Feasibility of Recycled HDPE Planks for Sustainable Furniture Applications: A Physio-Mechanical Study

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Abstract. Plastic waste generation has become a pressing environmental challenge due to the widespread use of plastic materials, which offer versatility, durability, and cost-effectiveness. This study investigates the feasibility of fabricating recycled high-density polyethene (HDPE) planks for furniture applications by evaluating their physio-mechanical properties. The research addresses the urgent need for effective waste management strategies, mainly plastic waste recycling, to mitigate environmental sustainability concerns. The study analyses the recycled HDPE planks' tensile strength, flexural strength, and water absorption characteristics. The results indicate that the planks exhibit an average tensile strength of 14.36 ± 1.24 MPa and flexural strength of 46.57 ± 3.11 MPa, highlighting their suitability for furniture applications. Moreover, less than 0.01% water absorption rate confirms their capability to withstand outdoor conditions. A survey was conducted with 70 participants to gather feedback on the furniture product and gauge user perception. Most users expressed high satisfaction and appreciation for this sustainable initiative, recognizing the importance of promoting daily sustainability practices. This positive user feedback reinforces the significance of waste management practices and encourages the broader adoption of sustainable engineering solutions. This study offers compelling evidence supporting the utilization of recycled HDPE planks in furniture applications. It underscores the importance of effective waste management in addressing environmental concerns associated with plastic waste. The study's findings highlight the feasibility of implementing sustainable engineering solutions to catalyze broader recycling practices adoption and promote a sustainable lifestyle.

1 Introduction

Effective waste management is a critical challenge facing societies worldwide. Among the various types of waste, plastic waste poses a unique and escalating problem due to its durability and widespread use. The escalating nature of the plastic waste issue is evident in statistics. For example, according to a report by the World Economic Forum, if current trends

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continue, there could be more plastic than fish in the ocean by 2050 [1]. This projection underscores the urgent need for effective waste management strategies to address the growing problem of plastic pollution. Plastics, being highly recyclable materials with a relatively straightforward process [2], offer immense potential to extend the lifespan of landfills. Plastic waste recycling encompasses various processes and technologies, producing multiple products beyond traditional plastic items like bags and bottles. In the construction industry, plastic waste finds applications in concrete materials [4], plastic wood composites [5], soil stabilization [6], and even pavement mixtures [7] and paver block [8].

There are two primary methods of plastic recycling: mechanical and chemical processes, with the latter being the most employed. The approach involves subjecting plastic waste to heat, mechanical stress, and oxidation [9]. Mechanical recycling entails physically degrading the waste through grinding and shredding. On the other hand, chemical recycling involves breaking down plastic waste into monomers or chemically modified new polymer materials [10].

The diverse array of recycling processes and recovery technologies can make the terminology surrounding plastic recycling complex and occasionally confusing. However, these approaches can be categorized based on the type and properties of the plastic waste, its applications, the products of the recycling process, or the re-processed waste plastic's equivalent value, such as lower/downgrading, chemical recovery, energy recovery, or valorization [11]. For example, hard plastic products, such as high-density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), exhibit significant potential for recycling, with over 40% of these materials capable of being recycled and these plastics' sorting and reprocessing potential exceed 50% [12]. The broad range of recycling possibilities demonstrates the potential for plastic waste to be transformed into valuable resources. Furthermore, by adopting appropriate recycling methods and technologies, we can reduce the environmental burden associated with plastic waste while simultaneously creating new products and contributing to a circular economy.

Various evaluation methods are used to ensure the quality and reliability of recycled materials. These methods typically assess physical, chemical, and mechanical properties to determine the suitability of recycled materials for specific applications. Common industry standards include ISO 14021, which provides guidelines for environmental labels and declarations; ASTM D7611/D7611M, which identifies plastic recycling codes; and ISO 15270, which focuses on recovering and recycling plastic waste. These standards help maintain consistency and quality across different recycling processes.

In this study, high-density polyethylene (HDPE) was specifically chosen due to its widespread use, resulting in substantial disposal rates and extensive recycling infrastructure [13]. HDPE is a commodity polymer readily accessible at an affordable price while offering ease of processing [14] and showcasing notable characteristics such as high rigidity and durability [15]. The research emphasizes the utilization of HDPE due to its advantageous features, including availability, cost-effectiveness, processability, and favorable mechanical properties. This deliberate choice enables an exploration of HDPE recycling potential in tackling the environmental issues as-sociated with plastic waste. Moreover, this approach aligns with established recycling practices and leverages existing industrial capabilities.

Hence, this research explores the feasibility of utilizing fabricated HDPE plastic waste for outdoor bench furniture applications. The investigation focuses on evaluating the engineering characteristics of the manufactured materials, specifically through tensile strength, flexural properties, and water absorption tests. The study also delves into the user perception of fabricated bench furniture products, providing valuable insights into their reception and acceptance. By comprehensively examining the engineering aspects and user perspectives, this research sheds light on the suitability and viability of utilizing recycled HDPE plastic waste for outdoor bench furniture.

2 Material Preparation and Characterization Method

This work includes the main sequential steps from raw materials (plastic waste) to recycled HDPE furniture finished products. It involves preparing and recycling HDPE waste fabrication and then characterizing recycled HDPE material's mechanical properties. An online survey was also used to evaluate the furniture product user survey. The following sections explain this further.

2.1 Material Preparation and Fabrication

This study collaborated with the local industry namely EZPlast Solution, based in Kota Kinabalu, Sabah, Malaysia, to collect and process plastic waste. Fig 1(a) illustrates the segregation and processing of high-density polyethylene (HDPE) waste collected from the surrounding communities, similar in our previous work [16]. The primary sources of HDPE waste are food and liquid daily-use packaging. HDPE is one of most important thermoplastics [13], that mechanically recyclable due to its ability to be reheated, molded and frozen multiple times [17]. The collected waste undergoes sorting, cleaning, drying, and shredding into smaller flakes measuring 1 to 3 mm. The recycled HDPE flakes are then heated at 200°C, slight lesser than the melting temperature of 210°C [18] and transferred to a compression mold to shape the desired product. The compression mechanism involves the use of a 20-tonne hydraulic press. After the mold has cooled to room temperature, the cured recycled HDPE plate can be demolded, resulting in a durable material suitable for furniture applications like outdoor bench planks, as illustrated in Fig 1(b).

Fig. 1. (a)HDPE waste preparation and recycling processes (1 to 3) and (b) Recycled HDPE plank for furniture material dimensions (table and bench).

2.2 Material properties characterization

The recycled HDPE material's mechanical properties (tensile strength, flexural strength, and water absorption) are characterized by its material feasibility and capability as a furniture material application.

2.2.1 Tensile and Flexural Strength

The recycled HDPE tensile strength characterization is conducted according to ASTM D638. Specimens' dimensions of 165 mm (length) X 20.5 mm (width) X 4.8 mm (thickness) are trimmed from the HDPE plank. The Gotech A1-7000L-10 universal testing machine conducts the tensile test at 1 mm/min. Figure 2(a) shows the specimens' stress versus strain curve plot.

The material flexural strength characterization is conducted using the same equipment of the Gotech A1-7000L-10 universal testing machine. The three-point bending test is performed according to ASTM D7264 with a 1 mm/min test rate to characterize the material's flexural stiffness. Specimens dimensions of 160 mm (length) X 20 mm (width) X 4.8 mm (thickness) are prepared, where the span length is 112 mm. The specimen flexural stress versus strain curve plot is shown in Fig. 2(b).

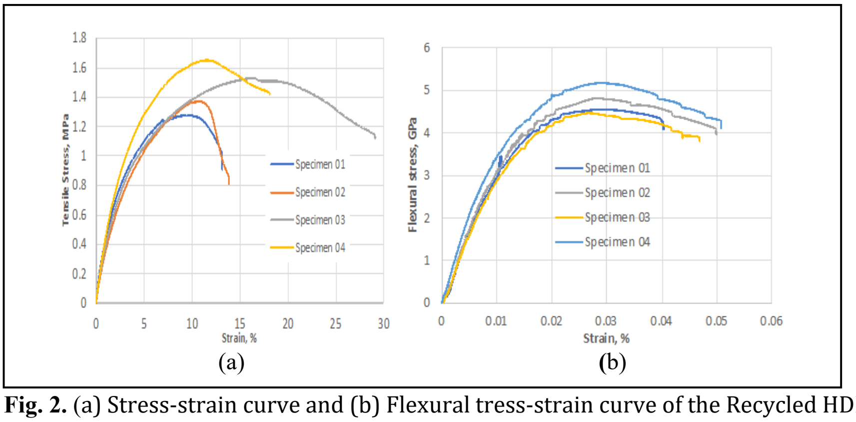

Fig. 2. (a) Stress-strain curve and (b) Flexural tress-strain curve of the Recycled HDPE specimens.

2.2.2 Water absorption

Moisture or water absorption refers to the capacity of a material or polymer to absorb moisture from its surrounding environment. In the case of recycled plastic planks used for outdoor furniture, high water absorption can indicate irreversible degradation of the polymer structure. Hence, a water absorption test is conducted following ASTM D570 guidelines. To determine the water absorption rate, HDPE specimens (both raw and recycled) are immersed in water at various temperature conditions (ranging from 30°C to 70°C) for 24 hours. The water absorption test specimens have dimensions of 30 mm (length) x 30 mm (width) x 4.8 mm (thickness). Therefore, this test can evaluate the extent of water absorption, providing valuable insights into the performance and durability of recycled HDPE material in outdoor furniture applications. The water absorption rate is determined by the weight difference before (w1) and after (w1) the submission, or it is defined as in Equation 1.

$$\text{Water absorption rate (\%)}: m = \frac{\Delta W_{2-1}}{W1} \times 100. \quad (1)$$

2.2.3 Assessing User Perception of Recycled HDPE Furniture Implementation

To gauge the feedback and perception of users regarding the fabricated HDPE recycled furniture product, a questionnaire in the form of a QR code linked to a Google Form was provided on the bench. The outdoor table was strategically placed at the main entrance of the Faculty of Engineering (coordinates: 6.0350° N, 116.1213° E) at Universiti Malaysia Sabah, UMS. The user feedback collection period spanned from January to April 2022, during which users had the opportunity to access the questionnaire and provide their ratings based on their perceptions of the recycled HDPE bench. The questionnaire remained open, allowing users to share their valuable insights and opinions on the product, contributing to the assessment of user satisfaction and overall perception of recycled HDPE furniture.

3 Results and Discussions

3.1 Observation of Tensile Strength and Stiffness of Recycled HDPE

The tensile strength of the recycled HDPE sample was determined by analyzing the stress value at the fracture point on the stress-strain curve, as depicted in Figure 2(a) previously. The average tensile strength was approximately 14.36 ± 1.24 MPa, with a coefficient of variance (COV) of 9%, as shown in Figure 3. The slight variations in the results could be attributed to factors such as the specimen's area or the molecular structure's orientation during the deformation process [19].

Comparatively, the tensile strength of the recycled HDPE sample is slightly lower than that of virgin HDPE, which typically exhibits a tensile strength of 18 MPa [20]. In addition, the recycled HDPE sample demonstrates ductile behavior, with the strain at the fracture point ranging from 10% to 16%. The evaluation of the tensile stress-strain curve yielded an average Young's Modulus of 495 ± 53.2 MPa, indicating the stiffness of the recycled HDPE material. The large standard deviation observed probably due to incomplete homogenization and presence of impurities [21].

The compression moulding method can yield virgin HDPE materials with Young's Modulus properties of 1000 MPa, while regrind HDPE materials can achieve a Young's Modulus of 1200 MPa [20]. In comparison, the recycled HDPE samples in this study exhibited a slightly lower Young's Modulus. This decline may be attributed to variations in the source and grade of the HDPE raw material, as the strength properties of recycled HDPE depend on the characteristics of the collected waste sources. Furthermore, the material processing method and melting temperature employed can also influence and potentially reduce the tensile strength of the recycled HDPE samples. This is expected as recycled plastic are generally less desirable than virgin [22] caused by molecular structure physical and chemical changes or contaminants in mixed plastic waste [23].

The analysis of the flexural stress-strain curve shown earlier in Figure 2(b) and the corresponding strength properties depicted in Figure 3 provides valuable insights into the flexural behavior of the recycled HDPE material. The recycled HDPE's average flexural strength was approximately 46.57 ± 3.11 MPa, with a maximum deflection range of 12.5 to 14 mm. The flexural stress-strain curve also yielded a flexural modulus of about 3500 MPa or 3.5 GPa.

Notably, the flexural property of the recycled HDPE in this study surpassed the values listed in the material database, which typically range from 0.97 to 1.38 GPa for the flexural modulus of virgin HDPE [24]. This increment in flexural property can be attributed to the larger dimensions of the test specimen geometry used in this study, which exceed the recommended dimensions in the standard test procedures. Furthermore, the flexural strain of the recycled HDPE, approximately 2.85 ± 0.14%, was lower than the tensile strain observed.

This can be attributed to the nature of the flexural stress mode, which consists of both compressive and tensile stresses acting simultaneously. Overall, the results indicate that the recycled HDPE material exhibits favorable flexural properties, surpassing the typical values reported for virgin HDPE. These findings highlight the potential of recycled HDPE in applications where enhanced flexural strength and stiffness are desired.

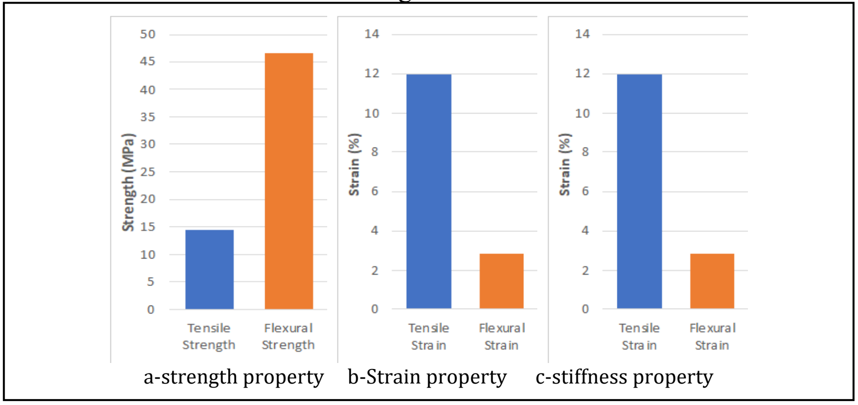

Fig. 3. Recycled HDPE tensile and flexural strength properties (average value).

3.2 Water Absorption Properties of Recycled HDPE Material

As illustrated in Figure 4, the water absorption test was conducted on both raw HDPE waste samples (virgin) and recycled HDPE material. The results revealed that the water absorption behavior of the recycled HDPE samples was influenced by temperature variations, similar to that of virgin HDPE material. Interestingly, the recycled HDPE's water absorption rate was lower than that of virgin HDPE at temperatures above 55°C.

Specifically, at a lower temperature of 55°C, the recycled HDPE material exhibited a water absorption rate of 0.005%, which is slightly higher than the values reported in other studies, such as 0.025% [25] and 0.369% [26]. Nevertheless, the recycled HDPE material demonstrated higher water absorption resistance than wood plastic composites, which typically exhibit water absorption rates ranging from 3.5% to 7% [27].

These findings emphasize the potential of recycled HDPE material as a suitable alternative to wood plastic composites, offering improved resistance to water absorption while promoting sustainable waste management practices.

Applying recycled HDPE material as a replacement for wood in outdoor furniture is feasible and advantageous, considering its strength properties and low water absorption rate. While recycled HDPE may exhibit lower rigidity compared to local furniture wood materials like 'Merpauh,' 'Kapur,' and 'Sesenduk,' which have stiffness values ranging from 7 to 13 GPa [28], it is essential to note that in an outdoor table and bench applications, the strength of the recycled HDPE plank is supported by a steel frame rather than serving as a load-bearing component. Therefore, the strength requirements for these furniture pieces are adequately met.

Furthermore, the feasibility of utilizing recycled HDPE in this application is bolstered by its exceptional resistance to water absorption. The material is highly resistant to water and can be considered a waterproofing material, which is crucial for outdoor use. With a water absorption rate of only 0.005%, recycled HDPE significantly outperforms typical furniture materials such as rubberwood, which has a water absorption rate of 55% [29].

Considering the strength properties supported by the steel frame and the low water absorption rate, it is evident that recycling HDPE is not only a viable but also a desirable choice for outdoor furniture materials. By utilizing recycled HDPE, we can effectively reduce waste and promote sustainability without compromising the functionality and durability required for outdoor furniture applications.

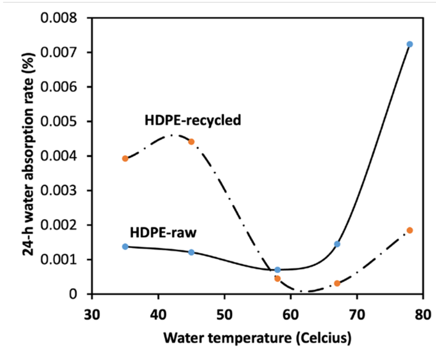

Fig. 4. Water absorption of HDPE material to water temperature.

3.3 User Perception and Feedback on Recycled HDPE Bench

The user community within the institution provided valuable feedback on the Recycled HDPE bench product, with 70 respondents participating in the survey. Overall, the feedback from users has been positive, reflecting their favorable perception of recycled HDPE furniture. The user ratings, measured on a Likert scale ranging from one to ten, are depicted in Figure 5. Most respondents gave excellent ratings (9 to 10 on the scale), indicating a strong positive perspective on the recycled HDPE bench.

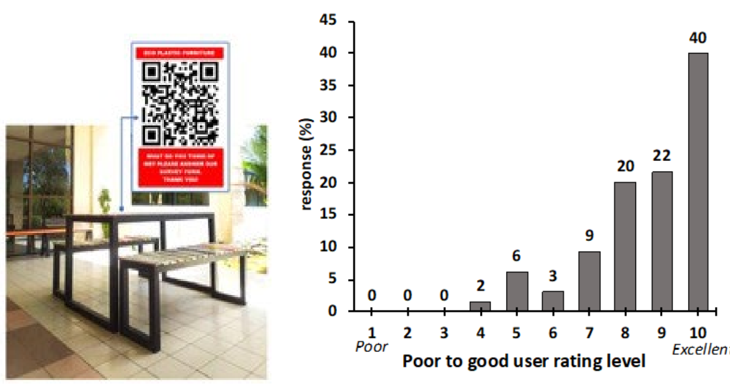

Fig. 5. Response Rating marks for the Recycled HDPE furniture.

While the feedback was largely positive, there were also constructive comments regarding potential improvements to the product. The qualitative feedback highlighted key areas for improvement, such as interface design and functionality. Many users mentioned concerns about the finishing of the bench, explicitly mentioning sharp edges and a perceived stiffness when sitting on it. These comments highlight the importance of addressing comfort-related issues and refining recycled HDPE furniture's overall design and ergonomics.

However, it is noteworthy that several users expressed satisfaction with the product and even recommended its promotion and increased awareness about plastic waste recycling. These users acknowledged the positive impact of recycling plastic waste in creating a healthier environment by reducing waste pollution and its associated dangers to humans and other living organisms. This feedback aligns with a previous study [30], which emphasizes consumers' growing inclination toward adopting healthy lifestyles and supporting sustainable, eco-friendly products.

The user perception and feedback obtained from this study provide valuable insights for further improvements in recycled HDPE furniture's design, comfort, and overall user experience. Furthermore, by addressing the mentioned concerns and continuing to promote the benefits of plastic waste recycling, the recycled HDPE bench and similar products have the potential to garner even greater acceptance and support from the community. It serves as a direct inspiration for creating sustainable communities that prioritize a higher quality of life while preserving the natural environment's ability to thrive [16]. This is achieved through the minimization of waste, pollution prevention, and the utilization of local resources to stimulate the local economy and promote revitalization.

4 Conclusion

This study demonstrated the feasibility of utilizing HDPE plastic waste as outdoor furniture for public use. The collected plastic waste underwent a thorough cleaning and treatment process before being compressed and molded into sturdy planks suitable for furniture applications. While the tensile strength of the recycled HDPE was slightly lower compared to virgin HDPE, indicating a modest reduction in strength properties, it still exhibited desirable ductile behavior with an acceptable range of strain at break. Moreover, the stiffness of the recycled HDPE, as quantified by Young's Modulus, fell within an appropriate range for furniture usage. The mechanical properties assessed through tensile and flexural tests proved sufficient for the intended furniture application, showcasing compatibility with outdoor conditions, including water exposure and varying temperatures. Nevertheless, it is essential to acknowledge that recycled plastic faces competition from conventional commercially available wood-based furniture materials. However, the positive feedback from users who interacted with the installed recycled HDPE furniture in public locations is an encouraging sign. This feedback demonstrates the users' appreciation of the initiative to reduce plastic waste and their inclination toward sustainable choices.

Despite the challenges established furniture materials pose due to their small-scale implementation, implementing recycled HDPE as outdoor furniture holds promise. The mechanical properties of the recycled HDPE meet the requirements for furniture functionality, while the positive user perception highlights the growing awareness and support for sustainable practices in waste management. Addressing the limitations and continuously promoting the benefits of plastic waste reduction and recycling, using recycled HDPE in outdoor furniture can contribute to a more sustainable and environmentally conscious approach to public space design and utilization.

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