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Circular Economy-Based Manufacturing of Hybrid Polymer Composites Using Wheat Straw, Sugarcane Bagasse, and Rice Husk Reinforcements

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Abstract
The open field burning of cereal and cane residues results in the loss of usable lignocellulosic material in one pass and particulate and greenhouse gas emissions at a national level. This study examines a low-energy, ambient-cure manufacturing process that captures three such residues – wheat straw, rice husk and sugarcane bagasse – in layered epoxy-matrix polymer composite panels, and explicitly evaluates the process and its product as an intervention in the circular economy, not just as a materials-science outcome. These were panels of 101.6 × 101.6 × 25.4 mm that were manufactured using a three-fibre-ply, two-resin-interply construction and subject to the independent laboratory testing. The cradle-to-gate mass balance indicates that one meter square panel with 40 % fibre mass fraction contains 15.75–19.05 kg of material and saves 6.30–7.62 kg of waste from being open burned, which is equivalent to 12.0–14.5 kg of particulate matter and 34.0–41.2 kg of carbon monoxide per 100 m². A pristine Material Circularity Indicator is calculated as 0.28 for the current configuration but increases to 0.73 if a bio-based matrix, fibre recovery and one cascaded re-use cycle are added, marking the virgin thermoset matrix as the limiting factor for circularity. The wheat straw composite is the best under structural weighting, the bagasse composite is the best under thermal weighting, and the rice husk composite is the best under object entropy weighting and equal weighting and circularity-oriented weighting. This is the most solid single selection to the circular deployment, even though it never had the highest mechanical values, a mechanical analysis wouldn't have been able to arrive at this conclusion. The main barriers to closing the loop are found to be feedstock seasonality, matrix origin, and the lack of product standards.

Keywords—Circular economy; agro-residue valorisation; hybrid polymer composite; material circularity indicator; entropy-TOPSIS; material flow analysis; wheat straw; rice husk; sugarcane bagasse; sustainable manufacturing.

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1. Introduction

1.1 A linear pathway that destroys usable material

Cereal and cane residue is mostly burnt in open fields in numerous areas of South Asia. According to inventory studies sources of Indian crop-residue generation are 500–620 Mt annually which is a significant portion of which is burnt on-farm due to the time lag between harvest and sowing of next crop [1,2]. Rice straw, wheat straw and cane trash are the main components of the burnt mass [1] and the emissions of carbon monoxide, carbon dioxide and PM are of the order of several million tonnes annually, over a hundred million tonnes annually and more than a million tonnes annually, respectively [1]–[3].

The consequences are well known. The significant impact of non-local fire emissions on the post-monsoon fine-particulate loading in the Indo-Gangetic plain has been established [4, 5]; the impact on human health has been quantified through epidemiological modelling, based on fine-particulate exposure, and has been estimated to cause tens of thousands of premature deaths annually [6]; and ambient monitoring data confirms measurable degradation both during the pre-monsoon and post-monsoon fire seasons [7, 8]. Regulatory prohibition has proven to be not enough, as the farmer has a real time and cost constraint [9].

In a circular economy, the issue is not just emissions, it's value destruction. Burning is the irreversible transformation of a structured lignocellulosic material, which is the product of an entire growing season in which water, nutrients and energy have been added, into heat and pollutants in one pass. It is called the archetypal linear flow in the literature on the circular economy, where material value is lost and not saved [10], [11], and there is recent interest in agricultural by-products in arguing explicitly that valorisation routes should be prioritized based on their preservation of material value rather than because they do not get thrown in the trash.

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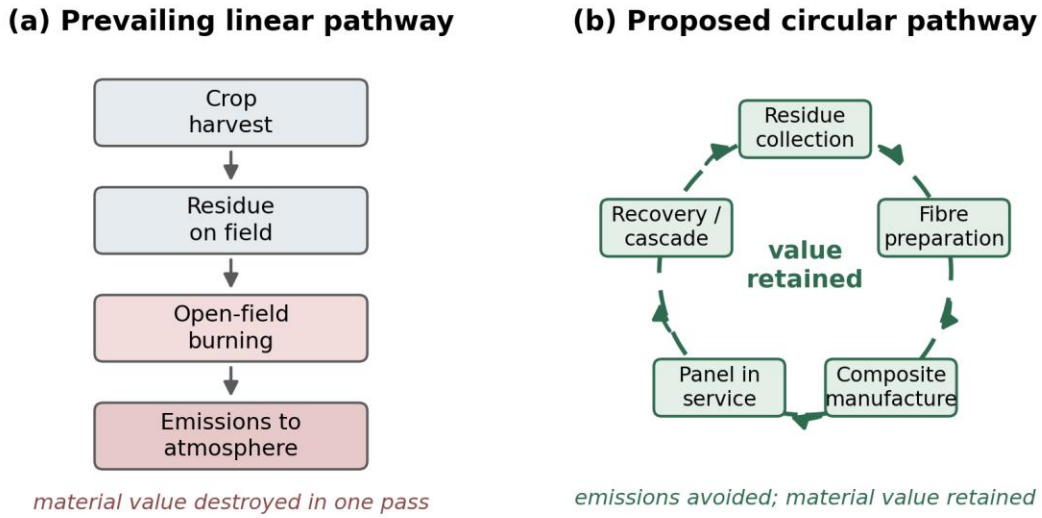


Fig. 1. Contrast between the prevailing linear residue pathway and the circular manufacturing pathway evaluated in this study.

1.2 Composite manufacture as a value-retention route

Residue to polymer composite is placed high in the value retention hierarchy since the fibre still serves as a structural function instead of just a nutrient or heat source [13, 14]. The agro-waste biocomposites are consistently reviewed as one of the circular-economy solutions that not only diverts waste but also replaces virgin material in the composites [15]–[17]. The bibliometric mapping of research on agricultural-waste recycling corroborates the fast development of this research field, where the two dominating application areas are construction and packaging [18, 19].

Circularity is not automatic, however. A composite made with a waste derived reinforcement and a virgin thermoset matrix is only semi-circular and the end-of-life process may be the same as the process for the material that has been replaced. [20] [21] There needs to be a metric that can be used to measure this partial circularity. The Material Circularity Indicator (MCI) is widely used and ranks the extent to which a product is used, recovered at end of life and/or the extent to which it can be restorative feedstock [22, 23] and has been adapted to construction products [24] and to biological cycles [23].

1.3 Research gap and contribution

The available literature on agro-residue composites is dominated by characterisation and fibre comparison studies in terms of strength, stiffness and moisture uptake, with the circularity of the composites being claimed in the discussion only. There are three particular gaps that follow. First, the amount of material actually diverted from landfill per tonne of product used is rarely

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measured, meaning that the waste-management advantage is only an empty promise. Second, indicators of circularity are rarely calculated for these materials, which makes it unclear what share of the materials comes from the feedstock and what from the end-of-life route. Third, the mechanical ranking is nearly always the sole determining factor for getting materials, even though there are criteria — material intensity, durability, recoverability — that may outweigh mechanical ranking for circular deployment.

In this study, these gaps are filled by analyzing one experimental dataset obtained under matched manufacturing conditions. Its contributions are:

- Cradle to gate mass balance, which measures the amount of residue diverted and virgin matrix consumed per square metre of area of panel deployed and for a variety of fibre mass fractions.
- Simplified Material Circularity Indicator (MCI) based on manufacturing route, while considering the importance of feedstock share and four end-of-life (EoL) configurations, and isolating the most important lever.
- An estimate of avoided emissions, based on the area of deployment, expressed in terms of emissions that would have happened if the same amount of residue mass had been burned.
- An entropy-weighted TOPSIS evaluation under five ranking stances to see if the mechanical ranking is maintained with the inclusion of circularity criteria.
- A formal barrier analysis that operationally determines the barriers that need to be addressed for the loop to close in practice.

Nomenclature note. Hybrid polymer composite here denotes the hybrid organic architecture of the material — a lignocellulosic reinforcement phase combined with a synthetic thermosetting matrix in a discretely layered fibre/resin stack. Each of the three laminates characterised experimentally (RC, WC, SC) contains a single residue species. Inter-fibre hybridisation is outside the experimental scope of this paper.

2. Circular Economy Framing

2.1 Position on the R-strategy hierarchy

The traditional progression of circular economy strategies is from R0 (refuse) to R9 (recover), with value retained in the materials getting lower further down the chain [10], [11]. It's a good exercise to put that route on that ladder to see what's been done and what's not.

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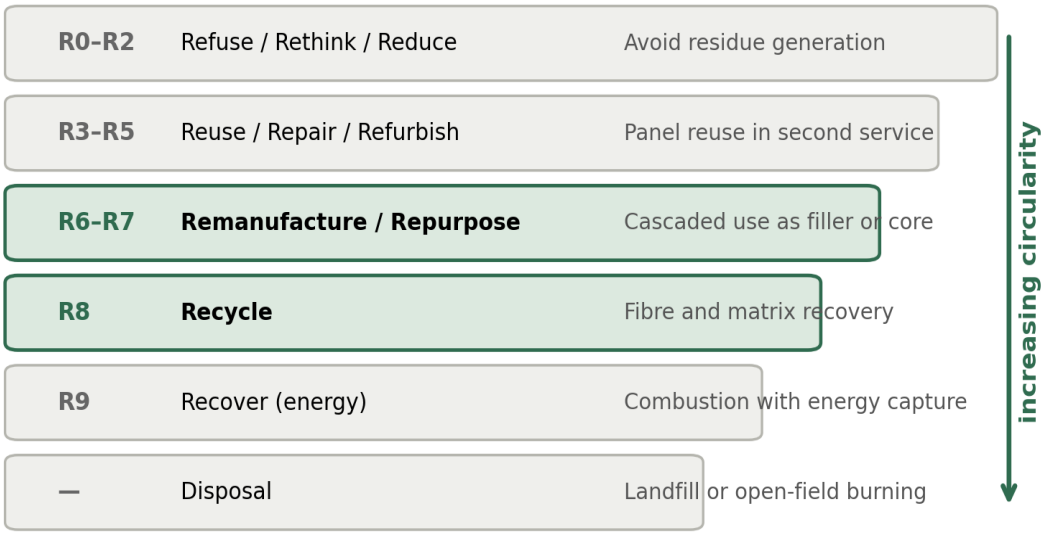


Fig. 2. R-strategy hierarchy with the position of the present manufacturing route indicated.

The change of the fate of the residue to a load carrying panel is a change of function operation (R7): a material that is supposed to be burned is diverted to a new function higher than its alternative function. Not much is being done downstream. This cured thermoset is not recyclable, as of yet, so the path is only half a loop, with recycling being done on the upstream end only [20]. This is a typical problem in first generation bio-composites and the key constraint quantified in the analysis in Section 5.

2.2 Residue-specific valorisation context

The three residues are not equivalent feedstocks, and the published valorisation routes vary in ways that are relevant to the design and development of a circular economy. Rice husk contains a significant fraction of amorphous silica in a cellulose matrix, providing some degree of hydrophobicity and desirable fire properties, and has been shown to work in many polymer matrices [25, 26]. Wheat straw culm is a high aspect ratio culm with good packing performance, which is used in both thermoset and thermoplastic systems and the low density straw-polypropylene composite has been reported specifically in a circular agro-economy framework [27]–[28]. Sugarcane bagasse has open parenchyma which reduces the strength but provides thermal conductivities in the insulation class [29],[30] and has been processed into low density foamed concrete [32] and polymer composites [33].

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Each residue already has a well-developed valorisation literature and what has not been established is a comparison of their circular performance under one manufacturing route, which is provided in this study.

2.2 System boundary and functional unit

This approach has been used throughout working to a functional unit of 1 square metre of final panel at 25.4mm thickness, thereby making it easy to compare with the standard product of partitioning and boarding, which is sold by area. The system boundary includes the residue collection, fibre preparation, resin input, lay-up, ambient cure and finishing.

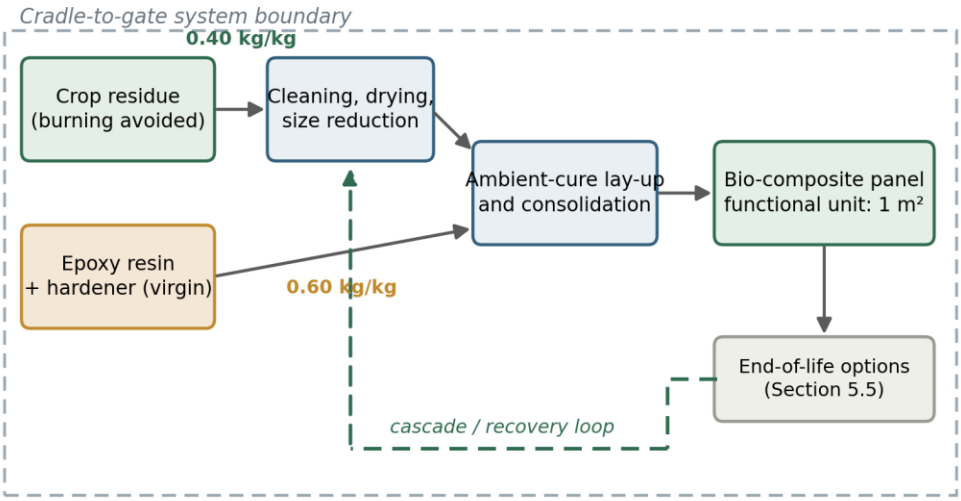


Fig. 3. Cradle-to-gate system boundary and material flows, with the cascade loop that the route does not yet close.

There are two decisions at the boundaries that should be made. First, the residue is fed into the system without any additional burden; it is an agricultural by-product that only bears the responsibility of the food crop as in the waste feedstocks of the bio-composite life-cycle literature [13] and [34]. Second, avoided burning is not included in the product footprint, but is reported separately as an avoided-burden credit (Section 4.3), to make the two claims distinguishable.

2.3 Value cascade positioning

The amount the embodied value remains depends on where the residue ends up in the cascade. Fig. 4 sorts the destinations available by the value retention in descending order.

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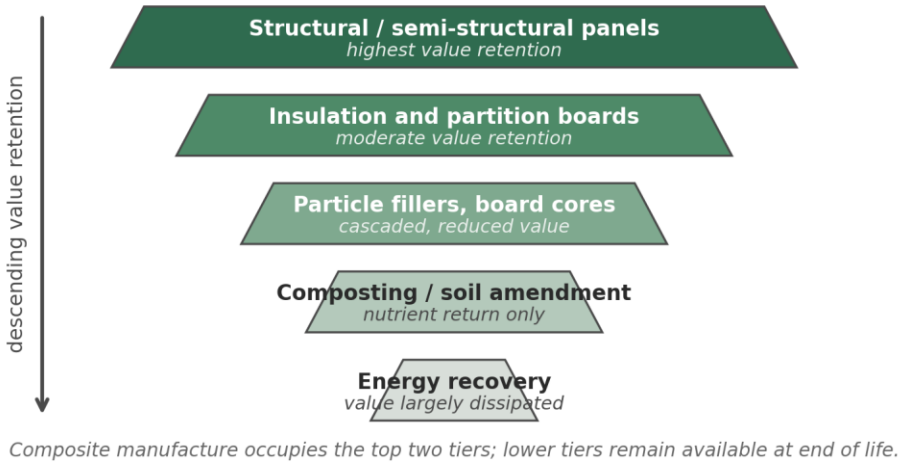


Fig. 4. Value cascade for lignocellulosic agro-residue, with composite manufacture occupying the upper tiers.

The highest two positions are in composite manufacture. Importantly, this selection does not preclude the opportunity to reduce the service life panel to filler, to compost or to burn and capture energy [12] [17]. Cascading residue up should thus provide optionality, a circular design goal.

3. Materials and Manufacturing Route

3.1 Feedstock and matrix

Wheat straw (Triticum aestivum), rice husk (Oryza sativa) and sugarcane bagasse (Saccharum officinarum) were sourced from farms and a cane-crushing unit within the study region. Short transport distance matters here for more than convenience: haulage is repeatedly identified as a decisive and sometimes dominant contributor to bio-composite life-cycle burden, capable of eroding the environmental advantage entirely if the collection radius grows [34], [35]. Decentralised, locally-sourced processing is also the configuration favoured by residue-management policy [3], [9].

The matrix was a commercial diglycidyl ether of bisphenol-A (DGEBA) epoxy cured with a room-temperature aliphatic amine hardener at 10:1 by mass. Epoxy was selected for low cure shrinkage, good wetting of lignocellulosic surfaces and ambient-cure capability [36], [37]. Its petrochemical origin is the principal circularity penalty of the route and is quantified in Section 5.2.

3.2 Fibre preparation and manufacturing sequence

All three residues went through the same preparation process – manual cleaning to remove soil and grain fragments, shade drying until constant mass, rejection of any grain that still contained

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visible moisture, and cutting to mould length but not subjected to oven or direct solar exposure. No surface treatment was applied with chemicals. This was on purpose: alkali and silane treatments increase mechanical performance significantly [38]–[40] but add a chemical effluent stream, water consumption and an extra energy stage which detract from the circularity of the route. The untreated baseline will be set first so any future treatment can be compared against the untreated area rather than the treated area.

A released wooden mould was used for the production of 101.6 × 101.6 × 25.4 mm panels (three fibre-ply, two-resin-interply – F1/R1/F2/R2/F3). Wheat straw is a straight hollow culm which was arranged orthogonal 20 × 20; rice husk and bagasse were arranged in random orientation mats. Needle pricking and a controlled pass with warm air were used to remove entrapped air. Cure was at ambient laboratory temperature (27 ± 3 °C) for 24–48 h with no external heat.

> The elimination of a heated cure stage is the single largest controllable process-energy saving available in thermoset composite manufacture, and it is a design decision made for circularity reasons rather than convenience. Its quantitative consequence is examined in Section 4.4.

3.3 Characterisation

Sample tests conducted by an independent, government accredited commercial laboratory. Observed values refer to individual raw readings, whereas experimental values are processed values over the replicate set. Deviation is:

$$\text{Deviation } (\%) = \left[\frac{(\text{Vexp} - \text{Vobs})}{\text{Vobs}}\right] \times 100 \quad (1).$$

Table 1. Characterisation programme and governing standards.

Domain	Test	Standard / method	Reported parameter
Physical	Bulk density	Mass–volume method (ASTM D792 basis)	ρ (g cm^{-3})
Physical	Water absorption	ASTM D570 immersion	WA (%)
Mechanical	Compressive strength	ASTM D695 geometry, 1 mm min^{-1}	σ_c (MPa)
Mechanical	Tensile strength	ASTM D638	σ_t (MPa)
Mechanical	Flexural strength	ASTM D790, three-point, 80 mm span	σ_f (MPa)
Mechanical	Izod impact strength	ASTM D256, notched	a_i (kJ m^{-2})

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Thermal	Comparative heat transfer	Hot-plate relative method, 10 min	ΔT (°C)
Thermal	Heat resistance	Solar exposure, 4 h/day × 3 days	T_{max} (°C)

4. Circular Performance Analysis

4.1 Measured property set

Experimental values for each analysis are summarized in a table (Table 2) and used for further analyses. Mechanical ranking: WC > RC > SC, regardless of the moisture ranking; RC > WC > SC, moisture ranking; SC > RC > WC, thermal-insulation ranking. No material dominates.

Table 2. Consolidated experimental property set (processed means).

Property	Unit	RC (rice husk)	WC (wheat straw)	SC (bagasse)	Best
Bulk density	g cm^{-3}	0.67	0.75	0.62	SC
Water absorption	%	1.10	1.53	2.10	RC
Compressive strength	MPa	4.80	6.20	4.10	WC
Tensile strength	MPa	3.80	5.00	3.10	WC
Flexural strength	MPa	5.70	7.60	4.80	WC
Izod impact strength	kJ m^{-2}	12.60	16.20	11.00	WC
Heat transfer ΔT (10 min)	°C	18	25	12	SC
Heat resistance limit	°C	55	60	50	WC

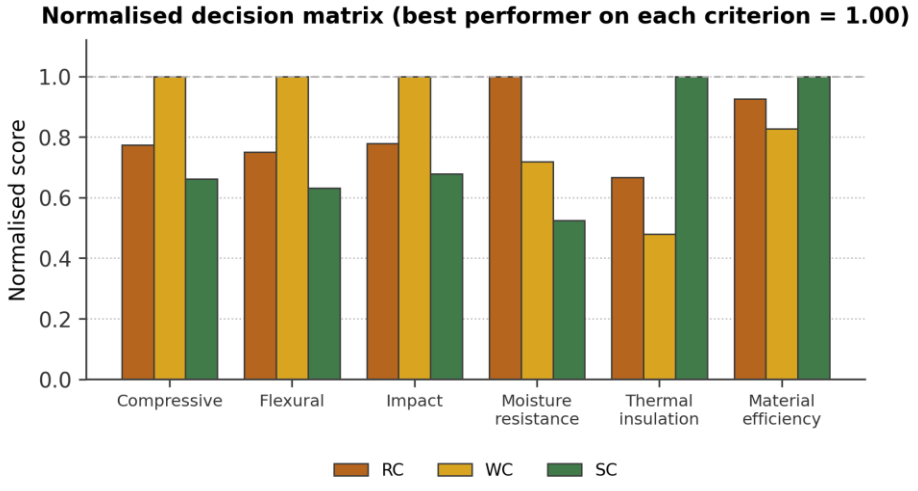


Fig. 5. Normalised decision matrix. Moisture resistance, thermal insulation and material efficiency are inverted so that a higher bar is always better.

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4.2 Mass balance and waste-absorption capacity

The absorption capacity of the waste increases by 10%, and the mass balance is restored.

The question isn't how powerful the panel is, it's how much residue a unit of deployed product can absorb. Each block of 101.6 × 101.6 × 25.4 mm occupies 262.2 cm^3, giving block masses of 175.7 g (RC), 196.6 g (WC) and 162.6 g (SC). The number of approximately 97 blocks per square metre means that 25.4 mm panel represents 17.02, 19.05 and 15.75 kg/m^2 of blocks respectively.

Table 3. Cradle-to-gate mass balance per square metre of 25.4 mm panel.

Quantity	Unit	RC	WC	SC
Bulk density	g cm^{-3}	0.67	0.75	0.62
Block mass (101.6 × 101.6 × 25.4 mm)	g	175.7	196.6	162.6
Blocks per m^2	–	96.9	96.9	96.9
Panel mass	kg m^{-2}	17.02	19.05	15.75
Residue diverted, W_f = 30 %	kg m^{-2}	5.11	5.71	4.72
Residue diverted, W_f = 40 %	kg m^{-2}	6.81	7.62	6.30
Residue diverted, W_f = 50 %	kg m^{-2}	8.51	9.53	7.87
Virgin matrix consumed, W_f = 40 %	kg m^{-2}	10.21	11.43	9.45

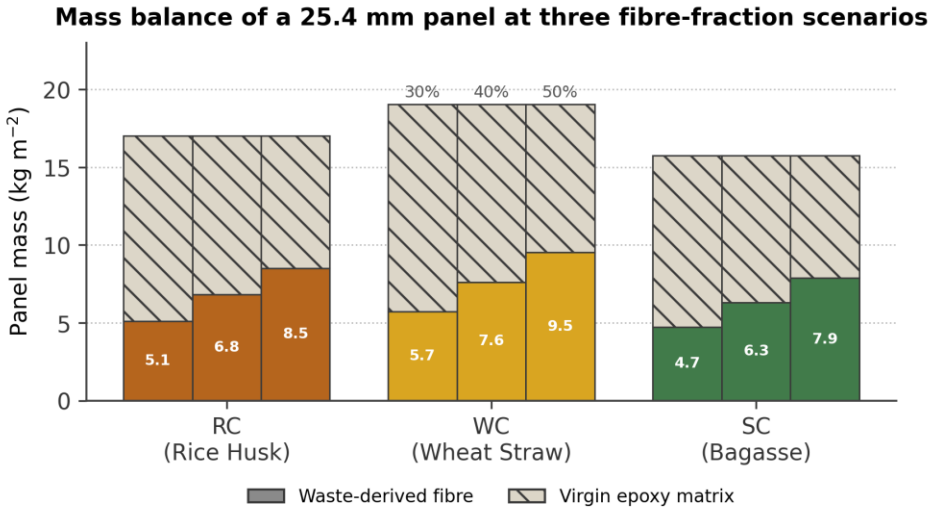


Fig. 6. Mass balance of a 25.4 mm panel at three fibre-fraction scenarios, separating waste-derived fibre from virgin matrix.

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Two observations follow. The wheat straw panel is the densest laminate and therefore absorbs the most residue per square metre (7.62 kg, compared to 6.30 kg for bagasse, which is 21 % more). The higher the density, the less efficient the material, but the more efficient it is in absorbing waste; hence, in terms of circular economy, there are conflicting forces. The second is more significant: In all the fibre fractions analyzed, virgin epoxy is the dominant by mass. The 40 % fibre content represents 60 % virgin petrochemical thermoset panel, a hard ceiling on the circularity that can be achieved without changing the matrix.

Wf is not independently controlled in this near-native-geometry lay-up, so it is used throughout as a scenario variable (30–50%), but not as a measured value. This is clearly set out as a restriction in Section 6.

4.3 Indicative avoided emissions

When coupled to published emission factors for open-field residue combustion, deployed area is a avoided emission. Factors have been generated from national inventory studies [1] and [2] and [5] and are indicative and not site specific.

Table 4. Indicative emissions avoided per 100 m² of deployed panel (W~f~ = 40 %).

Species	Emission factor (kg per t residue)	RC (kg)	WC (kg)	SC (kg)
Particulate matter	19.0	12.93	14.48	11.97
Carbon monoxide	54.0	36.76	41.15	34.02
Methane	9.5	6.47	7.24	5.98
NMVOC	10.3	7.01	7.85	6.49
Nitrogen oxides	1.6	1.09	1.22	1.01

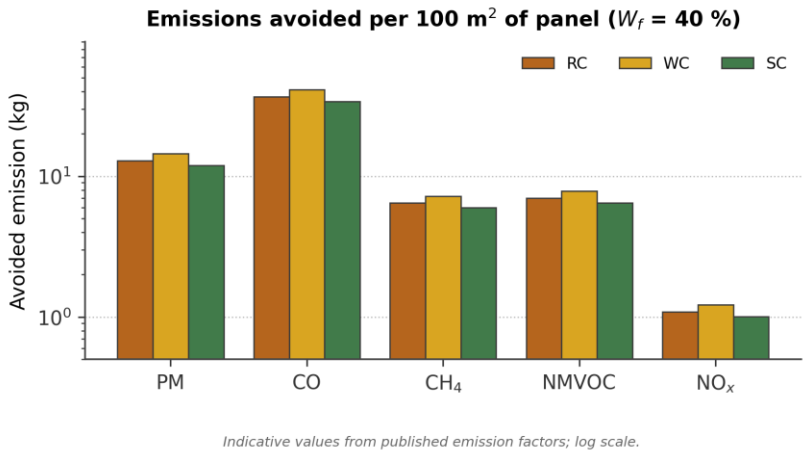


Fig. 7. Emissions avoided per 100 m² of deployed panel, logarithmic scale.

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An only slightly larger deployment of 100 m², the approximate partition area of a small building, helps to avoid particulate matter on the order of 12–14 kg and carbon monoxide on the order of 34–41 kg. Carbon dioxide is not included in Table 4 as it does not represent combustion of biomass as it produces mainly biogenic CO_2, a claim on avoided-CO_2 would need careful treatment of biogenic accounting and timing of sequestration, and this data set would not be suitable for that purpose. The species listed are those where avoidance of the species is clear evidence of a net benefit [2], [8].

4.4 Manufacturing energy intensity

Ambient cure eliminates the heated-cure step. The route is compared with the other conventional alternatives in Fig. 8 by indicating the literature values.

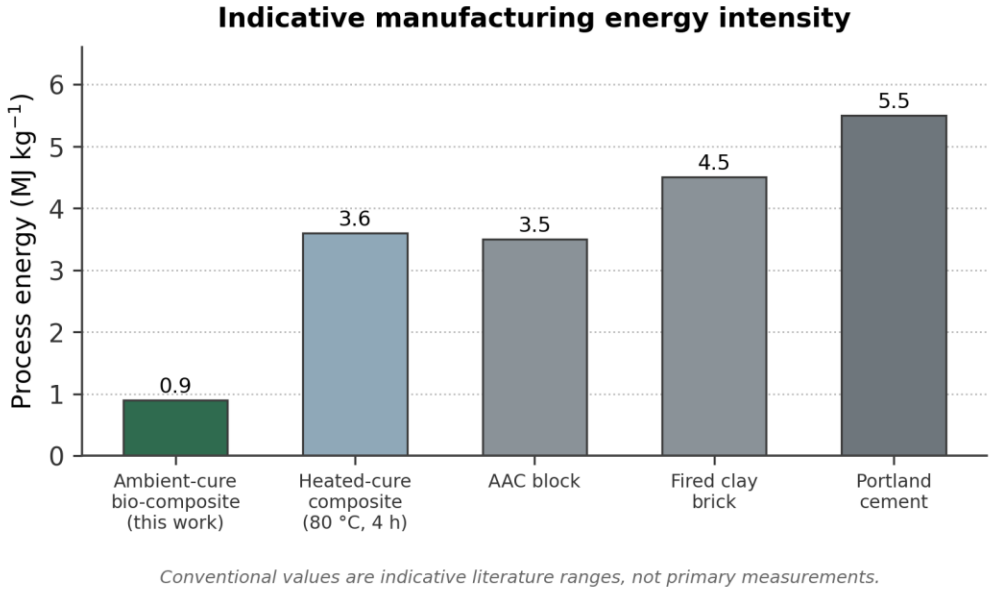


Fig. 8. Indicative manufacturing energy intensity of the ambient-cure route against conventional alternatives.

It is important to note that the comparison is not an actual measurement, but rather an order-of-magnitude estimate. Based on this, the ambient-cure route is approximately a factor of 4 less energy intensive than a heated-cure composite, and less than fired-clay or fired-cement energy profiles, whose high-temperature firing or calcination steps dominate their energy profiles [35], [41]. These are literature values and not primary data for this facility as such they support a direction only claim, a measured cradle-to-gate inventory is outstanding.

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5. Circularity Assessment and Material Selection

5.1 Simplified Material Circularity Indicator

The MCI quantifies the level of the linear flow minimized and the level of the restoring flow maximized [22, 23]. A reduced single-cycle form was used with the Linear Flow Index being defined as:

$$\mathrm{LFI} = \frac{(V + W)}{(2M)}; \quad \mathrm{MCI} = \max\left(0, 1 - \mathrm{LFI} \bullet \frac{0.9}{X}\right) \qquad \textbf{(2)}$$

where V is virgin feedstock mass, W is unrecoverable waste at end of life, M is product mass and X is a utility factor, representing the service life or intensity of use of the product compared to the industry average. Four configurations were tested within the range of fibre fractions that were plausible.

Table 5. Simplified Material Circularity Indicator across configurations.

Configuration	Fibre EoL recovery	Matrix EoL recovery	W_f = 30 %	W_f = 40 %	W_f = 50 %
S1 Present route, landfill EoL	0 %	0 %	0.235	0.280	0.325
S2 + fibre composting / energy recovery	85 %	0 %	0.350	0.433	0.516
S3 + bio-based matrix, matrix recovery	85 %	60 %	0.539	0.595	0.651
S4 + one cascaded reuse cycle (X = 1.5)	85 %	60 %	0.693	0.730	0.768

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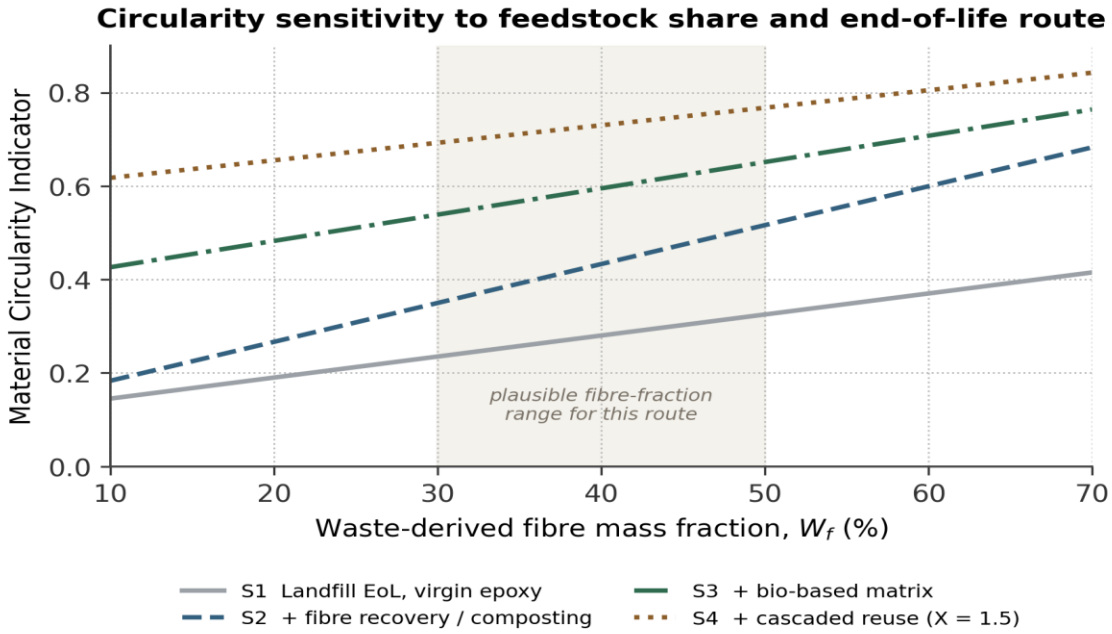


Fig. 9. Circularity sensitivity to waste-derived feedstock share and end-of-life configuration.

The outcome is clear: The leverage is in the hands of the recipients. A significant manufacturing change of increasing the fibre fraction from 30 % to 50 % brings an improvement in MCI from 0.235 to 0.325 which corresponds to +0.09. Compared with S1, it increases by 0.32 (which is over three times) when moving to S3 (where it is 40 % fibre fraction). A single cascaded reuse cycle brings it to 0.730.A single cascaded re-use cycle brings it up another level to 0.730.

Rather, the constraint is not the reinforcement. The matrix and the end-of-life pathway are. It contrasts with the majority of research on agro-composites that focuses almost exclusively on optimizing the fiber phase [15], [16] and is consistent with the building-products survey of circularity at the end of life, where the vast majority of building products have low scores for end-of-life options. [24].

5.2 The thermoset constraint

A cured epoxy network is not amenable to melting or reprocessing, so S1 has poor scores. There are three ways out of this limitation seen in the literature. Solvolysis is a chemical recycling method that can break down epoxy-amine networks under increasingly mild conditions and release reinforcement and generate reusable oligomers [21], [42]. Thermal routes, like pyrolysis, are not sensitive to contamination and involve a high energy burden as well as degradation of reinforcement [43, 44]. Designing recyclability in from the very beginning — through cleavable

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linkages, vitrimer chemistries or bio-based matrices — is the solution to the problem rather than the cause of the problem [20] [45].

The economics of solvolysis is unlikely to be feasible on a low cost building panel due to a relatively low value of the recovered fibre. The more positive route is matrix substitution with bio-based matrixes, for which the use of formaldehyde-free systems is already proven for bagasse panels in particular, [46], [47]. This is the one most valuable modification possible to the route and Section 5.5 estimates the benefit it would give.

5.3 Entropy-weighted TOPSIS material selection

Will the material ranking change when circularity criteria are added along with mechanical criteria? The seven criteria were evaluated by a TOPSIS assessment, which included water absorption, water transfer and bulk density (as cost criteria), and compressive strength, flexural strength, impact strength and heat resistance (as benefit criteria). The treatment of density as a cost is a circular objective, treating lower material intensity per unit function.

The objective weights were determined using the entropy method which weights each criterion in proportion to its information content [48], [49] and thereby avoiding the subjective weighting method that involves the analysts' bias [50], [51]. The closeness coefficients were calculated in a traditional manner [52], [53]:

$$\mathrm{Ci} = \frac{\mathrm{di}^{-}}{(\mathrm{di}^{\wedge}+ + \mathrm{di}^{\wedge}-)} \quad \textbf{(3)}$$

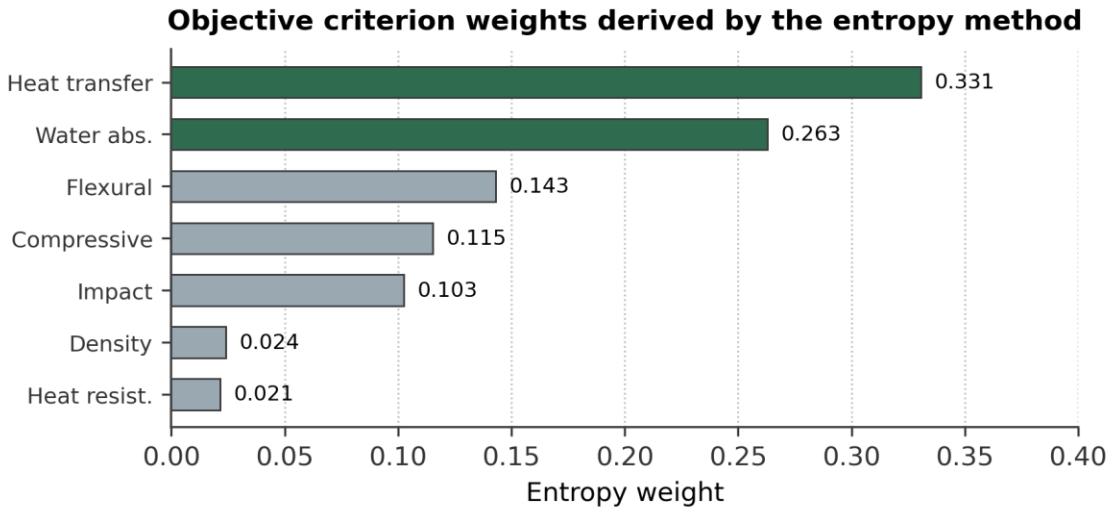


Fig. 10. Objective criterion weights derived by the entropy method.

The entropy weights contain information in their own right. The weight is almost entirely divided among the factors of heat transfer (0.331) and water absorption (0.263), with the three laminates being very different on these factors; density (0.024) and heat resistance (0.021) are

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the least significant, and the three materials are essentially equal on them. Objective weighting thus focuses on moisture and thermal behavior — exactly what a mechanically-framed study will consider secondary.

Table 6. TOPSIS closeness coefficients and ranks across five weighting scenarios.

Weighting scenario	RC C_i	RC rank	WC C_i	WC rank	SC C_i	SC rank
Entropy (objective)	0.6287	1	0.3531	3	0.5493	2
Equal weights	0.5627	1	0.5224	2	0.4223	3
Structural priority	0.4399	2	0.7483	1	0.2184	3
Thermal priority	0.5756	2	0.2491	3	0.6863	1
Circularity priority	0.6832	1	0.5331	2	0.3395	3

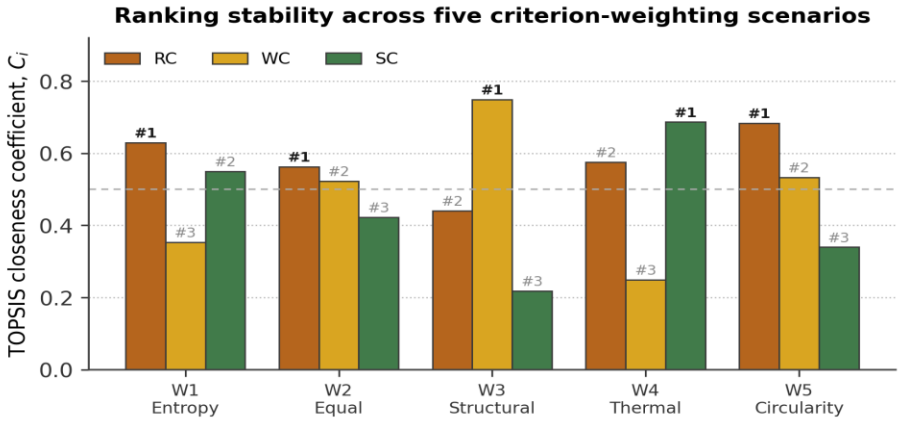


Fig. 11. TOPSIS closeness coefficients across five criterion-weighting scenarios.

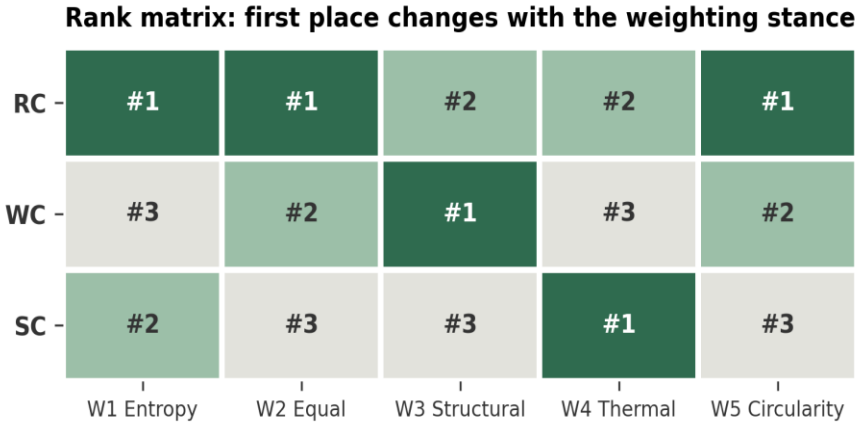


Fig. 12. Rank matrix showing that first place changes with the weighting stance.

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This results in rank reversal, which stands out as the main analytical result of this paper. The wheat straw composite is the clear mechanical winner, and only outranked by structural weighting (Ci = 0.7483) and only ranked last by entropy weighting (0.3531) and thermal weighting (0.2491). The bagasse composite leads only in case of thermal weighting (0.6863). Under objective entropy weighting (0.6287), under equal weighting (0.5627) and under weighting oriented towards the circularity (0.6832), the rice husk composite never takes the first rank, but always the second or higher, on any individual property.

RC is a system of embracing the robust, rather than the best! Its water absorbing properties are the lowest, its mechanical properties are intermediate and its thermal behaviour is intermediate, so it is never badly wrong for any reasonable application, while WC and SC are both very specialised. In the case of a circular system where the material might be reused in a second service context, which may be unforeseen, and where durability is a key consideration of the entire life cycle of the material, that robustness becomes more significant than a peak value of any single criterion [12] or [22]. The mechanically-framed evaluation would have ruled this out.

Two caveats apply. The results from TOPSIS are also sensitive to the alternatives added or removed and to the normalisation method used [51], [52]. Alternatively, the entropy weights are also calculated for small samples, with only three alternatives, and should be interpreted as suggestive. The importance of the analysis is the actual evidence of weighting-dependency of the ranking, not the actual values of the coefficients.

5.4 Waste absorption versus structural performance

Fig. 13 plots the two circular objectives that the mass balance showed to be in tension.

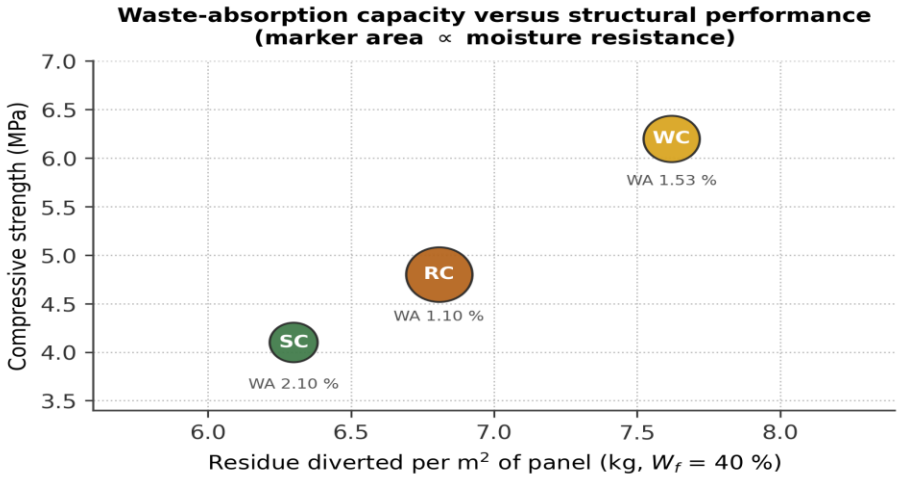


Fig. 13. Residue diverted per square metre against compressive strength, with marker area proportional to moisture resistance.

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WC is in the top right with the highest and strongest waste absorbing — which is the second lowest moisture resistance, as seen in the intermediate marker. SC is located in the bottom left corner of both axes, the lowest moisture resistance. RC is intermediate value along both axes, having distinctly the best moisture behaviour. Lignocellulosic composites are mainly degraded by moisture ingress when in service [33], [39] and thus service life determines X, the utility factor of RC's, which is a moisture advantage that no other two can compete with..

5.5 End-of-life scenarios

Fig. 14 compares the value retained under five end-of-life routes.

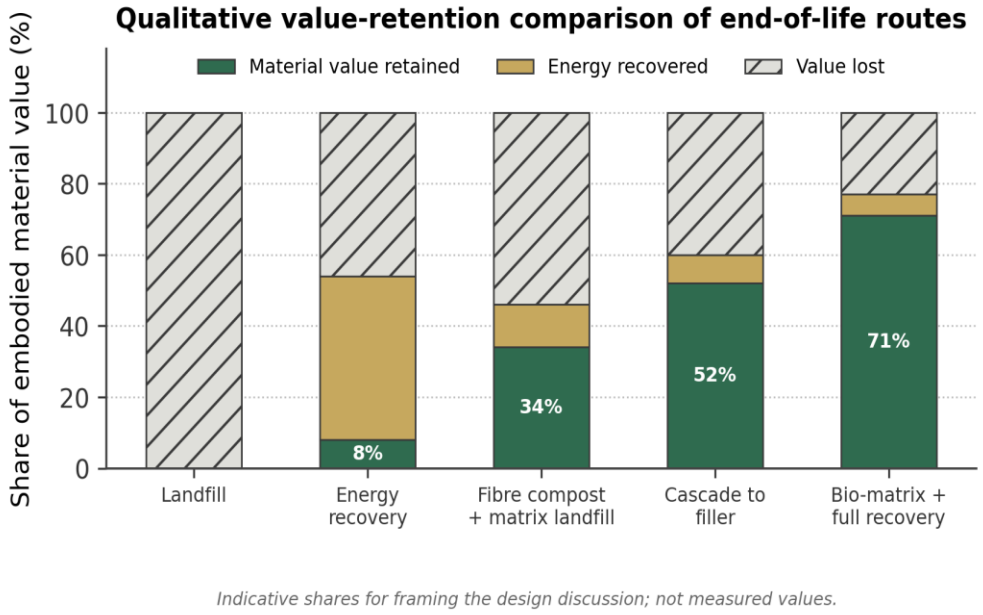


Fig. 14. Qualitative value-retention comparison across end-of-life routes.

Landfill retains nothing. Energy recovery will recover some of the embodied energy but lose the material structure [43]. When the matrix is landfilled, the nutrients are returned only from the fibre when composted. The comminuted panel can be cascaded as filler or board core and keep some useful functionality [12] [17]. A bio-based matrix that can be fully recovered has the highest recovery and it's the only configuration in which most of the phase is also circular. The shares in Fig. 14 are reference shares used for discussion of the design and not measured.

5.6 Barriers to closing the loop

Technical feasibility is a condition that must be met but is not sufficient. Fig. 15 evaluates six barriers on four dimensions.

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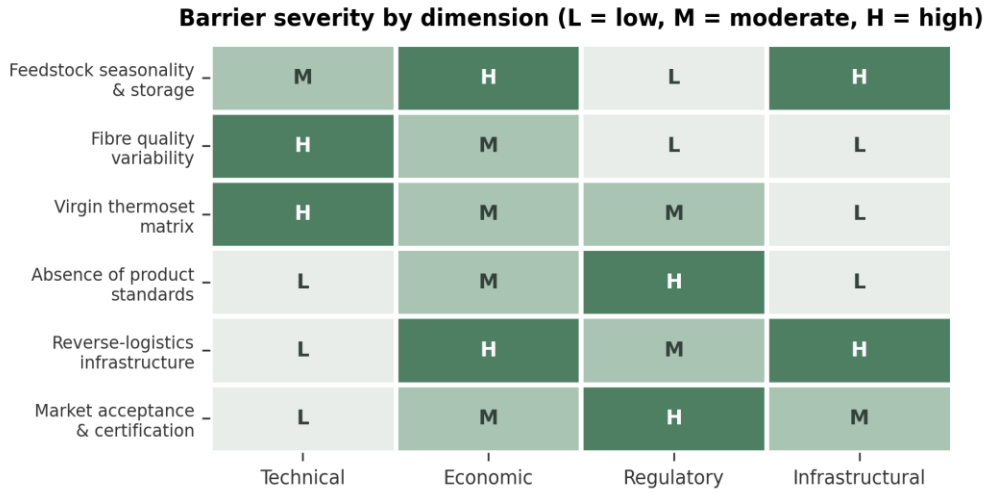


Fig. 15. Barrier severity across technical, economic, regulatory and infrastructural dimensions.

Feedstock seasonality is the least recognized. Residues are available in two periods of the year, while manufacture of panels must be continuous to justify the capital investment, so storage for several months of feedstock will be needed — storage where moisture ingress and microbial degradation must be prevented, as it was shown in Section 3.2 that moisture free feedstock is a prerequisite for sound panels. The arguments for surface treatment, and for close incoming specification [54] [55] are primarily technical and relate to the quality variability of fibres. The virgin thermoset matrix is technical and economic and the remedy to this has already been identified in Section 5.2. The lack of product standards is in the form of a regulation, and it can be argued that it is the "restrictive" one: a panel that has no known classification cannot be called out by an architect, irrespective of its measured properties [11] [24]. Reverse logistics infrastructure is infrastructural and economic and the barrier that stands most directly in the way of closing the cascade loop of Fig. 3.

5.7 Application mapping under a circular lens

Table 7. Application mapping incorporating circular criteria.

Application	Governing criteria	Recommended	Circular rationale
Non-load-bearing partitions	Compressive, flexural strength	WC	Highest σ_c and σ_f; also absorbs most residue per m^2
Humid or semi-exposed interiors	Water absorption, service life	RC	Lowest uptake (1.10 %) extends life and utility factor X

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Thermal insulation boards	Heat transfer, material intensity	SC	Lowest ΔT and lowest density; least virgin matrix per m²
General-purpose boards, mixed duty	Robustness across criteria	RC	Ranks first under entropy, equal and circularity weights
Products intended for reuse	Durability, damage tolerance	RC	Moisture resistance governs survival of a second cycle
Sun-exposed facings	Heat resistance	WC + coating	Highest thermal limit; SC softens at 50 °C

6. Limitations

The following bound every conclusion above.

- There was no independent measurement of fibre mass fraction. The residues were not compounded in a controlled loading, and Wf is therefore considered a 30 - 50 % scenario variable. All mass-balance, avoided-emission and MCI results are directly proportional to this assumption and are not absolute values, but outcomes of scenarios.
- The MCI applied is a streamlined, one-cycle application. These are comparative indicators, and not certified circularity scores; published critiques highlight the lack of multi-cycle retention values (also an oversimplified waste-allocation rule) [22].
- Avoided-emission figures are based on generic national emission factors and do not represent the emissions of the residues used. They are only approximate values. Biogenic carbon is not accounted for in this dataset and thus is not included in the list of carbon dioxide.
- The process-energy values given for the conventional materials are approximate ranges from the literature and are not a primary inventory. There was no cradle to gate life cycle assessment with measured inputs.
- The end of life value-retention shares in Fig. 14 are qualitative frames for design discussion and not based on experiment.
- The definition of the entropy weights is based solely on three alternatives and TOPSIS is sensitive to the normalisation process and to the alternative set [51, 52]. The weighting dependence of the ranking is much more robust than the individual coefficients are.
- The fibres were left untreated and the cure unpressurised, so the mechanical values are a lower bound, rather than what can be achieved with these fibre–matrix combinations [38],[40].

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- None of the durability, accelerated ageing or weathering testing was done, but the service life is exactly what is used to calculate the utility factor X that is used for the MCI. This is the most significant missing component from the current data set.

7. Conclusions

Three agro-residues were converted into layered epoxy-matrix panels by a low-energy ambient-cure route and assessed as a circular-economy intervention. The principal conclusions are:

- A 25.4 mm thick panel consists of 15.75–19.05 kg of material, and captures 6.30–7.62 kg of agricultural residue per 1 m2, compared to bagasse which captures 5.93–6.45 kg/1 m2 (density of 1.6 kg/m3 versus 1.2 kg/m3 for wheat straw laminate).
- An indicative particulate matter avoidance of 100 m2 corresponds to 12,0–14,5 kg particulate matter avoided per 1 kg of avoidable residue mass, 34,0–41,2 kg of carbon monoxide avoided per 1 kg of avoidable residue mass and 6,0–7,2 kg of methane avoided per 1 kg of avoidable residue mass.
- The current configuration is 0.280 simplified Material Circularity Indicator at 40 % fibre. The fibre fraction at 50 % is a gain of 0.045 with respect to the 40 % value, while using an end-of-life recovery with a bio-based matrix is a gain of 0.315 with respect to the use of a conventional matrix. It is the matrix and not the reinforcement which limits the extent of circularity.
- Illustrating a bio-based matrix, fibre recovery and one cascaded re-use cycle would increase the indicator to a forecast 0.730, which would make it a much more circular product than it is currently.
- In the entropy-weighted approach, the most important attributes are heat transfer (weight 0.331) and water absorption (weight 0.263), while density and heat resistance receive the lowest weights (0.024 and 0.021, respectively), focusing on other aspects which a mechanically framed study would consider secondary.
- TOPSIS exhibits rank reversal in all the weighting scenarios. Wheat straw is the main contributor when it comes to structural weighting while bagasse is the main contributor when it comes to thermal weighting, and rice husk is always in top two of the objective entropy, equal and circularity weighting. Rice husk will, therefore, be the most sturdy one for the circular deployment in spite of the lack of individual property maximum.
- Both waste-absorption capacity and material efficiency are subject to the density, and are in constant antagonism. Circular design thus has to opt for either a higher percentage of residues diverted per product or a lower amount of material used per function, and both are not always optimised.

- The major barriers are feedstock seasonality and the virgin thermoset matrix, as well as a lack of known product standards. The third of these is not technical, but regulatory, and could come into effect first in reality.

8. Future Scope

- **Bio-based matrix substitution.** Replace the DGEBA epoxy with a bio-epoxy or with the bio-binder which is not based on Formaldehyde, and re-calculate the MCI against the S3 projection. This is the most highly leveraged intervention identified and should be tried first [45]–[47].
- **Determined fibre volume fraction.** Find Wf by burn-off or density gradient, making the mass-balance/circularity results a measurement and not a scenario.
- **Durability & Service-life Testing.** Accelerated ageing, weathering and humidity cycling to obtain the utility factor X experimentally, it being the most sensitive parameter to MCI.
- **Cascade validation.** Break down end-of-service panels into filler, and re-manufacture, counting down the cascade and testing value-retention shares assumed in Fig. 14.
- **Primary cradle-to-gate LCA.** Compared the energy and material inventory with a sensitivity to direction of travel and electricity-mix, yielding a quantified result that can be defended. [34],[41]
- **Collection-radius optimisation.** Simulate the transport burden vs. plant size and determine the catchment radius at which the environmental benefit is compromised [35].
- **Seasonal storage study.** Characterise moisture ingress and microbial degradation in stored residue over a full inter-harvest interval, and its effect on panel properties.
- **Standards pathway.** Graph the measured property set against existing classification of non-load bearing partitions and non-load bearing insulation products to determine the shortest path to a specified property set [24].
- **Extended MCDM.** The result is repeated under new alternatives and rank stability of TOPSIS is tested by comparing with VIKOR and PROMETHEE [52],[53].
- **Fire performance.** Measure the limiting oxygen index and cone-calorimetry parameters especially for the silica-containing rice husk laminate [56].

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