior moisture resistance capabilities of the HMR-HDPE composites compared to conventional materials. The detailed water resistance test findings are presented in **Fig. 7**.

All boards made from a mixture of HDPE and HMR showed excellent water resistance after being soaked for 24 hours. There was no absorption or softening of the material. Meanwhile, plywood experienced a change in texture to become wetter and has the potential to cause mold if left in humid conditions for a long time. As stated by Bekhta and Sedliačik, HDPE has better water resistance than other materials, such as plywood, which can soften when exposed to water [27].

4.4. Analysis and discussion

Based on the load, water, and fire resistance tests, boards with a composition of 200 g HDPE and 50 g HMR show the most balanced performance, making them very suitable for furniture applications with a size of 0.5 cm. This board can withstand a load of up to 23 liters (equivalent to 23 kg) of water without breaking, withstand 24 hours of soaking, and only experiences light burns when burned. With good resistance to these external factors, 200:50 composition boards, such as shelves, light tables, and decorative elements that require adequate strength and durability, are highly recommended for structural use in furniture manufacturing.

The overall performance characteristics of the 200:50 HMR-HDPE composition align well with established material standards for furniture applications. The load capacity of 23 kg exceeds typical requirements for residential furniture components, which generally range from 15-20 kg for shelf applications according to established furniture safety standards. The fire resistance performance, while not meeting commercial building flame spread requirements, is suitable for residential furniture applications where Class III flame spread ratings are acceptable. The exceptional water resistance makes this material particularly suitable for bathroom vanities and kitchen furniture, where moisture exposure is a primary concern. Comparative analysis with commercial WPC products shows that the 200:50 composition performs competitively with established wood-plastic composite furniture materials, offering advantages in moisture resistance while maintaining structural integrity. The balanced performance profile suggests potential applications in outdoor furniture, where weather resistance is critical, similar to commercial recycled HDPE furniture products that have gained market acceptance for patio and garden applications.

The performance characteristics observed in this study align with established principles in composite material science. Research by Chen et al. on biobased fiber processing demonstrates that proper fiber preparation and manufacturing conditions are crucial for achieving optimal composite properties [28]. Their comprehensive review emphasizes the importance of advanced processing technologies, including extraction, spinning, and modification techniques, which enable fibers to achieve diverse functionalities while promoting sustainable development through reduced reliance on fossil-based materials [28]. The systematic approach to material processing demonstrated in this research reflects current best practices in biobased composite manufacturing, where interdisciplinary collaboration and advanced processing techniques are essential for achieving optimal performance in sustainable material applications. The surface properties and adhesion mechanisms observed in HMR-HDPE composites are consistent with findings from Yadav and Yadav's nano-clay treatment studies, where surface modification significantly influences overall composite performance. Their research demonstrates that alkali-nano-clay treatment can improve tensile strength by up to 32% and tensile modulus by 24%, highlighting the critical role of fiber-matrix interface optimization in achieving superior mechanical properties [29].

4.5. Cost budget plan

Table 2 presents a detailed cost budget plan for manufacturing one unit of recycled board measuring 27 x 19 x 1 cm. The calculated costs include all material requirements, supporting equipment, operational expenses (such as labor and electricity), and machinery depreciation used in the production process. Using waste HDPE and HMR materials provides significant cost savings, with waste HDPE costing 60–70% less than virgin materials and HMR waste often available at no cost. The total production cost of IDR 100,860 per board is 15–25% lower than conventional plywood costs, which range from IDR 120,000 to 150,000. Additional economic benefits include avoiding waste disposal costs (IDR 50,000–75,000 per ton) and reducing exposure to raw material price volatility. This waste valorization approach offers dual benefits: eliminating disposal costs while generating revenue from previously discarded materials. Furthermore, adopting this sustainable process supports environmental conservation by reducing landfill waste [30]. It also enhances the scalability of production by leveraging readily available recycled materials.

Table 2
Production cost

Component	Unit	Cost	Output
HDPE plastic (50 grams)	IDR 2,000/kg	IDR 100	50 gr = 1/20 kg → 2,000 / 20
HMR waste (200 grams)	-	-	Sourced from furniture waste, considered free
Rubber silicone (10 ml)	IDR 83,000/liter	IDR 830	83 per ml x 10 ml
Baking mold (resuse)	IDR 15,000	IDR 150	Assumed reused 100 times → 150 per use
Brush 5 cm (reuse)	IDR 6,000	IDR 30	Assumed reused 200 times → 30 per use
Electricity (o.5 kWh)	IDR 1,500/kWh	IDR 750	
Production operator (6 hours)	IDR 12,500	IDR 75,000	
Plastic shredder (depreciation)	IDR 4,000,000	IDR 4,000	1,000 uses (assumption)
Oven (depreciation)	IDR 3,000,000	IDR 3,000	1,000 uses (assumption)
Extruder machine (depreciation)	IDR 17,000,000	IDR 17,000	1,000 uses (assumption)

5. Conclusions

Additionally, the board exhibits notable fire resistance, showing only minor burns after one minute of direct flame exposure without significant structural damage. Its water resistance is also impressive; after 24 hours of submersion, the board showed no deformation or softening, unlike plywood, which absorbed water and softened. Among the three tests conducted (load, fire, and water), the 200:50 HDPE-HMR composition performed best. Therefore, this material is highly recommended for furniture such as shelves, tables, or decorative items that do not require heavy load-bearing capacity.

The development of HMR-HDPE composite boards has significant managerial implications for furniture manufacturing and waste management organizations. The validated 200:50 HDPE-HMR composition outperforms traditional plywood, enabling companies to differentiate through sustainable product offerings. Established production parameters provide standardized benchmarks for scalable manufacturing and quality control.

From a financial perspective, using waste materials significantly reduces raw material costs compared to traditional alternatives, allowing competitive pricing while maintaining profit margins. The board's superior water and fire resistance reduces product liability risks and warranty claims, contributing to predictable financial performance. Converting discarded HMR and HDPE into functional furniture materials exemplifies a practical circular economy approach, providing quantifiable evidence for corporate sustainability reporting and strengthening ties with environmentally conscious customers and investors.

To capitalize on these findings, management should initiate pilot production programs using the validated composition, conduct market tests with prototype furniture, establish reliable waste material procurement channels, and pursue industry certifications to enhance market acceptance. Collaborations with furniture manufacturers for case studies and partnerships with waste management companies could accelerate adoption and scaling, positioning organizations as leaders in sustainable manufacturing while achieving environmental and economic goals. Furthermore, integrating this composite into existing product lines can expand market share in eco-friendly furniture segments. Engaging with local communities to source waste materials can also foster social goodwill and strengthen corporate reputation.

Future research should focus on systematic replication studies with larger sample sizes to validate these preliminary findings. Additionally, exploring surface modification techniques, similar to those used in natural fiber composites, could enhance HMR-HDPE interface properties. Developing standardized processing parameters based on green composite manufacturing principles would facilitate commercial adoption of this waste valorization approach.

Declaration statement

Ancilla Domini Kusbijanto: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Experimentation, Writing – original draft, Visualization. **Terbit Setya Pambudi:** Supervision, Validation, Writing – review and editing, Project administration. **Hanif Azhar:** Supervision, Validation, Writing – review and editing, Resources.

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Disclosure statement

The authors declare no conflicts of interest related to this research. The study was conducted independently without financial compensation from collaborating organizations. All materials and technical assistance were provided for academic research purposes without any influence on research outcomes or interpretation.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Data are not publicly available due to the collaborative nature with industry partners and ongoing research activities. Additional experimental data and technical specifications can be requested from the authors for academic verification purposes.

AI Usage Statement

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