



Article

Mechanical and Durability Performance of Recycled Tetra Pak PolyAl–Rice Husk Wood-like Boards for Urban Furniture

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Abstract

Global outdoor furniture consumes large amounts of virgin wood and polyolefins, while multilayer beverage cartons and rice husks are often landfilled or burnt despite their polymeric and lignocellulosic value. This study aims to evaluate the feasibility of converting both waste streams into pilot-scale, wood-like boards for low-load urban furniture using an industrially relevant extrusion plus compression-moulding route, and to identify a balanced PolyAl–rice husk formulation. Hybrid composites based on recycled Tetra Pak PolyAl and ground rice husk were manufactured as full-thickness boards and characterised in terms of density, tensile and flexural behaviour, Shore D hardness, and moisture uptake. A preliminary UV screening was also performed using short-term narrow-band UVC irradiation at 254 nm, which should not be interpreted as outdoor weathering. Increasing rice husk content enhanced hardness and stiffness but increased water uptake, evidencing the expected stiffness–durability trade-off in lignocellulosic-filled systems. Overall, the intermediate 70PolyAl–30rice husk composition provided the most balanced performance for the targeted low-load applications, supporting an industrial symbiosis pathway that valorises two locally available residues into a potentially scalable product.

Keywords: recycled PolyAl; rice husk; composite boards; wood–plastic composites; short-term UVC ageing; water absorption; UV ageing; circular economy; urban furniture

1. Introduction

Single-use packaging is one of the most critical sources of solid waste worldwide. Recent analyses estimate that around 40% of global plastic waste originates from packaging applications, with similar shares in regions that generate the largest amounts of plastic waste, such as Europe, the United States and China [1]. In the European Union (EU), packaging waste reached about 79.7 million tonnes in 2021, corresponding to roughly 178 kg per inhabitant [2,3]. Within this stream, plastic packaging alone accounts for more than 35 kg per person, of which only about 40–45% is effectively recycled [3]. These figures highlight the need for new solutions that simultaneously reduce the demand for virgin polymers and create higher-value outlets for post-consumer packaging fractions that are currently under-utilised [1–3].

Beverage cartons such as Tetra Pak® are a representative example of complex multilayer packaging. A typical used carton contains approximately 73–75 wt.% cellulose fibres, 20–23 wt.% polymers and 4–5 wt.% aluminium [4,5]. After conventional hydropulping, high-quality fibres can be efficiently recovered, but the remaining polymer–aluminium fraction (commonly referred to as PolyAl) is more challenging to manage because the



Academic Editor: Reza Salehiyan

Received: 14 January 2026

Revised: 1 February 2026

Accepted: 6 February 2026

Published: 23 February 2026

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polyethylene layers and aluminium foil are strongly bonded [5]. In the last decade, carton manufacturers and recycling companies have invested in dedicated PolyAl recycling lines and in the development of new products such as pallets, crates and outdoor items [5–9]. However, existing capacities remain limited compared with the total volume of cartons placed on the market, and additional high-value applications for PolyAl-rich composites are still needed [5].

In parallel, agro-industrial residues are increasingly recognised as strategic resources within the transition to a circular bioeconomy. Rice husk is one of the most abundant agricultural by-products in rice-producing countries; it is generated in large volumes, is difficult to dispose of and is often under-utilised [10]. Recent reviews describe rice husk as a lignocellulosic material with relatively low density, significant silica content and a chemical composition that makes it attractive as a filler or reinforcement in polymer matrices [10]. Studies on rice-husk-reinforced polymer composites show that increasing husk content typically enhances stiffness and sometimes tensile strength, but at the expense of reduced impact resistance and increased water absorption, unless the fibre–matrix interface is carefully engineered with appropriate compatibilizers or surface treatments [10,11].

Natural-fibre-reinforced polymer composites and wood–plastic composites (WPCs) have evolved from early formulations based on virgin polymers and wood flour to more complex systems combining recycled polyolefins, diverse lignocellulosic fillers and tailored additives [10–12]. Gardner et al. [12], for example, show how WPCs are now widely used in decking, cladding and outdoor furniture, where moderate mechanical performance and adequate durability under outdoor exposure are required rather than high structural capacity. When these composites incorporate recycled polymers and waste lignocellulosic resources, they can substantially reduce the consumption of tropical hardwoods and virgin plastics in building and outdoor applications [12].

Alongside agricultural residues, post-consumer multilayer beverage cartons have emerged as a promising but technically demanding waste stream for composite production [5–9]. Several thermo-mechanical and mechanical recycling routes have been proposed to transform the polymer–aluminium fraction into cement-based materials, polymer concretes or polymer composites [5–9]. Martínez-López et al. [9] manufacture polymer concretes using recycled high-density polyethylene and PET from Tetra Pak® containers and report compressive and flexural strengths suitable for small structural elements. Macías-Gallego et al. [6] evaluate composite materials made from recycled Tetra Pak® containers, while Martínez-Barrera et al. [7,8] investigate the incorporation of Tetra Pak-derived components into concrete and other construction materials, demonstrating viable mechanical performance in non-structural applications. Overall, these studies focus on a single waste stream (either beverage-carton PolyAl or a lignocellulosic residue) and often on laboratory-scale specimens; only a limited number address board- or panel-like products manufactured by extrusion or compression moulding using industrially relevant equipment [5–10]. Furthermore, the combined use of PolyAl and rice husk within a single WPC-like board system has not been systematically explored across a formulation range that is explicitly bounded by industrial processability.

The concept of industrial symbiosis provides a useful framework to integrate these different waste streams into value-added products. Industrial symbiosis is commonly described as a specific application of industrial ecology in which traditionally separate industries collectively gain competitive advantage by exchanging materials, energy, water and by-products within local or regional networks [13]. Key features include collaboration among firms and the synergistic opportunities created by geographical proximity, which allow for one company's waste stream to become another company's feedstock [13]. Recent reviews emphasise that well-designed industrial symbiosis initiatives can significantly

reduce waste generation, decrease primary resource demand and improve the overall environmental performance of industrial clusters [14,15]. From a policy perspective, industrial symbiosis is increasingly recognised as a practical implementation tool for circular economy strategies: the European Circular Economy Action Plan calls for high-value uses of secondary raw materials in resource-intensive sectors such as construction, plastics and packaging [16], while the United Nations 2030 Agenda stresses the need for resilient infrastructure (SDG 9), sustainable cities (SDG 11), responsible consumption and production (SDG 12) and climate action (SDG 13) [17]. Symbiotic schemes that valorise industrial and agro-food by-products into new materials and construction products directly contribute to these objectives by reducing landfilling, substituting virgin raw materials and enabling more sustainable infrastructure solutions [14–17].

Against this background, coupling recycled Tetra Pak® PolyAl with rice husk within a single composite material aligns with the core principles of industrial symbiosis and circular economy. The polymer–aluminium fraction of beverage cartons can act as a secondary polymeric matrix, while rice husk provides a lignocellulosic filler that partially replaces virgin wood flour or mineral fillers. If properly formulated and processed into wood-like boards, such composites could divert both packaging and agricultural residues from low-value uses or disposal while supplying municipalities and other stakeholders with components suitable for low-load urban furniture applications. Crucially, demonstrating manufacturability using a straightforward, industrially transferable route is an essential step to move beyond laboratory feasibility and towards scalable circular products.

Despite the substantial body of work on rice husk composites, WPCs and recycled Tetra Pak® materials [5–12], there is, to the best of our knowledge, no systematic study of hybrid boards that combine recycled PolyAl and rice husk in different proportions and that are produced by extrusion plus compression moulding at board thicknesses representative of real products. The existing literature seldom reports a comprehensive mechanical and durability characterisation—including tensile and flexural behaviour, surface hardness, water absorption and UV ageing—for such hybrid systems, nor does it explicitly link the measured properties to design windows for low-load structural elements such as park benches or beach walkways [6–12]. Accordingly, the novelty of this work lies in three complementary aspects: (i) the combined valorisation of two distinct, locally available residue streams within a single board-grade composite; (ii) the use of an industrially relevant manufacturing route to produce full-thickness, product-representative boards rather than solely laboratory-scale specimens; and (iii) a formulation-window approach in which multiple PolyAl/rice husk ratios are evaluated to identify a balanced compromise between mechanical performance and moisture-related durability indicators for low-load urban elements. This work addresses these gaps by manufacturing wood-like boards from recycled Tetra Pak® PolyAl and ground rice husk through single-screw extrusion followed by compression moulding. Four formulations with different PolyAl/rice husk ratios are prepared and characterised in terms of density, tensile and flexural properties, surface hardness, water absorption and accelerated UV exposure. The experimental stress–strain curves are further analysed using the constitutive laws of Hollomon and Voce [18,19] to extract parameters relevant for mechanical design. By comparing the performance of the different formulations with data reported for rice husk and Tetra Pak-based composites [6–12] and with typical property ranges for outdoor wood–plastic composites [12], the study aims to identify a composition that offers a suitable compromise between mechanical performance and durability for low-load urban furniture applications; as shown in the following sections, the intermediate PolyAl/rice husk ratio provides the most balanced solution within the tested range.

2. Materials and Methods

2.1. Raw Materials

The polymer matrix was an industrially pelletised PolyAl (PA) fraction supplied by Plásticos Trans Sabater (Valencia, Spain), obtained from post-consumer Tetra Pak[®] beverage cartons after fibre recovery by hydropulping. The PA consisted of polyethylene as the continuous phase, containing finely dispersed aluminium and residual cellulose fibres.

Rice husk (RH) was supplied by Mifsud (Valencia, Spain). The material was dried and mechanically ground to obtain a particulate lignocellulosic filler with a maximum particle size of approximately 1 mm. A maleic-anhydride-grafted polyethylene (MAPE) compatibilizer was used to improve interfacial adhesion between the hydrophobic PA and the hydrophilic RH. A brown colouring masterbatch was added to obtain a wood-like appearance suitable for outdoor applications. Both MAPE and the colouring masterbatch were supplied by Irisem (Valencia, Spain).

Throughout the paper, PA and RH refer to the mass fractions (wt.%) of PolyAl and rice husk, respectively.

2.2. Composite Formulations

The selected PA–RH mass ratios were defined to span a practically processable formulation window while providing a representative range of rice husk contents for comparative characterisation. Preliminary qualitative trial batches were produced outside the main experimental campaign to identify the upper feasible RH bound under the available industrial processing route; RH contents above 50 wt.% led to visibly defective boards after hot processing/pressing, surface scorching and poor consolidation. Therefore, 50 wt.% RH was set as the practical upper limit for the study. The intermediate and lower RH contents (43, 30 and 20 wt.%) were then chosen to capture the transition region near this limit and to include compositions commonly reported for wood–plastic composites, where melt processing remains robust [20–22].

Four formulations were selected to cover a realistic range of RH contents while maintaining processability in extrusion and compression moulding. The compositions are summarised in Table 1.

Table 1. Composite formulations (mass fractions in wt.%).

Formulation ¹	PA (wt.%)	RH (wt.%)
F1	80	20
F2	70	30
F3	57	43
F4	50	50

¹ All formulations contained fixed additive loadings of 3 wt.% MAPE compatibilizer and 1 wt.% colouring masterbatch, kept constant across all formulations.

2.3. Processing of Wood-like Boards

Composite boards were produced by Proto-Tech Group (Valencia, Spain) using a single-screw extrusion followed by compression moulding. PA pellets, ground RH, compatibilizer and colourant were first homogenised in a gravimetric mixer and fed into a conventional single-screw extruder. The barrel temperature was set to 160 °C along the entire screw/barrel. Inside the barrel, PA melted and wet the RH particles, generating a viscous composite melt under standard processing conditions for PA-based materials as defined by the partner. The extrudate throughput at the die exit was approximately 150 kg/h.

The molten strand leaving the die was deposited into a pre-heated steel mould with an internal cross-section of approximately 108 × 36 mm and a length of up to 3 m. Once

the cavity was filled, the mould was closed and placed in a hydraulic press, where the material was consolidated under pressure with a maximum press force of up to 20 tonnes, and then cooled under controlled conditions. In-mould cooling was applied for 4 min before demoulding; the boards were then allowed to cool further outside the mould to ambient temperature. After demoulding, continuous solid boards with wood-like colour and surface finish were obtained.

2.4. Specimen Preparation

Specimens for mechanical and physical testing were machined from the boards using standard woodworking tools. Full-section beams were cut along the extrusion direction for three-point bending tests, with typical dimensions of about $440 \times 108 \times 35$ mm (length $\times$ width $\times$ thickness), constrained by the board geometry.

Rectangular plates were extracted from the board faces and further machined into tensile specimens with a reduced central gauge, following the general philosophy of dog bone specimens used for plastics. Smaller prismatic pieces were prepared for density measurements, and fragments were reserved for hardness, water absorption and UV-ageing tests.

All specimens were labelled with their formulation code (F1–F4) and conditioned at laboratory ambient temperature and humidity for at least 48 h prior to testing. For each formulation and test, several specimens were used and mean values and standard deviations were calculated.

2.5. Mechanical Testing

Tensile tests were carried out on a universal testing machine under displacement control using mechanical wedge grips. Specimens were waterjet-cut from the boards into a dog bone geometry with a nominal gauge length of 100 mm and a constant rectangular cross-section in the gauge region of 19 mm (width) $\times$ 12 mm (thickness). Force was measured using the machine load cell, and specimen elongation was obtained from the built-in crosshead displacement, machine-corrected. Because specimen geometry was constrained by the available industrial boards, the procedure followed the general recommendations of UNE-EN ISO 527 [23] as closely as possible while acknowledging minor deviations from preferred standard specimen geometries. Six specimens per formulation were tested; tests deemed invalid (e.g., fracture within the grips or obvious geometry-related defects) were excluded from property averaging, resulting in 21 valid tensile specimens overall (F1: $n = 6$; F2: $n = 5$; F3: $n = 6$; F4: $n = 4$). Force–displacement data were converted into engineering stress–strain curves using the initial cross-sectional area and gauge length. Stress–strain curves were then obtained assuming negligible volume change in the plastic regime.

Flexural behaviour was characterised by three-point bending tests performed directly on full-section industrial boards (as-produced beams) in the same universal testing machine. A simply supported configuration with a span of 400 mm was used; given the nominal board thickness of 35 mm, this corresponds to a span-to-thickness ratio $L/h \approx 400/35 = 11.4$. Flexural results are reported as nominal engineering flexural stress and strain derived from standard beam-bending relationships, and comparisons with literature values obtained under fully ISO-compliant spans should be made with caution. All formulations were tested under the same span and loading configuration to ensure consistent internal comparability. Five specimens per formulation were tested in bending ($n = 20$ total), and the applied force and mid-span deflection were recorded to determine flexural modulus and strength.

2.6. Physical and Durability Testing

Surface hardness was measured on small specimens cut from the board surfaces using a Shore D durometer mounted on a stand. The methodology was based on UNE-EN ISO 868 [24].

For each specimen, several readings were taken at different locations and averaged to obtain a representative hardness value; three specimens per formulation were tested. Each specimen had an exposed face of 50 mm × 25 mm and a thickness of 12 mm.

Apparent density was determined on prismatic specimens by dry measurements. Mass was recorded using an analytical balance and dimensions were measured with a calliper. The procedure was inspired by UNE-EN ISO 1183 [25]. Density specimens had nominal dimensions of 41 mm × 14 mm × 11 mm, and one specimen per formulation was measured ($n = 4$ total).

Water absorption was evaluated on prismatic specimens (41 mm × 14 mm × 11 mm) obtained from cutting operations. Specimens were dried to constant mass, weighed and then immersed in water at room temperature. At selected exposure times (from hours to several days), specimens were removed, wiped to remove surface water and re-weighed. Specimens were not sealed; therefore, water ingress could occur through all faces. Water uptake is reported as mass gain per unit exposed area (g/m^2) to reduce geometry-driven bias associated with area-to-volume effects when using mass-percentage metrics. Thickness swelling was not measured in the present test campaign and will be addressed in future work as a key indicator of dimensional stability. The protocol followed the philosophy of UNE-EN ISO 62 [26] but with non-standard specimen shapes and an adapted immersion schedule. Two specimens per formulation were tested ($n = 8$ total).

Short-term UV ageing was studied by exposing rectangular specimens (50 mm × 25 mm exposed face; 12 mm thickness) to a low-pressure mercury lamp with a dominant wavelength of 254 nm. Six specimens per formulation were subjected to increasing exposure times ($n = 24$ total). After each interval, Shore D hardness was measured using the same procedure as for unexposed material. Because 254 nm corresponds to UVC and is not representative of terrestrial solar UV, outdoor exposure is dominated by UVA/UVB while UVC is effectively filtered by the atmosphere [27]; this test is used here as a short-term comparative screening among formulations rather than an outdoor weathering simulation. Visual inspection was performed during the exposure campaign to identify macroscopic surface changes; however, no quantitative colour measurements and no post-irradiation flexural re-testing were conducted in this study since the specimens were too small to test their flexural properties. The method provided a qualitative assessment of the influence of UV radiation on surface properties, inspired by the general concept of accelerated weathering methods in UNE-EN ISO 4892 [28].

2.7. Microstructural Analysis and Constitutive Modelling

Microstructural observations were performed on polished cross-sections of selected specimens by optical microscopy. The analysis focused on RH particle dispersion, the presence of voids or defects and the apparent quality of the PA–RH interface. Representative images were used to support the interpretation of the mechanical and physical results.

Stress–strain curves obtained from tensile tests were fitted to two classical work-hardening laws: Hollomon and Voce [18,19]. Non-linear regression was applied to the plastic portion of the curves to identify the corresponding parameters for each formulation. These parameters were later used to compare the mechanical response of the PA–RH boards and to discuss the suitability of each constitutive law for design and numerical modelling of low-load structural elements made from the studied material.

3. Results

This section presents the experimental results obtained for the PA–RH boards, structured by type of test. First, the tensile and flexural responses are analysed together with the constitutive parameters identified from the stress–strain curves. Then, the physical

properties (hardness and apparent density) and water absorption behaviour are reported, followed by a brief assessment of short-term UV ageing and microstructural observations. Unless otherwise stated, reported values correspond to the mean of all tested specimens for each formulation, and the detailed numerical data are provided in the corresponding tables and figures.

3.1. Tensile Behaviour and Constitutive Parameters

The stress–strain curves in tension for the four PA–RH boards are shown in the experimental and fitted plots, Hollomon and Voce. All compositions display a non-linear response from very low strain levels, with a short quasi-linear initial segment followed by a marked strain-hardening region up to fracture. Maximum stresses are in the range of 8–10 MPa. Within this range, the 57PA–43RH board consistently reaches the highest stress levels over most of the strain interval, whereas 80PA–20RH shows the lowest tensile strength; 50PA–50RH and 70PA–30RH exhibit intermediate behaviour. The scatter between specimens of the same composition is moderate, indicating acceptable reproducibility of the manufacturing process.

The experimental curves were first fitted to the Hollomon law:

$$\sigma = K \cdot \varepsilon^n, \quad (1)$$

using stress σ and strain ε . The global parameters obtained for each formulation (refer to Table 2) show strength coefficients K between 29.29 and 76.85 MPa and strain-hardening exponents n between 0.43 and 0.60. The highest K and n values correspond to 50PA–50RH, followed by 57PA–43RH, while 70PA–30RH presents the lowest values; 80PA–20RH partially recovers both K and n . In all cases, the determination coefficients R^2 lie between 0.94 and 0.97, confirming that this simple power law reproduces the overall curvature of the tensile response, although it cannot represent the gradual saturation observed at larger strains.

Table 2. Hollomon parameters for the tensile stress–strain curves of the PA–RH composites.

Formulation	k (MPa)	n (-)	R ²
50PA–50RH	76.853	0.6027	0.9456
57PA–43RH	62.409	0.5687	0.9404
70PA–30RH	29.290	0.4303	0.9638
80PA–20RH	38.159	0.4929	0.9655

After fitting the global Hollomon parameters, the experimental stress–strain curves for all tensile specimens were compared with the corresponding model predictions. Figure 1 shows, for each PA–RH board, the individual tensile curves and the global Hollomon fit, illustrating both the scatter between specimens and the ability of the power law to reproduce the overall shape of the response.

To capture this saturation effect, the Voce law was also applied:

$$\sigma = \sigma_s - (\sigma_s + \sigma_0) \cdot e^{-c \cdot \varepsilon}, \quad (2)$$

where σ_0 is the initial flow stress, σ_s the saturation stress and c a material constant. The resulting global parameters for each composite are summarised in Table 3. Saturation stresses σ_s range from 7.76 MPa (80PA–20RH) to 10.36 MPa (57PA–43RH), in agreement with the ranking observed in the experimental curves. The parameter c takes values between 50.5 and 88.0, reflecting different rates of approach to saturation. The coefficients of determination R^2 are between 0.94 and 0.99 and are systematically equal to or higher

than those of the Hollomon fits, while the global Voce curves closely follow the envelopes of the experimental data for all formulations. On this basis, the Voce model is selected as the reference constitutive law for subsequent analysis of the tensile behaviour of the PA–RH boards.

Table 3. Voce parameters for the tensile stress–strain curves of the PA–RH composites.

Formulation	σ_s (MPa)	σ_0 (MPa)	c (-)	R^2
50PA–50RH	8.152	0.370	88.005	0.9466
57PA–43RH	10.359	0.741	50.525	0.9386
70PA–30RH	8.600	0.563	51.214	0.9857
80PA–20RH	7.760	0.275	68.799	0.9888

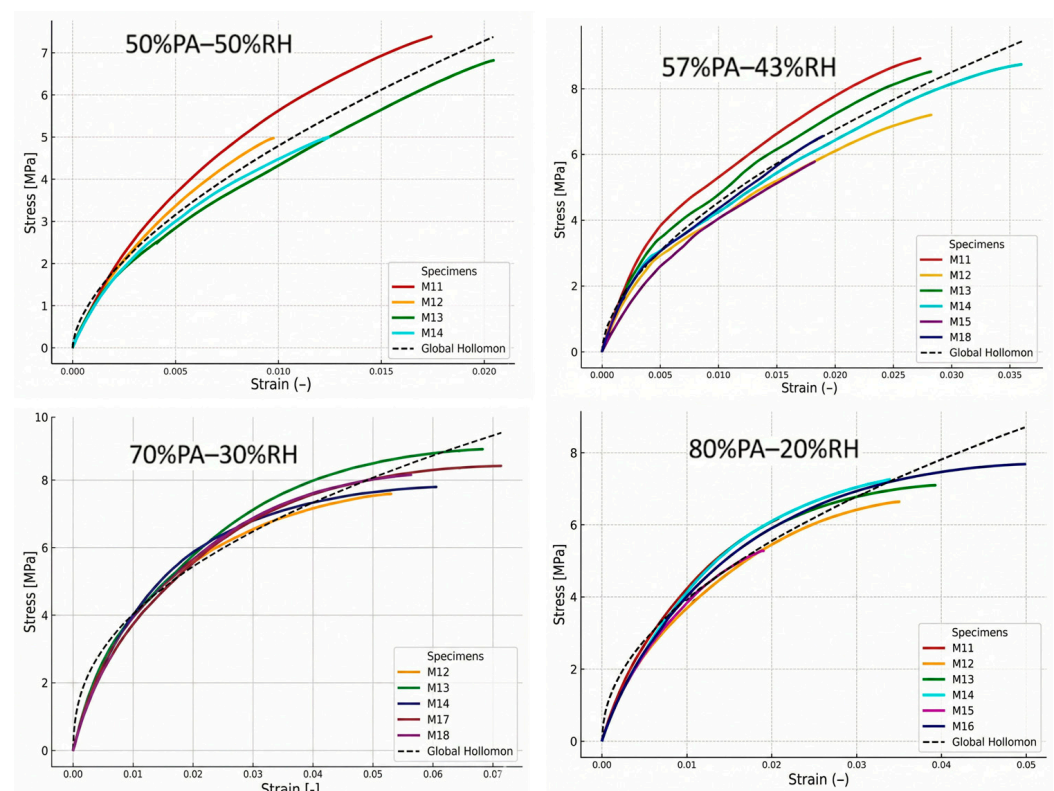


Figure 1. Tensile stress–strain Hollomon curves for the PA–RH boards.

After identifying the global Voce parameters, the experimental stress–strain curves of all tensile specimens were compared with the corresponding model predictions. Figure 2 shows, for each PA–RH board, the individual tensile curves together with the global Voce fit, illustrating both the experimental scatter and the ability of the Voce law to reproduce the non-linear hardening behaviour up to saturation.

To provide an overall comparison between formulations, the four global Voce curves were plotted together in a single graph. Figure 3 summarises the fitted tensile behaviour of the PA–RH boards, highlighting the differences in stress level and hardening rate associated with the PA/RH ratio.

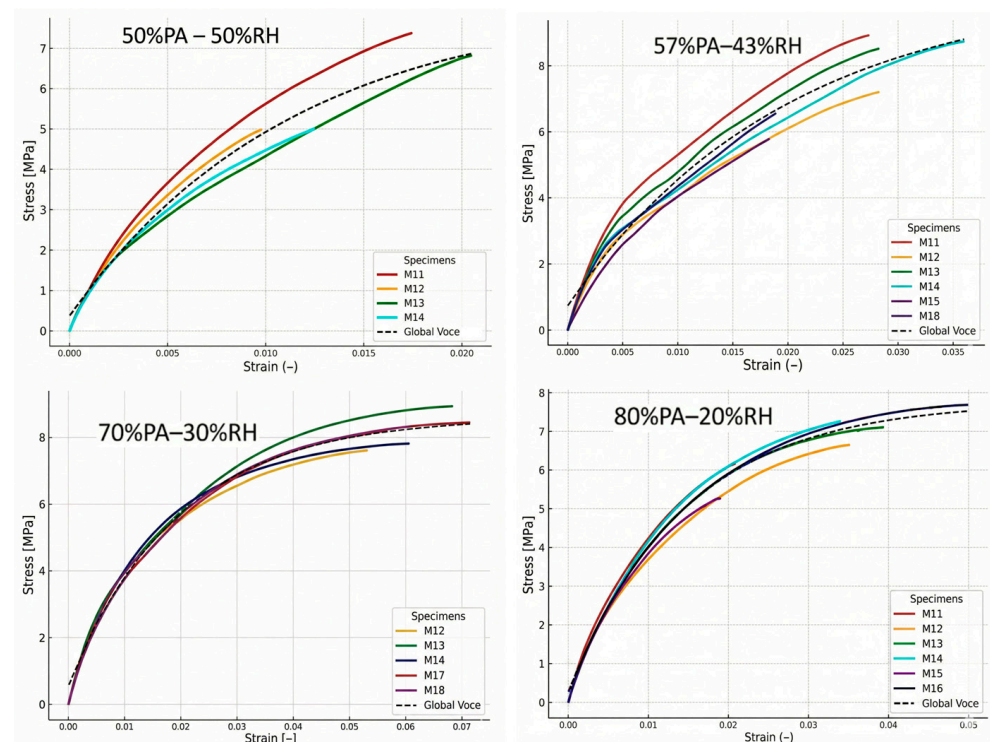


Figure 2. Tensile stress–strain Voce curves for the PA–RH boards.

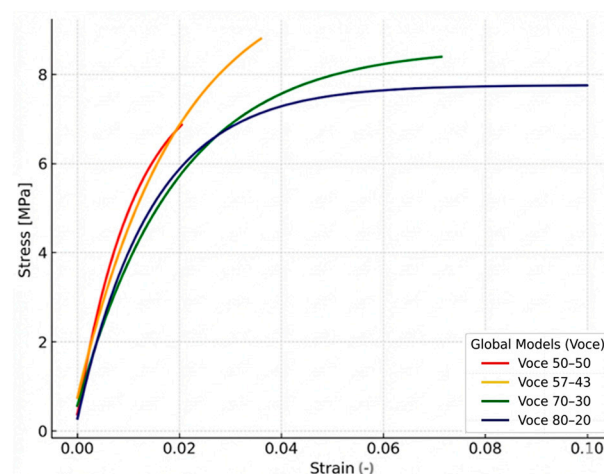


Figure 3. Global Voce tensile stress–strain curves for the four PA–RH formulations.

3.2. Bending Behaviour and Constitutive Parameters

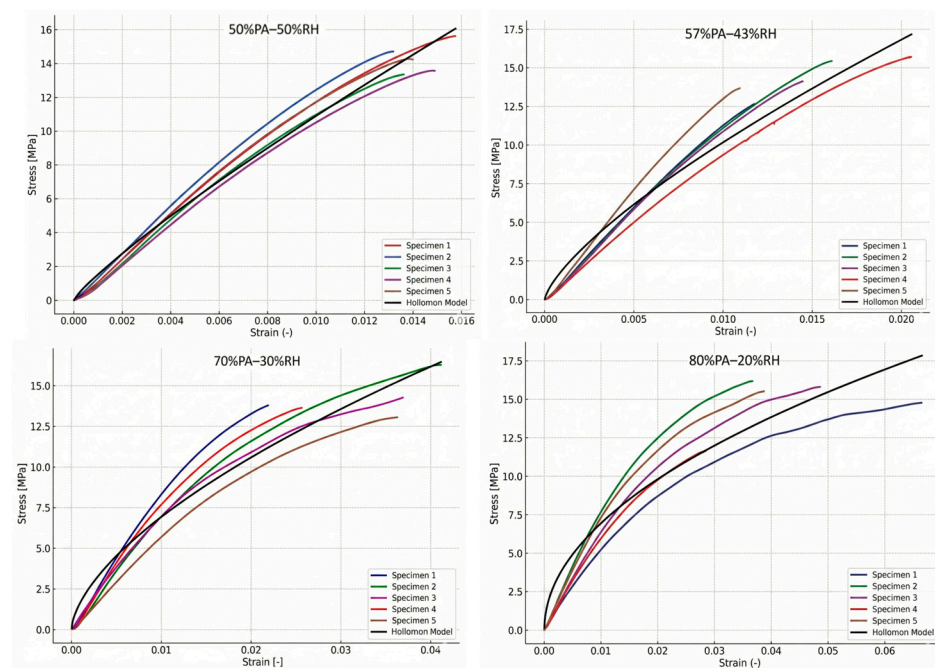
Three-point bending tests were carried out on full-section beams to characterise the flexural response of the PA–RH boards. Flexural stress–strain curves were derived from the force–deflection data and used to identify the parameters of the Hollomon and Voce work-hardening laws (Equations (1) and (2)), following the same procedure as in tensile.

The flexural curves were first fitted using the Hollomon law (Equation (1)). The global parameters obtained for each formulation are summarised in Table 4. The strength coefficient K shows a clear decreasing trend from approximately 665 MPa for 50PA–50RH down to about 70 MPa for 80PA–20RH, while the strain-hardening exponent n decreases from around 0.90 to 0.51. The coefficients of determination R^2 remain relatively high (between 0.86 and 0.98), indicating that the Hollomon law provides a reasonable description of the overall flexural hardening behaviour of the boards.

Table 4. Hollomon parameters for the three-point bending tests on PA–RH composites.

Formulation	k (MPa)	n (-)	R ²
50PA–50RH	664.725	0.8988	0.9798
57PA–43RH	310.686	0.7497	0.9242
70PA–30RH	117.109	0.6153	0.9280
80PA–20RH	70.262	0.5061	0.8590

After fitting the global Hollomon parameters, the experimental flexural stress–strain curves for all specimens were compared with the corresponding model predictions. Figure 4 shows, for each formulation, the individual flexural curves together with the global Hollomon fit, illustrating both the experimental scatter and the capability of the power law to reproduce the main features of the response.

**Figure 4.** Comparison between experimental flexural stress–strain curves and global Hollomon fits for the four PA–RH formulations.

To better capture the saturation tendency observed at higher flexural strains, the same curves were fitted using the Voce law (Equation (2)). The corresponding parameters are listed in Table 5. The saturation stress σ_s decreases from about 38 MPa for 50PA–50RH to roughly 16 MPa for 80PA–20RH, in line with the reduction of apparent flexural strength as the PA content increases. The initial stress σ_0 is practically negligible in all cases, and the parameter c takes values between approximately 33 and 64, controlling how quickly the curves approach σ_s . The Voce fits yield R^2 values between about 0.92 and 0.98, systematically higher than those obtained with the Hollomon model.

Table 5. Voce parameters identified from flexural tests on PA–RH composites.

Formulation	σ_s (MPa)	σ_0 (MPa)	c (-)	R ²
50PA–50RH	37.910	<0.1	33.14	0.9837
57PA–43RH	21.631	<0.1	63.78	0.9414
70PA–30RH	16.342	<0.1	56.26	0.9513
80PA–20RH	15.709	<0.1	54.22	0.9227

Figure 5 illustrates the agreement between the experimental flexural data and the Voce predictions for each formulation. The model closely follows the non-linear hardening over the whole strain range, particularly in the high-strain region. For design and comparative purposes, the four global Voce curves are finally plotted together in Figure 6, providing a compact summary of the flexural response of the PA–RH boards as a function of composition. In view of the higher average R^2 and its ability to reproduce the saturation behaviour, the Voce law is selected as the preferred constitutive model in bending.

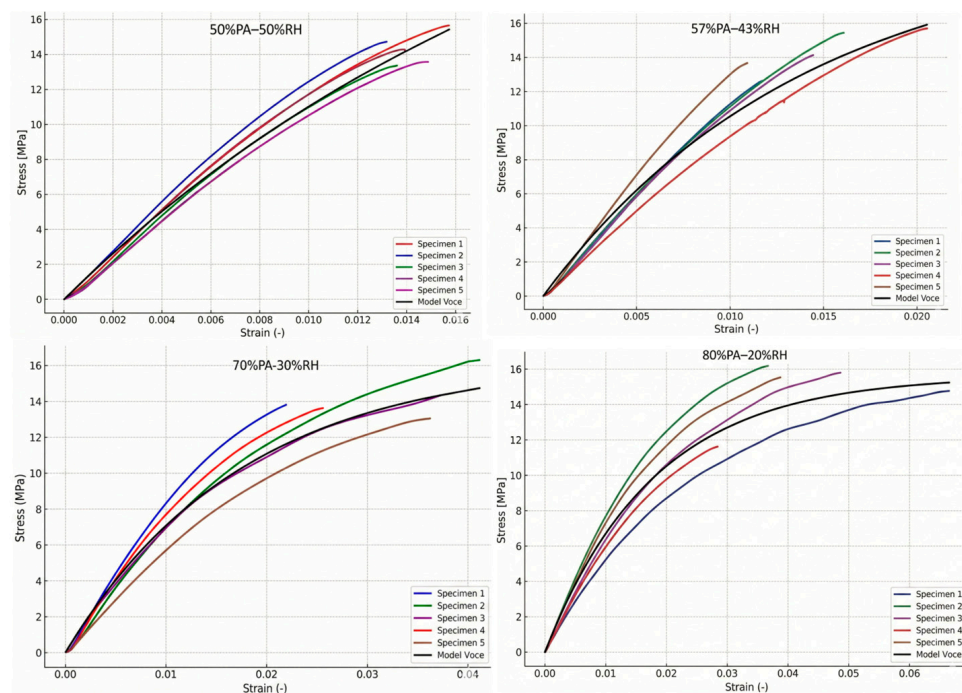


Figure 5. Experimental flexural stress–strain curves and corresponding Voce fits for the four PA–RH formulations.

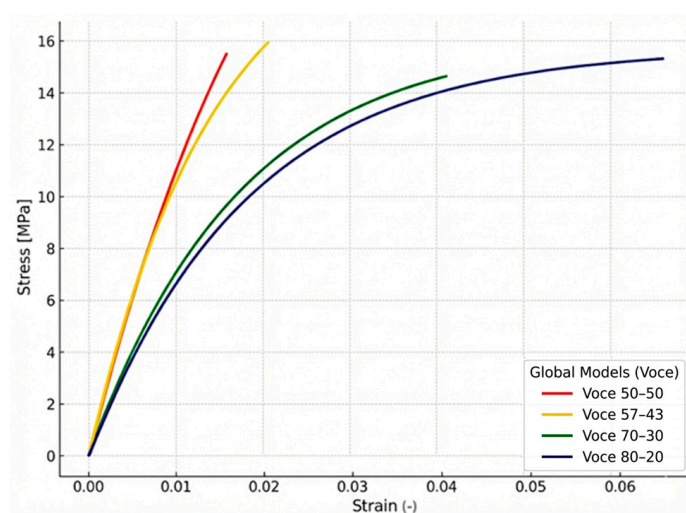


Figure 6. Global Voce flexural stress–strain curves for the four formulations, obtained from the fitted parameters.

3.3. Surface Hardness

Shore D hardness in dry condition was measured on all PA–RH boards. The descriptive statistics for each formulation are summarised in Table 6, including number of specimens, mean value, standard deviation and minimum/maximum hardness. The highest average

hardness was obtained for the 50PA–50RH board (≈ 61.67 Shore D), followed by 57PA–43RH (≈ 58.30). The 70PA–30RH and 80PA–20RH formulations showed lower mean values, around 52.36 and 50.36, respectively. Standard deviations remained modest in all cases, which indicates a good reproducibility of the hardness measurements.

Table 6. Descriptive statistics of Shore D hardness for each formulation.

Formulation	N	Mean Hardness, μ	Standard Deviation, σ	Minimum	Maximum
50PA–50RH	9	61.67	1.12	60.0	63.0
57PA–43RH	10	58.30	3.39	55.0	61.5
70PA–30RH	10	52.36	2.24	49.0	56.0
80PA–20RH	7	50.36	0.74	49.5	51.0

The distribution of hardness values is illustrated in Figure 7 by means of box-and-whisker plots. For each composition, the median hardness is highlighted by a black line inside the box, and the numerical mean is plotted next to it. This representation makes it possible to visualise both intra-composition variability and the systematic decrease in hardness as the PA (Tetrabrik) content increases and the RH fraction is reduced.

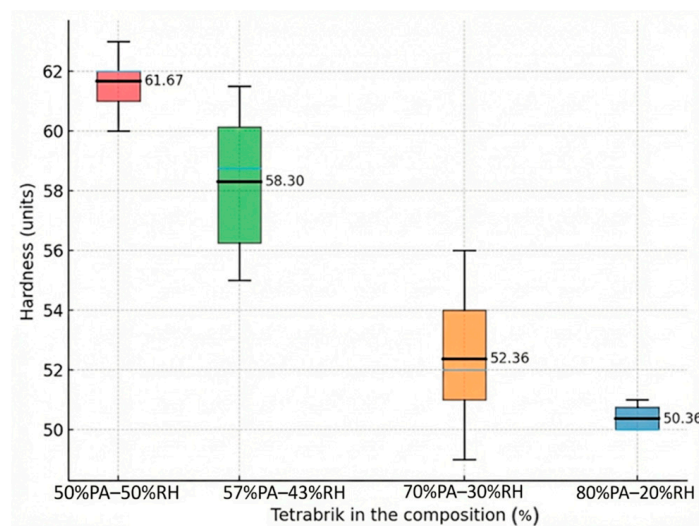


Figure 7. Box-and-whisker representation of Shore D hardness by formulation.

The relationship between hardness and formulation was further quantified by a linear regression of the mean hardness against the PA content, expressed as Tetrabrik percentage in the mixture (Figure 8). The experimental data show a clear decreasing trend, which is well described by the regression line.

The equation representing this trend being

$$\text{Hardness} = 80.48 - 0.39 \cdot (\%PA); \quad R^2 = 0.975, \quad (3)$$

this result indicates that each 1 wt.% increase in Tetrabrik content leads, on average, to a reduction of about 0.39 Shore D units in surface hardness within the studied composition range.

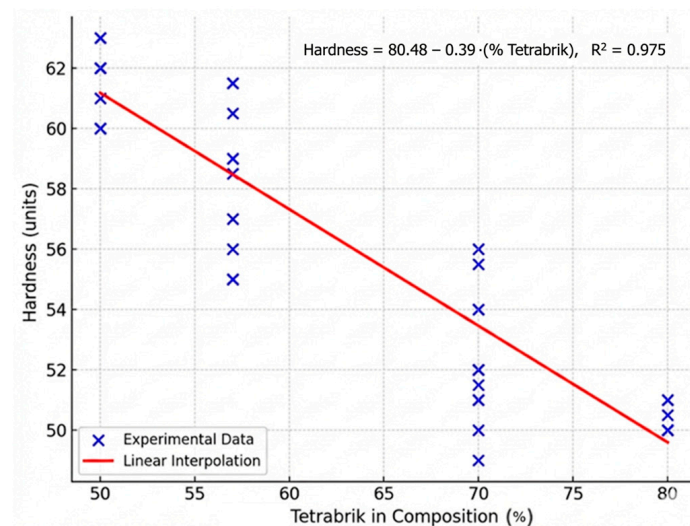


Figure 8. Relationship between Shore D hardness and Tetrabrik (PA) content in the composites, with linear regression fit.

3.4. Apparent Density

Apparent density was determined for all PA–RH boards using prismatic specimens cut from the moulded panels. Figure 9 shows the evolution of density as a function of PA content. A clear increasing trend is observed, from approximately $1.12 \text{ g}\cdot\text{cm}^{-3}$ for the 50PA–50RH composite to about $1.20 \text{ g}\cdot\text{cm}^{-3}$ for 80PA–20RH, with intermediate values around $1.14 \text{ g}\cdot\text{cm}^{-3}$ and $1.18 \text{ g}\cdot\text{cm}^{-3}$ for the 57PA–43RH and 70PA–30RH formulations.

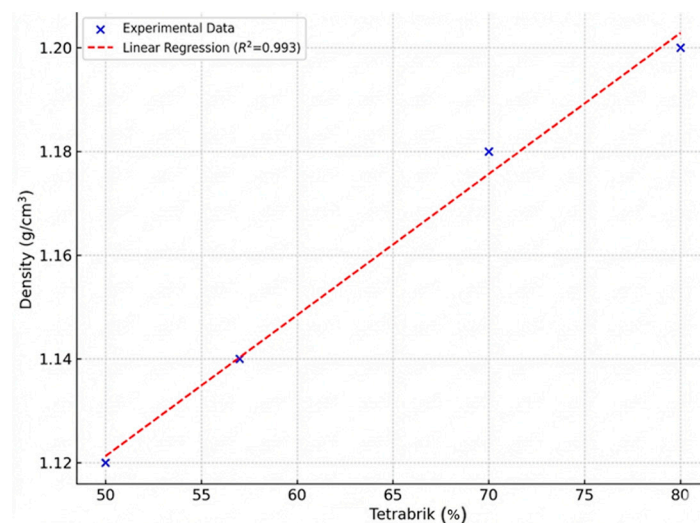


Figure 9. Apparent density as function of PA content, with linear regression fit ($R^2 = 0.993$).

Apparent density results are summarised in Table 7.

Table 7. Measured apparent density of each formulation (g/cm^3).

Formulation	Apparent Density (g/cm^3)
50PA–50RH	1.12
57PA–43RH	1.14
70PA–30RH	1.18
80PA–20RH	1.20

The linear regression of density versus PA percentage yields a high coefficient of determination ($R^2 = 0.993$), confirming the strong correlation between both variables. The fitted relationship can be expressed as

$$\text{Density} = 0.00272 \cdot (\% \text{ PA}) + 0.985 \quad (4)$$

within the composition range considered in this study.

3.5. Water Absorption

Water absorption tests were performed on all PA–RH boards by monitoring the normalised mass gain per exposed surface area as a function of the square root of immersion time. The mean curves for each formulation are compared in Figure 10. All compositions exhibit an initial quasi-linear increase of absorbed water versus $\sqrt{t}$, consistent with a diffusion-controlled surface mechanism, followed by a gradual approach towards a quasi-steady state as immersion time increases.

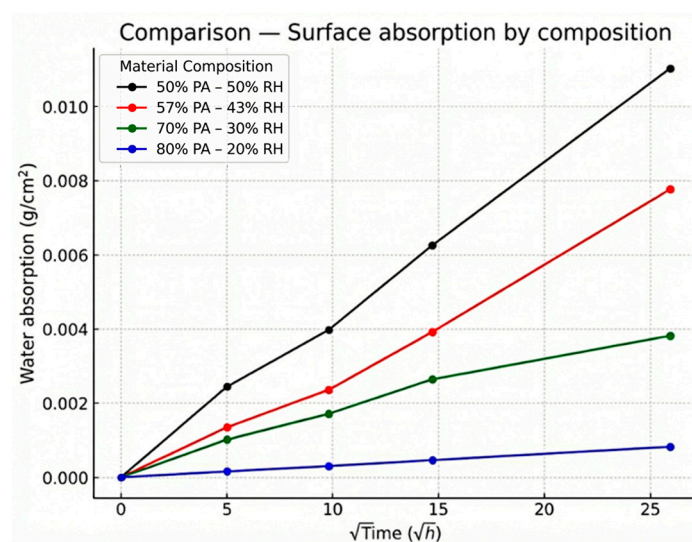


Figure 10. Normalised surface water absorption as a function of the square root of immersion time.

To complement the comparative trends shown in Figure 10, Table 8 reports the numerical values of the normalised surface water absorption measured at the different immersion times. The tabulated data correspond to the mean mass gain per unit exposed surface area for each formulation and provide the quantitative basis of the $\sqrt{t}$ representation, enabling a direct comparison of the time-dependent moisture uptake among the PA–RH boards.

Table 8. Normalised surface water absorption (g/cm^2) of PA–RH boards at different immersion times.

Formulation	25 h	96 h	216 h	672 h
50PA–50RH	0.0025	0.0041	0.0064	0.0114
57PA–43RH	0.0015	0.0026	0.0044	0.0079
70PA–30RH	0.0010	0.0017	0.0027	0.0038
80PA–20RH	0.0002	0.0002	0.0005	0.0009

A clear dependence on composition is observed. The 50PA–50RH and 57PA–43RH boards show the highest absorption rates and final uptake levels, whereas the 80PA–20RH composite exhibits the lowest values throughout the test, confirming the beneficial effect of a higher PA fraction on resistance to moisture ingress. The 70PA–30RH formulation displays intermediate behaviour, with noticeably lower water uptake than the more RH-rich boards

while still retaining significant bio-based content. Normalisation by exposed surface area removes geometric effects between specimens, enabling a consistent comparison among the four materials. Within the range studied, 70PA–30RH appears as a reasonable compromise between stiffness (Sections 3.1 and 3.2) and water resistance.

3.6. Microstructural Observations

Representative optical micrographs of the PA–RH boards are shown in Figures 11–14. The bright regions correspond to PolyAl-rich domains containing aluminium foil fragments, whereas the darker background is associated with the polymeric matrix and the lignocellulosic filler. In all formulations, PolyAl particles appear as irregular clusters with variable size, and their spatial distribution is clearly non-uniform, with zones of higher and lower particle density.

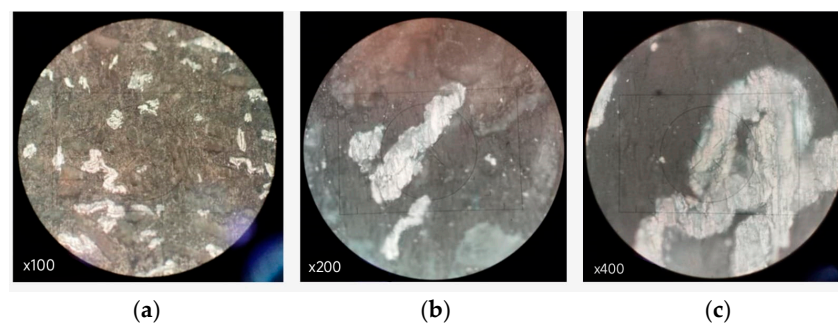


Figure 11. Representative optical micrographs of the 80PA–20RH composite: (a) overview of the microstructure at 100 $\times$; (b) detail of PolyAl-rich domains and surrounding matrix at 200 $\times$; (c) close-up of PolyAl clusters and neighbouring regions at 400 $\times$.

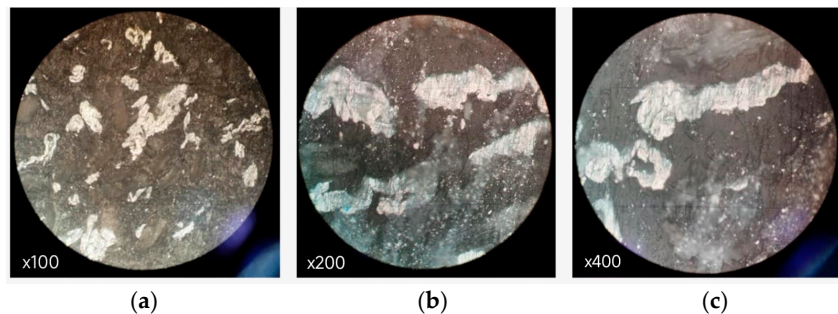


Figure 12. Representative optical micrographs of the 70PA–30RH composite: (a) overview of the microstructure at 100 $\times$; (b) detail of PolyAl-rich domains and surrounding matrix at 200 $\times$; (c) close-up of PolyAl clusters and neighbouring regions at 400 $\times$.

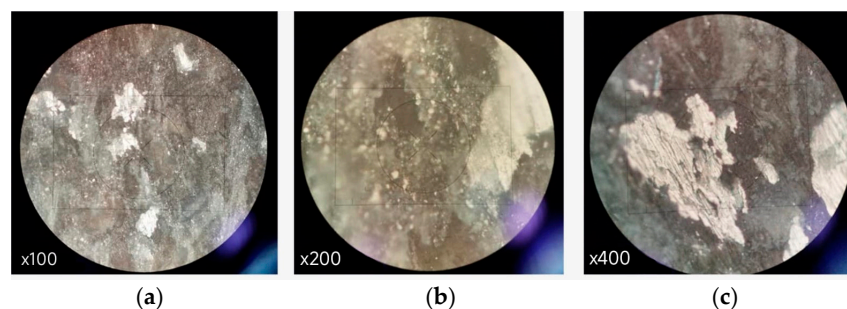


Figure 13. Representative optical micrographs of the 57PA–43RH composite: (a) overview of the microstructure at 100 $\times$; (b) detail of PolyAl-rich domains and surrounding matrix at 200 $\times$; (c) close-up of PolyAl clusters and neighbouring regions at 400 $\times$.

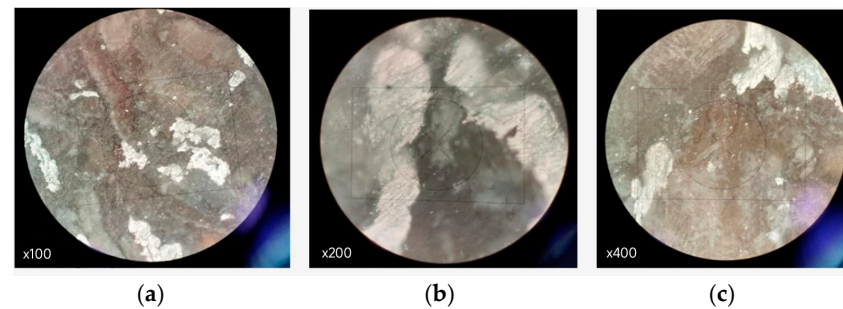


Figure 14. Representative optical micrographs of the 50PA–50RH composite: (a) overview of the microstructure at 100×; (b) detail of PolyAl-rich domains and surrounding matrix at 200×; (c) close-up of PolyAl clusters and neighbouring regions at 400×.

Within these qualitative pictures, the boards with higher PA content tend to exhibit larger PolyAl-rich agglomerates and more pronounced local heterogeneities, while the more RH-rich formulations show a slightly finer dispersion. Due to the absence of metallographic etching and the optical contrast limitations, individual rice husk particles cannot be clearly distinguished from the surrounding matrix, and a quantitative assessment of porosity or interfacial defects is not possible with the present images. Nevertheless, these observations support the interpretation that microstructural heterogeneity and the distribution of PolyAl-rich domains are likely to influence the tensile and flexural behaviour of the boards discussed in Sections 3.1 and 3.2.

3.7. UV Ageing

The evolution of surface hardness under UV exposure was monitored for all PA–RH boards up to 100 h (test conditions described in Section 2). Figure 15 shows the mean Shore D hardness of each formulation as a function of exposure time. All composites exhibit a progressive increase in hardness with irradiation time, without abrupt changes or signs of surface degradation during the test window. It should be noted that the irradiation was performed at 254 nm (UVC), which is not representative of outdoor sunlight; therefore, the observations below are interpreted as short-term comparative screening indicators rather than evidence of outdoor durability [27].

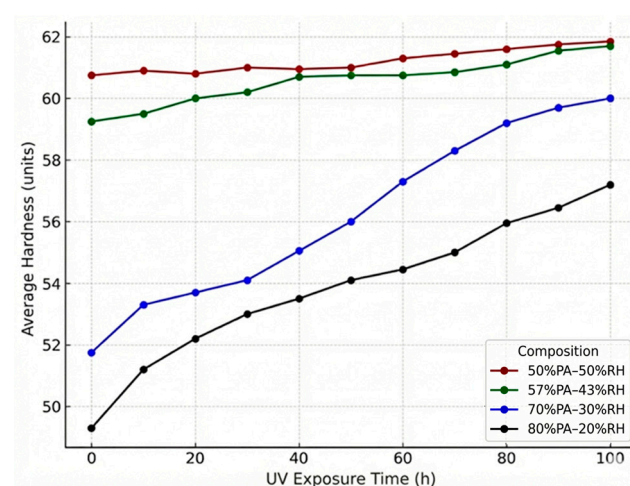


Figure 15. Evolution of mean Shore D surface hardness as a function of UV exposure time.

Formulations with higher RH content start from the highest initial hardness levels. The 50PA–50RH board increases from about 60.7 to 61.9 Shore D between 0 and 100 h, while 57PA–43RH evolves from roughly 59.3 to 61.1 Shore D with very small variations throughout the test. In contrast, the 70PA–30RH and 80PA–20RH boards begin from lower

hardness values (≈ 50.5 and ≈ 49.5 Shore D, respectively) and show a more pronounced hardening, reaching about 61 and 56–57 Shore D after 100 h. Overall, all four formulations present a moderate increase in surface hardness under the applied UV conditions, with final values that tend to converge towards a relatively narrow range, and no macroscopic surface cracking was observed during visual inspection within the 100 h window. However, since only surface hardness was monitored under UVC irradiation, and no quantitative colour measurements or post-irradiation flexural testing were performed, these results cannot be used to infer changes in bulk mechanical performance or outdoor weathering resistance.

4. Discussion

This section integrates the mechanical, physical and durability results obtained for the PA–RH composite boards and compares them with previous studies on rice-husk-reinforced polymers and Tetra Pak-based composites [5–12]. The aim is to clarify how the PolyAl/rice husk ratio controls stiffness, strength, hardness and water uptake, and to outline the implications for low-load structural applications where outdoor exposure may occur, while explicitly recognising the limitations of the present flexural test geometry and the non-representative nature of the short-term UVC (254 nm) screening when discussing outdoor performance [13–17].

4.1. Mechanical and Physical Behaviour in the Context of Previous Composites

The boards manufactured from PA and RH exhibit densities between about 1.12 and 1.20 g/cm³, increasing almost linearly with the PA (Tetra Pak) fraction. This range is fully consistent with typical wood–plastic composites (WPCs) and with other materials derived from recycled Tetra Pak containers, such as polymer concretes, composite panels and concrete-like elements, which generally lie between 1.0 and 1.3 g/cm³ depending on matrix type and filler content [6–9,12]. In addition, Table 9 provides quantitative benchmarks from representative Tetra Pak-containing polymer composites: recycled PE-based WPC produced with used Tetra Pak boxes and wood flour typically report densities around 0.94–1.02 g/cm³ [29], while recycled PP-based composites filled with Tetra Pak-derived material report densities of approximately 0.99–1.11 g/cm³ [30].

Table 9. Benchmark comparison of density, flexural strength, Shore D hardness and water absorption for this study and representative Tetra Pak-containing wood–plastic composites.

Material System	Density (g/cm ³)	Flexural Strength (MPa)	Hardness (Shore D)	Water Absorption (Metric)
This study	1.12~1.20	14.3~16	49.0~63.0	0.009~0.0114 g/m ²
Rpe + TPB + wood flour WPC	0.942~1.017	13.5~19.8	51.3~57.4	-
rPP + TPB + wood flour WPC	0.988~1.107	26.3~36.9	71~73	% (0.72~4.64); TS% (0.89~4.11)

Flexural strength values around 16 MPa place the present boards in the lower–medium range of WPCs used for decking and cladding and in the same order of magnitude as Tetra Pak-based composites reported by Gallego et al., Martínez-López et al. and Martínez-Barrera et al. [6,8,9]. In those works, bending strengths between roughly 15 and 30 MPa and moduli above 3 GPa were obtained for boards and polymer concretes manufactured from recycled Tetra Pak fractions [6,8,9]. Compared with these references, the PA–RH boards achieve competitive stiffness and strength while simultaneously valorising two residue streams (PolyAl and rice husk), which imposes additional constraints on processing and dispersion. Table 9 further anchors this comparison numerically: recycled PE/TPB/wood

flour WPC report flexural strengths in the ≈ 13.5 – 19.8 MPa range with flexural moduli below ≈ 1.0 GPa [29], whereas recycled PP/TPB composites can reach ≈ 26.3 – 36.9 MPa with flexural moduli around ≈ 1.4 – 1.7 GPa [30]. These benchmarks highlight the strong influence of matrix type (PE vs. PP), filler architecture and processing route on the stiffness–strength balance and provide a quantitative frame for interpreting the trends observed across the PA–RH formulations.

The trend observed in this work—higher stiffness and hardness with increasing RH content, accompanied by reduced ductility—is in good agreement with reviews and parametric studies on polypropylene–rice husk composites [10,11]. These studies show that lignocellulosic fillers generally increase tensile and flexural modulus but can reduce tensile strength and elongation at break when the filler content becomes too high, due to stress concentrations and imperfect stress transfer at the matrix–fibre interface [10,11]. The behaviour of the present PA–RH boards therefore follows the same micromechanical tendencies, despite the more complex PolyAl matrix and the presence of aluminium layers. From a processing–structure perspective, increasing RH loading also increases melt viscosity and reduces flowability, which can raise sensitivity to dispersion quality and local porosity during consolidation; this offers a mechanistic interpretation of composition-dependent responses beyond a repetition of average values.

From a constitutive viewpoint, the tensile and flexural curves of all formulations are strongly non-linear and can be described using classic work-hardening laws. Among the two models considered (Hollomon and Voce) [18,19], the Voce law gives the highest coefficients of determination and, importantly, captures the saturation of flow stress at large strains. This is relevant for design, because Hollomon-type power laws tend to overestimate stresses at high strain levels [18], whereas the Voce formulation was originally proposed to represent realistic saturation behaviour in metals [19] and can be directly implemented in numerical simulations of boards and structural details. Accordingly, the constitutive fitting is used here primarily as an interpretative tool to compare formulation trends and to support future model-based design, while the quantitative benchmarking against WPC and Tetra Pak-derived composites is summarised separately in Table 9 [29,30].

4.2. Effect of the PA/RH Ratio: Stiffness–Strength–Hardness Balance

Changing the PA/RH ratio proved to be an efficient way of tuning the mechanical response. Compositions with higher RH content showed higher Shore D hardness and increased flexural stiffness, as expected when a more rigid lignocellulosic phase is introduced into a polyolefin matrix [10–12]. At the same time, these RH-rich boards exhibited slightly lower flexural strength and reduced deformation capacity, which can be attributed to stress concentrations around rigid particles, local debonding at the PA/RH interface and a higher probability of micro-voids [10,11].

Conversely, PA-rich formulations (70PA–30RH and 80PA–20RH) benefited from a more continuous polymeric matrix and from the presence of aluminium flakes, which helped to maintain strength and improved moisture resistance, but they displayed lower modulus and hardness. Similar trade-offs between stiffness, strength and ductility have been reported in WPC technology, where the optimal natural-fibre content is often found in the range 30–40 wt.% [12]. As summarised in Table 9, published Tetra Pak-containing polymer composites span a broad flexural and hardness envelope depending on matrix type and processing route (e.g., PE-based WPC vs. PP-based composites) [29,30], which provides a quantitative frame for the trade-offs observed here.

Within the composition window studied here, the 70PA–30RH board stands out as the best compromise. It reaches the highest flexural stiffness while maintaining flexural strength values comparable to RH-richer boards and keeping water absorption at intermediate levels.

Its hardness remains within the typical range reported for commercial WPC decking and cladding [12]. This balance between rigidity, strength, hardness and moisture sensitivity makes the 70PA–30RH formulation a plausible candidate for low-load board applications where serviceability (deflection and surface wear) is as important as ultimate strength. It should also be noted that the flexural span-to-thickness ratio was constrained by the available board geometry and test rig limits (Section 2.4); therefore, the flexural outputs are interpreted primarily for comparative assessment across formulations rather than as fully standard-compliant MOR/MOE values [31].

4.3. Water Absorption and UV Ageing in Relation to Durability Studies

Normalised water absorption curves revealed an initial regime approximately proportional to the square root of immersion time, followed by a gradual approach to saturation. This behaviour is typical of Fickian diffusion controlled by surface ingress and has been widely reported for PP–RH composites and other WPCs [10–12]. In the present boards, compositions with higher RH content showed higher slopes and higher saturation levels, whereas PA-rich formulations absorbed less water over the same exposure time. This is consistent with the hydrophilic nature of the lignocellulosic phase and the hydrophobic barrier effect of the PolyAl fraction [10–12].

In absolute terms, the maximum mass gains measured are comparable to, or lower than, those reported for other Tetra Pak-based composite panels and concrete-like materials [6–9]. For example, Bekhta et al. and Martínez-Barrera et al. observed water absorption levels of a few percent in Tetra Pak/polyethylene composites and Tetra Pak-reinforced concrete, respectively, with values strongly influenced by porosity and panel thickness [6–8]. However, direct one-to-one comparison with studies reporting % mass gain should be treated with caution because the present work reports water uptake as area-normalised mass gain (g/m^2) with unsealed edges, whereas % mass gain is inherently sensitive to specimen geometry (surface-to-volume ratio) and edge sealing assumptions. Accordingly, Table 9 reports literature water-uptake metrics “as reported” (typically %) alongside the present g/m^2 results, to retain quantitative benchmarking while remaining transparent about the measurement basis [30]. The relatively moderate water uptake of the PA–RH boards suggests that high PolyAl content provides an effective barrier against moisture ingress, improving performance with respect to PP–RH composites without metallic layers, which typically show higher absorption after prolonged immersion [10,11].

Regarding UV ageing, the exposure performed in this study corresponds to short-term UVC irradiation at 254 nm (up to 100 h), which is not representative of natural sunlight and only covers a narrow part of the spectrum relevant for outdoor weathering. All formulations exhibited a progressive increase in surface hardness with exposure time. The effect was more pronounced for PA-rich compositions, which may be associated with surface-level photo-oxidation and physical ageing of the polyolefin-rich phase during the test window, leading to hardening without abrupt visible surface damage. Because no quantitative colour assessment and no post-irradiation flexural re-testing were performed, the present results should be interpreted strictly as a preliminary screening indicator of surface response under UVC rather than as evidence of retained bulk mechanical performance or outdoor durability. Broader-spectrum ageing protocols and combined UV–moisture cycles are required before making claims related to long-term outdoor performance in urban furniture service conditions [28].

4.4. Microstructure–Property Relationships

Optical microscopy qualitatively confirmed the heterogeneous microstructure that is typical of Tetra Pak-derived composites [6–9]. Bright PolyAl-rich domains containing

aluminium foil fragments were observed within a darker polymer–filler matrix. These domains appeared as irregular clusters with a broad size distribution and a clearly non-uniform spatial arrangement, with regions of higher and lower particle density. Such heterogeneity has also been reported in polymer concretes and panels produced from ground Tetra Pak fractions, where the fragmentation process generates flakes that are difficult to disperse uniformly [6,8,9].

Although the absence of specific etching prevents a clear distinction of individual rice husk particles, the qualitative observations support the mechanical results. Local clustering of rigid PolyAl particles and associated voids can act as stress concentrators, promoting micro-crack initiation under tensile and flexural loading and partly explaining why the strength of the boards remains moderate despite their relatively high stiffness. On the other hand, the presence of rigid PolyAl domains near the surface likely contributes to the measured hardness and may contribute to abrasion resistance potential, which is advantageous in the context of pedestrian traffic and board-like applications; however, dedicated abrasion testing would be required to substantiate this point.

In addition, the present microscopy is qualitative, and no quantitative microstructural metrics were obtained; future work should include such measurements to strengthen structure–property arguments beyond qualitative observations.

These findings suggest that further optimisation of grinding, compounding and extrusion conditions, together with potential surface treatments or compatibilizer adjustments for rice husk, could reduce clustering, improve interfacial adhesion and enhance both strength and durability without compromising the high recycled content.

4.5. Implications for Circular Economy and Future Work

From a circular economy perspective, the material system developed in this work simultaneously valorises two abundant residue streams: post-consumer beverage cartons and rice husk. This approach fits within the concepts of industrial symbiosis and resource efficiency described in the literature [13–15] and aligns with European policy frameworks on circular economy and sustainable production [16,17]. By transforming difficult-to-recycle PolyAl fractions and agricultural by-products into usable boards for benches, walkways and similar low-load components, the solution proposed here can help to reduce landfilling, substitute tropical timber and partially displace virgin fossil-based polymers [5,12].

The results obtained, especially for the 70PA–30RH formulation, indicate that PA–RH boards can potentially compete with conventional WPCs for certain low-load board applications while offering a higher level of waste valorisation [6–9,12]. Importantly, the present study should be regarded as a pilot-scale feasibility assessment based on boards manufactured using an industrially scalable route with short-term mechanical and physical characterisation intended to screen a practical formulation window.

Two key methodological limitations must be explicitly acknowledged when discussing potential outdoor/urban furniture relevance. First, flexural testing was performed under span/thickness constraints dictated by available board geometry and equipment limits (Section 2.4); therefore, flexural results are best interpreted comparatively across formulations rather than as fully standard-compliant design values [31]. Second, the ageing protocol used here is short-term UVC irradiation at 254 nm and is not representative of outdoor solar weathering; thus, it cannot be used to substantiate long-term outdoor durability claims [27,28]. In addition, the UV campaign was coupled to surface hardness monitoring and visual inspection only; no post-irradiation flexural re-testing or quantitative colour measurements were performed, and thickness swelling was not measured in the water-immersion campaign.

Nevertheless, several aspects require further research before large-scale deployment:

- Optimisation of processing parameters to minimise microstructural heterogeneity and improve strength;
- Quantitative microstructural characterisation to strengthen structure–property correlations;
- Long-term durability tests including cyclic wetting–drying, freeze–thaw cycles and combined UV–moisture weathering using representative protocols;
- Assessment of creep, fatigue and impact behaviour under service-like conditions;
- Life-cycle and techno-economic analyses comparing PA–RH boards with WPCs and impregnated timber products [12–17].

These future activities will allow for translating the present feasibility results into robust design data and performance envelopes suitable for outdoor service conditions.

Overall, the present study shows that PA–RH composites are promising candidates for valorising PolyAl and rice husk into industrially manufacturable boards for low-load applications, providing a concrete example of how industrial symbiosis can support the transition towards more circular and climate-responsible materials systems [12–17]. Claims related to standard compliance or long-term outdoor durability should be reserved for future work based on representative testing protocols and service-condition validation [28,31].

5. Conclusions

This work presents a pilot-scale feasibility study on recycled PolyAl–rice husk composite boards manufactured by an industrially scalable route and evaluated through short-term mechanical and physical testing. The main findings are as follows:

1. All formulations show densities and flexural properties comparable to commercial wood–plastic composites and Tetra Pak-based boards. These results support the potential suitability of PA–RH boards for low-load board applications, while noting that standard-compliant flexural configurations are required before using the values as design data [31].
2. The Voce law provides the most accurate description of the tensile and flexural stress–strain curves, offering a compact constitutive model for design and numerical simulations.
3. Increasing the rice husk fraction enhances stiffness and surface hardness but increases water uptake, whereas PolyAl-rich boards show lower hardness but improved moisture resistance; the 70PA–30RH formulation offers the best overall compromise.
4. Short-term UVC irradiation (254 nm, up to 100 h) led to a moderate increase in surface hardness without macroscopic surface cracking during visual inspection within the screening window. However, because UVC at 254 nm is not representative of outdoor solar UV and no post-irradiation flexural re-testing or quantitative colour measurements were performed, these observations should be interpreted as preliminary comparative screening indicators rather than evidence of outdoor durability [27,28].
5. By jointly valorising beverage carton PolyAl and rice husk residues, these boards illustrate a viable industrial symbiosis aligned with circular economy objectives. Future work should focus on representative weathering protocols (UVA/UVB, UV–moisture cycling), standard-compliant mechanical testing geometries, quantitative microstructural metrics, and long-term performance indicators (e.g., creep/fatigue/impact, thickness swelling) to enable outdoor service validation and industrial adoption [28–31].

Author Contributions: Conceptualisation, M.Á.P.P. and O.L.; methodology, A.L.L.; validation, M.Á.P.P., F.S., O.L. and A.L.L.; formal analysis, A.L.L.; investigation, A.L.L.; resources, data curation, A.L.L.; writing—original draft preparation, A.L.L.; writing—review and editing, A.L.L.; visualisation, M.Á.P.P., F.S. and O.L.; supervision, M.Á.P.P., F.S. and O.L.; project administration, M.Á.P.P., F.S. and O.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The APC was funded by the authors.

Data Availability Statement: The data supporting the findings of this study are contained within the article (tables and figures). Additional raw data are available from the corresponding author upon reasonable request. The data presented in this study are available on request from the corresponding author due to the collaborative agreement with the industrial partner that supplied the composite boards.

Acknowledgments: The authors would like to thank the laboratory technicians of the Materials and Mechanical Testing Laboratory at the Universitat Politècnica de València for their support. The authors also gratefully acknowledge the industrial partner that provided the PA–RH composite boards used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EU	European Union
ISO	International Organization for Standardization
MAPE	Maleic-anhydride-grafted polyethylene
PA	PolyAl fraction from recycled Tetra Pak beverage cartons
PA-RH	PolyAl-rice husk composite boards
PP	Polypropylene
RH	Rice husk
SDG	Sustainable Development Goal
UV	Ultraviolet
WPC	Wood–plastic composite

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