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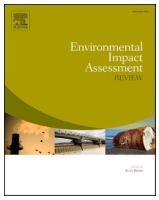

Process-level impact assessment of wood waste pre-treatments: Isolating environmental trade-offs through a gate-to-gate life cycle approach

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ABSTRACT

Pre-treatment of wood waste represents a technically necessary but often methodologically underexplored stage in the life cycle of wood–plastic composites (WPCs). This study applies an attributional, gate-to-gate life cycle assessment to quantify the environmental implications of five representative laboratory-scale conditioning routes, including three chemical compatibilization pathways (SA1–SA3), thermo-mechanical pelletization (SB) and thermo-physical thermal modification (SC). Life cycle inventories were reconstructed from experimentally reported parameter ranges documented in laboratory-scale studies, and the resulting scenarios were modelled in SimaPro. Impact assessment was performed using three complementary methods, ReCiPe 2016 Midpoint (H), EF 3.0, and Cumulative Energy Demand, to capture climate, resources, and toxicity-related burdens. Main results indicate that chemically intensive scenarios generally exhibit higher impacts than energy-driven treatments, with SA1 showing the highest values across climate, toxicity, and resource-related categories (e.g., 0.91 kg CO_2-eq, 4.09 CTUe, 2.76 Pt). SB and SC, which rely primarily on electricity and moderate heat inputs, display comparatively lower burdens, although SC shows a more intermediate profile due to its exclusive dependence on electricity. To explore whether alternative reagent choices may offer environmental advantages, a set of substitution scenarios was developed based on options documented in experimental literature. The outcomes showed divergent effects: while the replacement of acetic anhydride with maleic anhydride in SA1 lead to modest reductions in several categories, other substitutions, such as those involving citric acid, exhibited mixed effects. Results suggested that the environmental performance of "lower-severity" or bio-based reagents strongly depends on their upstream production profiles and should be evaluated on a case-by-case basis. Overall, the study highlights the relevance of conditioning steps within early-stage environmental assessment of WPC systems and emphasizes the importance of transparent boundary definition and scenario analysis when evaluating alternative pre-treatment strategies.

1. Introduction

The sustainable management of industrial residues remains one of the defining challenges in the transition toward low-carbon and circular production systems. Within this context, Environmental Impact Assessment (EIA) offers analytic frameworks to quantify and compare alternative management routes, supporting evidence-based decisions for resource efficiency and waste reduction. In line with the European Green Deal (European Commission, 2025), the Renovation Wave strategy (European Commission, 2020), and the United Nations 2030 Agenda (United Nations, 2015), circular strategies and industrial symbiosis are aimed to decrease reliance on virgin materials, mitigate greenhouse gas emissions, and minimize waste generation across sectors (European Commission, 2017). Within this broader framework, wood waste has emerged as a valuable secondary raw material (Leone et al., 2025a). Global generation exceeds 300 million tons per year, with Europe alone contributing more than 37 million tons, primarily from construction and demolition activities (FAO, 2020; Eurostat, 2022). Nevertheless, a substantial share remains unrecovered: recent European estimates indicate that roughly 40–45% of post-consumer wood waste is still landfilled or incinerated, while in North America and parts of Asia direct incineration continues to dominate (Camia et al., 2018; UNECE and FAO, 2024). These practices generate avoidable environmental burdens and impede the shift toward more circular material flows (Hossain et al., 2018). A

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promising valorization pathway involves the transformation of wood waste into wood–plastic composites (WPCs) (Leone et al., 2025b). In Europe, the WPC market reached about 612 thousand tons in 2020 and is projected to grow at an annual rate of over 9% until 2030, with Germany standing out as the largest national consumer (KBV Research, 2024). These hybrid materials are increasingly used in building, automotive, and consumer-goods applications (Shih et al., 2024), where they reduce reliance on virgin inputs and contribute to material circularity (Caldas et al., 2020; Balti et al., 2023). However, untreated residues cannot be directly incorporated into polymer matrices: variability in particle size, moisture content, and surface chemistry limits processability and weakens interfacial adhesion (Ayana et al., 2024). Pre-treatment operations are therefore essential to ensure compatibility and enable compounding. Over the past two decades, multiple pre-treatment strategies have been developed to address these limitations. Among the existing, the most used are chemical compatibilization, pelletization, and thermal modification. The former is used to modify the surface polarity of the lignocellulosic fibres to improve adhesion with hydrophobic polymers, typically through coupling agents such as maleic anhydride, silanes, or bio-based reagents, i.e., citric acid (Rodríguez-Llamazares et al., 2011; Lee et al., 2020). Pelletization is a proceed applied to densify and homogenize the waste, improving its feeding behavior and dispersion during extrusion (Pokhrel et al., 2022). Thermal modification, by contrast, alters the micro-structure of wood polymers at moderate temperatures, reducing hygroscopicity and improving dimensional stability (Pelaez-Samaniego et al., 2013). Although these routes address different technical barriers in wood–polymer interface design, their environmental implications remain insufficiently explored.

Existing environmental impact assessment studies, particularly life cycle assessment (LCA), typically focus on product-level formulations or cradle-to-grave analyses (Sommerhuber et al., 2017; Khan et al., 2021). In doing so, they subsume pre-treatment within downstream product systems, leaving its specific role largely invisible. This gap limits the ability of LCA to support early-stage design, as the burdens of conditioning may be either fully exposed or completely masked depending on system boundaries (Reap et al., 2008). Evidence from other bio-based materials confirms that conditioning and surface-modification steps can substantially influence environmental outcomes, as observed for organosolv pulp extraction, thermally modified wood, and cotton fibre processing (Pazzaglia et al., 2024; Rosson and Byrne, 2020). Parallel methodological developments also emphasize the need for improved traceability and boundary clarity in sustainability assessments (Sarmento dos Muchangos et al., 2025; Shanbhag and Dixit, 2025), suggesting a growing interest in process-level evaluation. Against this background, the present study conducts a comparative, laboratory-scale LCA to quantify the environmental implications of the main pre-treatment approaches used for conditioning wood waste prior to WPC production. The analysis focuses only on the conditioning stage, which is often integrated into broader product systems and therefore remains methodologically underrepresented. By examining representative chemical, thermo-mechanical and thermo-physical routes documented in experimental research, the study identifies how different pre-treatments shape the environmental profile of wood-based fillers. These results contribute to filling a gap in current LCA literature and provide process-level insights that can support early design choices for more sustainable WPC formulations.

2. Materials and methods

2.1. Goal and scope definition

Goal of this study is to quantify and compare the environmental impacts of laboratory-scale pre-treatment operations applied to wood waste. The analysis isolates the conditioning phase from downstream WPC manufacturing so that the contribution of pre-treatments can be assessed independently. By evaluating representative chemical, thermo-mechanical, and thermo-physical routes documented in experimental research, the study generates process-level evidence that supports informed decision-making in the early stages of WPC development. This process-oriented perspective is aligned with recent methodological advances in environmental assessment, where prospective and design-relevant LCA frameworks are increasingly adopted to capture the influence of upstream decisions on system evolution (Fang et al., 2025; Su et al., 2025). An attributional, process-based LCA was conducted within a gate-to-gate system boundary (Lewis et al., 2022) extending from untreated wood residues to the production of pre-treated filler. Processes beyond this boundary, including polymer compounding, extrusion, product manufacturing, use phase and end-of-life, were excluded, as were transport processes, since all inventories reflect on-site, laboratory-scale operations. The system boundaries include all inputs required to obtain the conditioned filler, namely energy, chemicals and water and the impacts associated with producing these inputs, as represented in the corresponding ecoinvent market datasets. In this work, the functional unit (FU) was defined as 1 kg of pre-treated wood waste suitable for WPC compounding. This FU ensures comparability across scenarios that differ in conditioning method but ultimately serve the same qualitative technical purpose: improving the compatibility between wood particles and thermoplastic matrices. Because the scenarios were reconstructed from heterogeneous laboratory-scale studies and no harmonized mechanical or interfacial performance data exist, functional equivalence is defined at the process level as the shared objective of enhancing interfacial adhesion, rather than through quantitative performance metrics. The FU therefore reflects the mass of conditioned filler while acknowledging that the extent of compatibility enhancement may vary among pre-treatment routes, consistent with best practice for early-stage and laboratory-scale LCA studies (ISO, 2006; Guinée, 2002).

Three conditioning strategies were examined: chemical compatibilization (SA), pelletization (SB) and thermal modification (SC). A qualitative overview of the main characteristics of the three pre-treatment strategies is provided in the Supplementary Material (SM4). The chemical route was further articulated into three configurations (SA1–SA3) to represent distinct reagent combinations and operating conditions reported in the literature. In total, five baseline scenarios were modelled. An overview of the system boundary and modelled flows is provided in Fig. 1.

2.2. Life cycle inventory (LCI)

The life cycle inventory represents laboratory-scale conditioning processes for the original scenarios SA1–SA3, SB and SC. All foreground flows, chemical reagents, water inputs, electricity, and thermal energy were modelled in *SimaPro 9.5* (PRé Sustainability, 2023) using standard ecoinvent 3.9.1 market datasets (Guinée et al., 2011), reflecting the fact that laboratory operations rely on commercially supplied materials and energy carriers. No customized datasets or process-specific emission factors were introduced.

The quantities assigned to these datasets were reconstructed from experimentally documented parameter ranges reported across studies on wood-flour functionalization, lignocellulosic fibre treatment, thermal conditioning, and laboratory-scale pelletization. These sources provide realistic intervals for reagent to solid ratios, temperatures, residence times, moisture adjustments, and specific energy requirements. Representative midpoint values within these intervals were selected and scaled to the FU of 1 kg of pre-treated wood waste, ensuring internal consistency across all scenarios (ISO, 2006; Guinée, 2002).

SA1–SA3 represent three configurations of laboratory-scale surface modification commonly reported for wood flour and lignocellulosic fibres (Hao et al., 2021). Although all three scenarios pursue the same qualitative function, enhancing compatibility between wood particles and polymer matrices, they were structured to represent a progressive range of modification intensities. SA1 reflects the most chemically

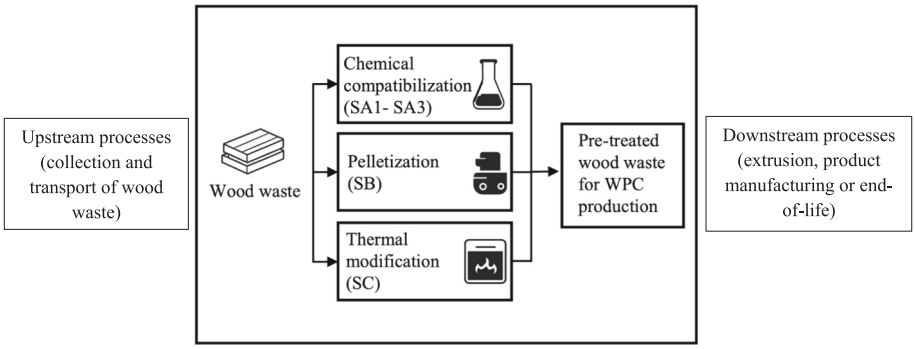

Fig. 1. System boundaries and modelled process configurations for the pre-treatment scenarios.

demanding configuration, SA2 represents an intermediate treatment, and SA3 corresponds to the mildest option. The differentiation among SA1–SA3 stems solely from the variation in reagent type, dosage and liquid-to-solid ratios reported in the literature. These parameters were used to define three representative configurations, all lying within experimentally documented ranges for alkaline activation, anhydride-based treatments and mild esterification (Diao et al., 2025; Abdel Kader et al., 2025). Electricity demand for stirring, heating and solution preparation was estimated from nominal power ratings of standard laboratory devices and scaled to the corresponding treatment duration. This approach ensures a consistent gradation of energy intensity across the conditioning routes, ranging from stronger to milder surface modification, while remaining fully aligned with the operational intervals documented in experimental studies (Kallakas et al., 2015; Poletto, 2016; Samyn, 2024; Elsheikh et al., 2022).

SB represents thermo-mechanical densification performed at laboratory scale. Experimental studies report mechanical energy consumptions between 0.1 and 0.25 kWh per kilogram of pellets and thermal requirements of 2.3–3.5 MJ per kilogram of water removed. Representative values within these ranges were selected to model electricity use during mechanical compression and thermal energy for moisture adjustment. As in typical laboratory-scale practice, the process requires no chemical inputs and operates in closed electric equipment, which means that no process-level flue gases or effluents are generated; environmental burdens are therefore captured through upstream energy provision (Carvalho et al., 2022; Shang et al., 2013; Finell et al., 2009; Rueda et al., 2022).

SC reflects thermo-physical conditioning performed in an electric laboratory oven. Published studies report treatment temperatures between 120 and 200 °C and residence times ranging from tens of minutes to several hours. A representative treatment at approximately 180 °C for 3 h was selected. Electricity consumption was estimated by combining nominal power ratings of standard laboratory ovens with the corresponding operating time. As the process involves no chemical inputs and is carried out in closed electric equipment, no measurable process-level flue gases or effluents are generated under laboratory conditions (Luo et al., 2012; Krapež Tomec et al., 2024; Ayrilmis et al., 2011; Chien and Yang, 2024).

Across all scenarios, treatments are conducted using closed electric ovens, small batch reactors and benchtop pellet presses, none of which produce measurable flue gases, wastewater or solid residues under laboratory-scale conditions. The chemical reactions involved in alkaline activation, esterification and anhydride-based treatments do not generate quantifiable off-gases at this scale. As a result, all environmental burdens are captured through the upstream production of reagents and the electricity and heat required to operate the equipment. This behavior is consistent with published laboratory protocols and with standard practice in laboratory-scale LCA, where direct process emissions are typically absent or fall below quantification limits (Rosson and Byrne, 2020).

All electricity inputs were mapped to either low-voltage or medium-voltage market datasets, depending on the connection level typically associated with each device: mixers, stirrers and small mills were linked to low-voltage supply, whereas ovens and pellet presses, requiring higher power input, were modelled using medium-voltage electricity datasets (Wernet et al., 2016).

Thermal energy in scenario SB was modelled using a fossil-based heat carrier, selected as a conservative and widely available proxy for laboratory-scale thermal conditioning. Although industrial or pilot-scale pelletization may rely on alternative fuels or integrated heat supply systems, such configurations fall outside the laboratory-scale system boundaries defined in this study. Likewise, the exclusive use of electricity as the thermal source in scenario SC reflects typical laboratory oven operation. At larger scales, thermal modification processes often employ different fuel mixes or waste-heat recovery systems, but these options are beyond the scope of the present gate-to-gate assessment and were therefore not considered.

2.2.1. *Data quality assessment*

Data quality was assessed using the ecoinvent Pedigree Matrix structure. While the methodology formally includes five criteria, only the three criteria relevant for reconstructed laboratory-scale foreground flows (reliability, geographical correlation and technological correlation) were applied. Completeness and temporal correlation are inherent to the background datasets and therefore were not reassessed for the parametrized foreground inputs (Wedeima et al., 2013). In this study, the Pedigree Matrix was applied qualitatively to distinguish two sources of uncertainty: (i) the inherent quality of the background datasets, which is consistently high due to the standardized and well-documented structure of ecoinvent market processes; and (ii) the uncertainty associated with the parametrization of foreground flows reconstructed from experimentally reported ranges. Because all foreground inputs were linked to ecoinvent 3.9.1 market datasets, uncertainty does not originate from the datasets themselves but from the quantities assigned to them. The values used for reagents, water and energy were derived from heterogeneous laboratory-scale studies, whose variability in reporting detail, geographical origin and operational conditions introduces moderate uncertainty, particularly in reliability, geographical representativeness and technological correlation. Nevertheless, all selected parameters fall within experimentally documented intervals and reflect realistic laboratory conditions for wood-waste conditioning.

This qualitative use of the Pedigree Matrix captures the uncertainty structure of the reconstructed inventories without overstating data precision and aligns with established practice for laboratory-scale LCA studies (Moutik et al., 2024; Balcioglu et al., 2025).

Table 1 provides a qualitative overview of the foreground flows included in each scenario and explains the rationale behind the selection of the corresponding ecoinvent datasets. Electricity datasets were distinguished according to the typical power demand of the laboratory equipment reported in the experimental literature. Devices used for

Table 1
Foreground flows and corresponding ecoinvent 3.9.1 datasets for each pre-treatment scenario, including their technical role and the rationale for proxy selection.

Scenario	Dataset (ecoinvent v3.9.1)	Function in pre-treatment	Rationale / proxy choice
A1	Acetic anhydride (GLO)	Functionalizing agent for esterification	No European dataset available; global proxy adopted
	Melamine (GLO)	Surface modifier/ coupling agent	Proxy reflecting reported experimental dosage
	Organic chemical, unspecified (GLO)	Generic compatibilizing input	Proxy for unspecified organic inputs
	Water, deionized (EU w/o CH)	Solution preparation and rinsing	Required to avoid ionic interference during anhydride-based reactions
	Electricity, medium voltage (EU w/o CH)	Heating and high-power mixing	Proxy for energy-intensive laboratory equipment
	Sodium hydroxide 50% (GLO)	Alkaline activation	Proxy reflects typical dosage in laboratory-scale use
A2	Sulfuric acid (RER)	Acid neutralization	Dataset with European coverage
	Tap water (EU w/o CH)	Dissolution and rinsing	Standard for alkaline/ acid cleaning steps
	Electricity, low voltage (EU w/o CH)	Mixing, dispersion and reaction steps	Proxy for low-power laboratory operation
	Oxalic acid (GLO)	Hydrolytic agent	No European dataset available; global proxy adopted
A3	Urea formaldehyde resin (RER)	Surface modifier	Reported in experimental formulations
	Water, deionized (EU w/o CH)	Solution preparation and rinsing	Required for controlled hydrolysis and resin deposition
	Electricity, low voltage (EU w/o CH)	Mixing and reaction	Proxy for laboratory-scale energy demand
B	Electricity, medium voltage (EU w/o CH)	Grinding and pellet pressing	Proxy for mechanical densification
	Heat, propane (RoW)	Thermal stabilization	Fossil-based baseline selected intentionally as conservative laboratory-scale proxy
C	Electricity, medium voltage (EU w/o CH)	Heating at 180 °C for 3 h	Proxy for controlled thermal treatment

sustained heating, such as ovens and small batch reactors, were associated with medium-voltage electricity as a proxy for higher energy intensity, whereas low-power devices used for mixing, dispersion or mild hydrolysis were mapped to low-voltage electricity. This modelling choice does not represent the physical supply voltage of the laboratory but provides consistent alignment between equipment intensity and the corresponding ecoinvent datasets. Water quality was differentiated according to the chemical of each pre-treatment. Deionized water was assigned to reactions where ionic impurities may interfere with esterification, hydrolysis or resin deposition (e.g., acetic anhydride, oxalic acid, UF resin), while tap water was used for alkaline or rinsing stages, in line with typical laboratory practice reported in the experimental studies. These modelling choices ensure internal chemical and operational coherence across scenarios and reflect the conditions described in the literature. Full quantitative inventories, including all flow amounts and Pedigree Matrix scores, are reported in the Supplementary Material (Tables SM1.1–SM 1.5).

2.3. Life cycle impact assessment (LCIA)

Environmental impacts were modelled in SimaPro 9.5 using three complementary impact assessment methods. ReCiPe 2016 Midpoint (H) was used as the primary method and provides a broad midpoint framework comprising 17 impact categories (Huijbregts et al., 2017). In this study, the following ReCiPe indicators were retained because they were the most sensitive to differences among pre-treatment routes: global warming, human carcinogenic toxicity, human non-carcinogenic toxicity, and fossil resource scarcity.

To extend the assessment to impact pathways of relevance for bio-based materials, the Environmental Footprint 3.0 (EF 3.0) method was additionally applied (Sala et al., 2021). EF 3.0 supplied the indicators ionizing radiation, ecotoxicity, freshwater, land use, water use, and resource use, fossils, which complement the ReCiPe categories and align with current European eco-design frameworks.

Finally, Cumulative Energy Demand (CED) was used to characterize the total energy requirements of each pre-treatment route. The CED method distinguishes between different energy carriers, reported here as non-renewable fossil, non-renewable nuclear, renewable biomass, renewable wind/solar/geothermal, and renewable water (Hischier et al., 2010).

All results were calculated per functional unit and expressed in both absolute and normalized terms to ensure comparability across scenarios.

2.4. Assumptions and methodological limitations

This study relies on a set of assumptions consistent with laboratory-scale, gate-to-gate modelling of pre-treatment operations. All scenarios represent bench-scale processes, implying simplified energy supply conditions and the absence of measurable process emissions or waste streams. This reflects the operating characteristics of closed-vessel chemical treatments, electric thermal conditioning and benchtop pelletization, where direct releases are negligible or below quantification limits.

The functional unit represents 1 kg of pre-treated wood waste ready for compounding. Because no harmonized mechanical or interfacial performance data exist across the experimental studies used to reconstruct the scenarios, functional equivalence is defined at the process level and does not imply equivalence in downstream performance. Foreground inventories were reconstructed from representative values selected within experimentally reported parameter ranges. This introduces inherent variability related to differences in reporting detail and laboratory-scale procedures, which was made explicit through a qualitative Pedigree Matrix assessment. The system boundary excludes transport, compounding, extrusion, product manufacturing, use and end-of-life; therefore, potential shifts in environmental burdens beyond the conditioning phase are not captured. Energy carriers reflect laboratory practice, where electricity is the dominant source. Alternative fuels or integrated heat supplies, which may be used at industrial scale, fall outside the scope of this gate-to-gate model.

Finally, the impact assessment focuses on selected midpoint indicators from ReCiPe 2016 (H), EF 3.0 and CED. These indicators cover climate, toxicity, resource, and energy related pathways, but they do not represent a comprehensive environmental profile.

3. Results and discussion

3.1. Environmental impact comparison of pre-treatment scenarios

Fig. 2 displays the normalized results for the five pre-treatment scenarios, while Table 2 reports the corresponding absolute values, both obtained through the impact assessment methods described in the LCIA (see Section 2.3). Normalized results make the differences among scenarios immediately visible, whereas absolute values retain the full numerical detail and allow consistent comparison across categories. For

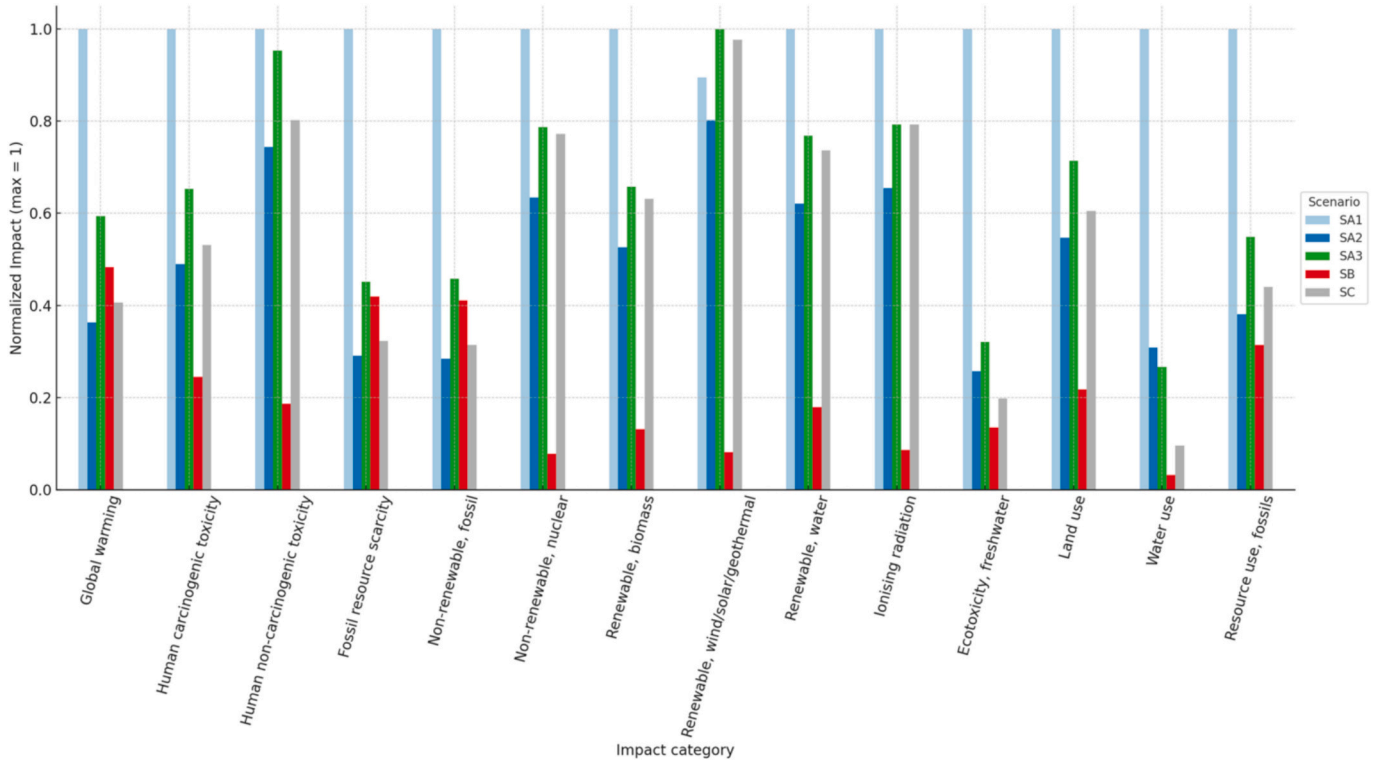

Fig. 2. Normalized LCA results for the pre-treatment scenarios across the impact categories, obtained using the three impact assessment methods applied in the study: ReCiPe 2016 (H), EF 3.0 and Cumulative Energy Demand (CED).

Table 2
Life cycle impact assessment results for the pre-treatment scenarios (absolute values), obtained using the three impact assessment methods applied in the study: ReCiPe 2016 (H), EF 3.0 and Cumulative Energy Demand (CED).

Impact category	Unit	SA1	SA2	SA3	SB	SC
Global warming	kg CO_2 eq	0.91	0.33	0.54	0.44	0.37
Human carcinogenic toxicity	kg 1,4-DCB eq	0.049	0.024	0.032	0.012	0.026
Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.86	0.64	0.82	0.16	0.69
Fossil resource scarcity	kg oil eq	0.31	0.09	0.14	0.13	0.10
Non-renewable, fossil	MJ	14.47	4.11	6.63	5.94	4.55
Non-renewable, nuclear	MJ	5.17	3.28	4.07	0.40	3.99
Renewable, biomass	MJ	0.38	0.20	0.25	0.05	0.24
Renewable, wind/solar/geothermal	MJ	0.77	0.69	0.86	0.07	0.84
Renewable, water	MJ	0.95	0.59	0.73	0.17	0.70
Ionizing radiation	kBq U-235 eq	0.29	0.19	0.23	0.025	0.23
Ecotoxicity, freshwater	CTUe	4.09	1.05	1.31	0.55	0.81
Land use	Pt	2.76	1.51	1.97	0.60	1.67
Water use	m^3 depriv.	0.94	0.29	0.25	0.03	0.09
Resource use, fossils	MJ	18.50	7.05	10.16	5.82	8.14

completeness, the full numerical tables and the percentage contributions of the key input parameters discussed in the following sections are provided in the Supplementary Material (SM3.1-SM3.4).

The environmental performance of the five conditioning scenarios shows a clear stratification driven by the nature and intensity of the required inputs. SA leads to the highest burdens, while energy-driven treatments such as SB and SC display substantially lower impacts. The contribution analysis clarifies these differences by quantifying the share of each foreground flow in the overall environmental profile.

SA1 exhibits the most pronounced impacts among all treatments. The inventory combines several high-impact reagents, namely acetic anhydride, melamine and an organic chemical together with deionized water and medium-voltage electricity. Electricity alone accounts for 47% of global warming, 56% of human carcinogenic toxicity and over 60% of human non-carcinogenic toxicity. In categories dominated by electricity generation, such as ionizing radiation, its contribution exceeds 92%. Chemical reagents amplify these burdens: acetic anhydride contributes 19% of global warming and more than 58% of freshwater ecotoxicity, while melamine adds 22% to global warming and 14% to ecotoxicity, freshwater. Deionized water influences water deprivation (13%) but remains negligible elsewhere. These contributions explain the high absolute values of SA1, including 0.91 kg CO_2 eq (GWP), 4.09 CTUe (ecotoxicity) and 2.76 Pt (land use).

SA2 shows a markedly reduced environmental profile compared with SA1, reflecting both its simpler set of reagents and the fact that the inventory is driven almost entirely by electricity demand. Across all impact categories, low-voltage electricity represents the dominant contribution, ranging from 83% to 97% and approaching 98% for indicators that are particularly sensitive to electricity generation, such as ionizing radiation and wind/solar-related renewable categories. Among the reagents, sodium hydroxide is the only flow with a discernible influence, contributing between 10% and 12% in toxicity-related categories and up to 31% in freshwater ecotoxicity. Sulfuric acid remains marginal and rarely exceeds 6–7%, while tap water affects almost exclusively the Water Use indicator, where it reaches 59% due to the deprivation potential associated with water supply. Overall, SA2 exhibits substantially lower absolute values, 0.33 kg CO_2 eq for global warming, 1.05 CTUe for freshwater ecotoxicity and 1.51 Pt for land use and is clearly the least impactful of the chemical routes. Its environmental signature is therefore characterized by an almost entirely electricity-driven process, modulated by relatively mild reagent inputs.

SA3 occupies an intermediate position between SA1 and SA2, with

an environmental profile shaped jointly by electricity demand and the more evident influence of its reagents. Low-voltage electricity remains the main contributor, accounting for 62–98% of total impacts and approaching 99% in ionizing radiation. However, unlike SA2, reagents exert a more visible effect, particularly oxalic acid, which emerges as the principal non-energy contributor. Oxalic acid accounts for 27% of freshwater ecotoxicity, around 25% of land occupation and fossil resource use, and more than 28% of global warming. Urea–formaldehyde resin adds a consistent additional burden, typically between 3% and 6% across impact categories, while deionized water becomes relevant almost exclusively for Water Use, where it contributes 33%. This combination results in a profile more burdensome than SA2 yet less severe than SA1: 0.54 kg CO_2 eq for global warming, 1.31 CTUe for ecotoxicity and 1.97 Pt for land use. SA3 therefore represents a "moderate" chemical treatment, where chemical severity is reduced relative to SA1, but the upstream burdens of the reagents remain sufficiently significant to amplify electricity-related impacts.

SB displays the lowest environmental burdens of the entire set, owing to the complete absence of chemical reagents and water flows and to an inventory composed solely of electricity and a moderate amount of thermal energy. The balance between electricity and heat creates a distinctive impact pattern: thermal energy dominates the categories associated with combustion and fossil resource use, accounting for 64% of global warming, 70% of fossil resource scarcity and 52% of freshwater ecotoxicity, while electricity controls categories linked to nuclear or renewable electricity generation, rising above 87% for ionizing radiation and wind/solar-related indicators. Without any chemical inputs, SB maintains very low absolute values across the board: 0.44 kg CO_2 eq for global warming, 0.55 CTUe for freshwater ecotoxicity and 0.60 Pt for land use. As such, SB stands out as a low-impact conditioning route, its environmental profile entirely defined by the energy required for mechanical densification and thermal stabilization.

SC is the simplest configuration among all those analyzed, as the entire process relies exclusively on medium-voltage electricity. Consequently, every impact category is driven 100% by the upstream burdens of electricity production. Despite this, absolute impacts remain low due to the moderate energy demand of the thermal treatment: 0.37 kg CO_2 eq for global warming, 0.81 CTUe for ecotoxicity and 1.67 Pt for land use. Compared with SB, SC is slightly more burdensome in several impact categories due to its exclusive reliance on medium-voltage electricity, which entails higher upstream impacts per functional unit than the mixed electricity–heat supply used in pelletization. As a result, SC exhibits an intermediate environmental profile: while climate change impacts remain low, the exclusive dependence on electricity leads to higher contributions in electricity-related impact categories, preventing SC from reaching the overall low-impact level observed for SB. Since electricity supply dominates several impact categories, particularly in electricity-driven scenarios such as SC, the results are sensitive to the assumed electricity mix. While alternative electricity configurations could influence the absolute values of energy and nuclear related indicators, the relative comparison among scenarios remains robust due to the consistent use of the same electricity background across all cases.

3.2. Substitution-based scenarios

After analyzing the baseline scenarios, a natural question emerged: *would the environmental profile of chemical pre-treatments change if some of their reagents were replaced with the "greener" alternatives increasingly proposed in recent literature?* Several studies on lignocellulosic modification suggest that certain functionalizing agents can be substituted with milder or bio-based reagents while maintaining comparable surface activation effects. However, these claims are rarely tested through LCA, and it is not known whether such substitutions reduce impacts once upstream burdens are considered. To explore this question, we reviewed the literature used to construct SA1–SA3 and identified which of the reagents included in our inventory have documented functional substitutes. Only three reagents met this criterion; for the others, no validated ecological alternative has yet been proposed. Based on this evidence, in SA1, the strong functionalization system was reformulated by replacing acetic anhydride with maleic anhydride, a coupling agent widely used in WPC manufacturing and frequently cited as an efficient compatibilizer for wood–polymer interfaces (Hao et al., 2021; Blanco et al., 2022; Rindayatno et al., 2023). In SA2, the activation system originally based on sodium hydroxide and sulfuric acid was adjusted by substituting sulfuric acid with citric acid, in line with studies demonstrating that citric and other organic acids can act as lower-severity alternatives to mineral acids in lignocellulosic processing (Simonini and Dorigato, 2025). In SA3, oxalic acid was replaced with citric acid as well, reflecting evidence that citric acid can induce comparable esterification on lignocellulosic surfaces while exhibiting a more favorable environmental and toxicological profile (Kohli et al., 2019; Lee et al., 2020).

SB and SC were not analyzed, as they contain no chemical reagents for which alternative functional equivalents exist.

To ensure comparability across scenarios, each substitution was applied at equal mass to the original reagent. This assumption does not imply stoichiometric equivalence and is acknowledged as a limitation, but it allows us to isolate the effect of the substitution itself and evaluate whether a theoretically "greener" input truly leads to lower environmental impacts under consistent modelling conditions.

The alternative scenarios (SA1-alt, SA2-alt, SA3-alt), therefore serve as a targeted diagnostic step: they do not aim to redesign the treatments, but simply to test whether replacing conventional reagents with their literature-supported green counterparts yields any measurable environmental benefit. The alternative inventories are summarized in Table 3, which reports only the modified flows. All other inputs remain unchanged and can be cross-referenced in the baseline LCI (see Table 1). Full quantitative inventories, including all flow amounts, are reported in the Supplementary Material (Tables SM 1.6–SM 1.8).

3.2.1. Assumptions and limitations of alternative scenarios

The substitution scenarios developed in this study should be interpreted as exploratory what-if cases rather than prescriptive formulations. Their role is to test whether reagent substitutions frequently presented as "greener" in the literature translate into measurable

Table 3
Overview of the reagent substitutions modelled in the alternative scenarios (A1–A3).

Scenario	Step / input	Original input (dataset)	Alternative input (dataset)	Notes / assumptions
A1-alt	Functionalizing reagent	Melamine (GLO)	Maleic anhydride (GLO)	Substitution grounded in documented coupling efficiency of maleic anhydride in WPC systems. Mass retained for strict comparability with baseline.
A2-alt	Acid reagent	Sulfuric acid (RER)	Citric acid (GLO)	Citric acid selected as lower-severity alternative tested in lignocellulosic processing; mass-equivalent substitution.
A3-alt	Hydrolytic reagent	Oxalic acid (GLO)	Citric acid (GLO)	Supported by studies showing comparable esterification performance; mass-equivalent substitution.

environmental improvements when examined under harmonized, gate-to-gate conditions.

A key methodological assumption is that all substitutions were applied on a mass-equivalent basis. This approach does not reflect the exact dosages that would be required in practice, nor does it imply stoichiometric equivalence between reagents. Rather, it was a deliberate choice to maintain strict comparability with the baseline inventories. By holding the quantity constant, any difference in environmental impact can be attributed solely to the intrinsic life-cycle profile of the substituted reagent, rather than to arbitrary variations in input magnitude. This provides a transparent benchmark: if a "green" alternative performs worse even under equal-mass conditions, its presumed environmental advantage becomes questionable from the outset. It is also acknowledged that only a subset of the chemical inputs used in SA1–SA3 could be replaced. The literature supports functional equivalence only for the specific substitutions examined here; for the remaining reagents, no documented alternatives were identified, and to the best of our knowledge, no studies currently provide evidence of plausible ecological substitutes for these inputs.

3.2.2. *Comparative environmental assessment of alternative pre-treatment scenario*

Fig. 3 illustrates the comparative performance of the baseline and alternative pre-treatment scenarios, expressed as normalized values across the most relevant impact categories, while Table 4 complements the figure with absolute data. The impact methods and corresponding categories analyzed here are the same as those described in the LCIA (see Section 2.3) of the original five scenarios, ensuring full consistency across all assessments. For completeness, the full numerical tables and the percentage contributions of the key input parameters discussed in the following sections are provided in the Supplementary Material (SM1.6-SM1.8).

3.2.2.1. SA1 vs SA1-alt. Replacing acetic anhydride with maleic anhydride produces a modest reduction across most impact categories. Global warming decreases from 0.91 to 0.81 kg CO_2 eq, while human toxicity (carcinogenic and non-carcinogenic) similarly declines. The contribution analysis confirms that electricity remains the dominant driver (53–70% across impact categories), but the substitution reshapes the chemical component: acetic anhydride and the organic chemical together accounted for nearly half of the chemical burden in the baseline scenario, whereas maleic anhydride displays a slightly lower fossil and toxicity footprint. This shift explains the overall downward trend. Freshwater ecotoxicity and land use also decline, although the magnitude is limited because electricity still accounts for the majority of impacts. Overall, SA1-alt retains the high-intensity character of the original scenario but demonstrates that substituting the functionalizing reagent can yield measurable although not dramatic improvements.

3.2.2.2. SA2 vs SA2-alt. In SA2, replacing sulfuric acid with citric acid produces a mixed outcome. For several categories, global warming, toxicity-related indicators, fossil resource scarcity, the impacts increase slightly (e.g., GWP rises from 0.33 to 0.39 kg CO_2 eq). This behavior is consistent with the contribution structure: in SA2-alt, citric acid becomes a relevant hotspot, contributing up to 30% of land use, 65% of freshwater ecotoxicity and nearly 19% of water deprivation. By contrast, sulfuric acid in the original scenario contributed only 1–2% in most categories. Electricity continues to dominate the profile (75–96% depending on the category), but the introduction of citric acid adds a substantial biogenic and land-related burden, which offsets the expected "green" advantage. As a result, SA2-alt is consistently more impactful than SA2 in toxicity-related categories, land use and ecotoxicity, confirming that replacing mineral acids with organic acids does not necessarily lead to lower environmental impacts at the process level.

3.2.2.3. SA3 vs SA3-alt. The substitution of oxalic acid with citric acid in SA3 produces the strongest deviations among all alternative scenarios. While some indicators improve, global warming decreases from 0.54 to 0.44 kg CO_2 eq, the environmental profile becomes significantly worse in categories linked to land occupation and ecotoxicity. Citric acid represents 66% of freshwater ecotoxicity and 26,72% of land use in SA3-alt, far exceeding the contributions of oxalic acid in the baseline scenario (27% and 25%, respectively). Electricity still dominates most categories (82–98%), but the substantial burden associated with citric acid shifts

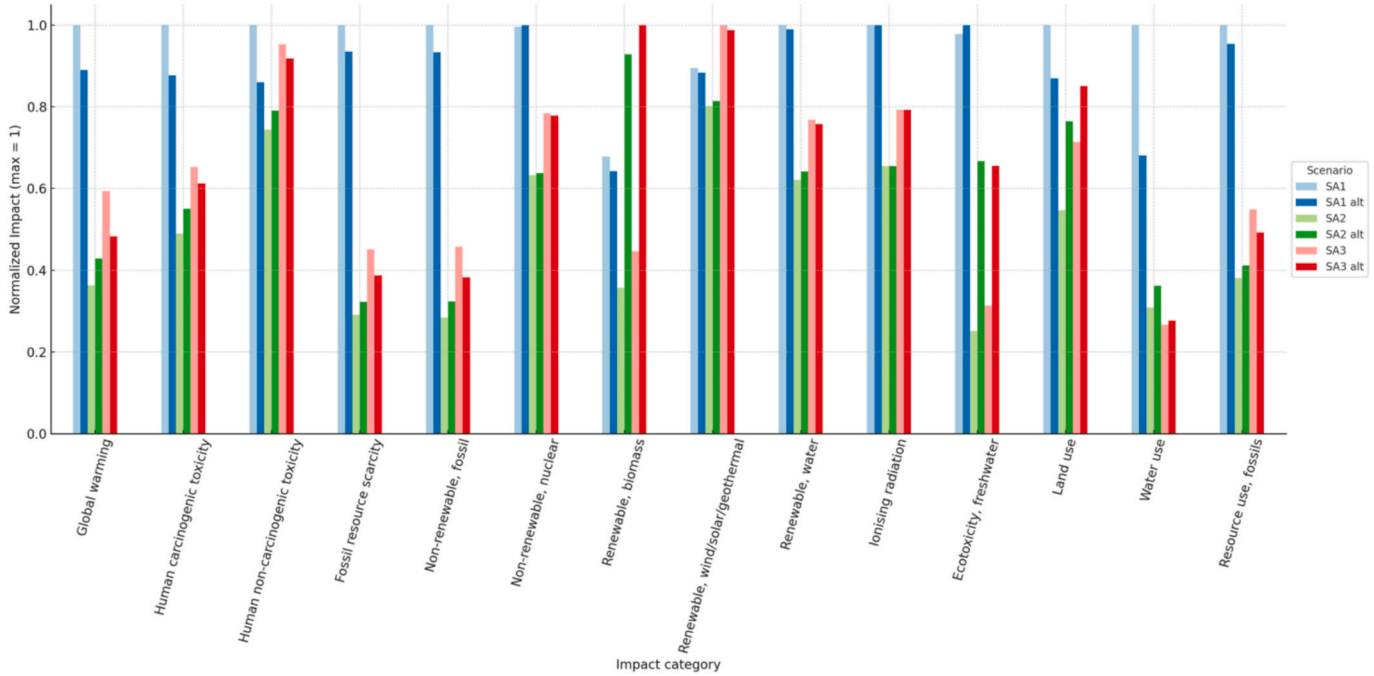

Fig. 3. Comparison of normalized environmental impacts: baseline vs alternative pre-treatment scenarios, obtained using the three impact assessment methods applied in the study: ReCiPe 2016 (H), EF 3.0 and Cumulative Energy Demand (CED).

Table 4
Absolute environmental impacts of i) baseline and ii) alternative pre-treatment scenarios, obtained using the three impact assessment methods applied in the study: ReCiPe 2016 (H), EF 3.0 and Cumulative Energy Demand (CED).

Impact category	Unit	SA1	SA1-alt	SA2	SA2-alt	SA3	SA3-alt
Global warming	kg CO_2 eq	0.91	0.81	0.33	0.39	0.54	0.44
Human carcinogenic toxicity	kg 1,4-DCB eq	0.049	0.043	0.024	0.027	0.032	0.030
Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.86	0.74	0.64	0.68	0.82	0.79
Fossil resource scarcity	kg oil eq	0.31	0.29	0.09	0.10	0.14	0.12
Non-renewable, fossil	MJ	14.47	13.51	4.11	4.68	6.63	5.54
Non-renewable, nuclear	MJ	5.17	5.19	3.28	3.31	4.07	4.04
Renewable, biomass	MJ	0.38	0.36	0.20	0.52	0.25	0.56
Renewable, wind/solar/geothermal	MJ	0.77	0.76	0.69	0.70	0.86	0.85
Renewable, water	MJ	0.95	0.94	0.59	0.61	0.73	0.72
Ionizing radiation	kBq U-235 eq	0.29	0.29	0.19	0.19	0.23	0.23
Ecotoxicity, freshwater	CTUe	4.09	4.18	1.05	2.79	1.31	2.74
Land use	Pt	2.76	2.40	1.51	2.11	1.97	2.35
Water use	m^3 depriv.	0.94	0.64	0.29	0.34	0.25	0.26
Resource use, fossils	MJ	18.50	17.65	7.05	7.61	10.16	9.11

the overall environmental pattern, particularly for ecotoxicity and land-related impacts, and drives the increase in water use due to the upstream agricultural production of the acid. Consequently, SA3-alt becomes environmentally superior to the baseline only in climate change and a handful of resource indicators, but worse in the categories most sensitive to biogenic and agricultural inputs.

3.3. Summary comparison and implications for eco-design

The comparative analysis of all baseline and alternative scenarios confirms that pre-treatment is not an accessory step but a defining contributor to the upstream environmental profile of wood–plastic composites. The three chemical routes maintain the highest burdens overall, driven by the combined influence of reagent production, water purification and electricity demand, whereas the energy-driven treatments (SB and SC) remain consistently less intensive but still sensitive to electricity mix and thermal energy sources.

Among the chemical routes, SA1 remains the most demanding configuration, but its alternative variant demonstrates that substituting a single reagent can reduce several impact categories without altering process intensity. The substitution of acetic anhydride with maleic anhydride, inspired by current compatibilization practice in WPC manufacturing, produces a measurable improvement in climate-related and energy-related indicators, confirming that even small modifications in reagent selection can shift the environmental balance.

By contrast, the alternative configurations of SA2 and SA3 reveal a different pattern. In both cases, replacing mineral or synthetic acids with citric acid does not translate into lower impacts. Instead, the upstream agricultural and bioprocessing burdens of citric acid substantially increase ecotoxicity, land use and water-related categories, often dominating the overall profile. These outcomes illustrate that a "bio-based" origin does not guarantee lower environmental pressure; when agricultural feedstocks and fermentation processes are involved, burden shifting can easily occur, particularly for impact categories sensitive to land occupation and nutrient-related emissions.

The non-chemical scenarios establish two important benchmarks. SB remains low impact compared with the chemical treatments, but its performance is strongly influenced by the thermal energy source. SC, entirely electricity-driven, displays a stable and intermediate environmental profile, with low climate change impacts but higher sensitivity to electricity-related categories. Taken together, these results highlight three eco-design insights. First, reagent substitution is an effective lever only when the upstream environmental footprint of the substitute is demonstrably lower, an assumption that cannot be taken for granted, especially for bio-derived chemicals. Second, the burden-shifting effects observed in SA2-alt and SA3-alt demonstrate the necessity of process-level LCA before adopting "greener" functionalization pathways. Third, energy-driven pre-treatments, although sometimes considered less sophisticated, can deliver balanced environmental performance and, in some configurations (e.g. SB), serve as credible low-impact alternatives within WPC design.

This evidence reinforces the idea that pre-treatment choices should be treated as active design variables: small adjustments in chemistry or energy supply can reshape environmental outcomes more decisively than downstream composite processing stages. To support interpretation, the impact categories were aggregated into three macro-dimensions, indicates in Table 5: (i) *Climate & Energy*, including global warming, non-renewable fossil and nuclear energy, renewable energy carriers (biomass, wind/solar/geothermal, water) and ionizing radiation; (ii) *Resources*, comprising fossil resource scarcity, resource use (fossils), water use and land use; and (iii) *Toxicity*, covering human carcinogenic toxicity, human non-carcinogenic toxicity and freshwater ecotoxicity. For each macro-dimension, scenarios were classified as Low, Moderate, or High impact based on the relative magnitude of their normalized results across the full set of scenarios. The Overall profile was then derived as High if at least one macro-dimension was classified as High, as Low only when all three macro-dimensions were classified as Low, and as Moderate in all other cases.

This synthesis highlights immediately the main contrasts already emerging from the quantitative results, namely the consistently higher burdens of chemical treatments and the comparatively lower impacts of energy-driven routes, while also showing that no configuration performs uniformly well across all dimensions. The table provides a qualitative summary of the scenario comparison.

4. Conclusions

This study demonstrates that the conditioning of wood waste is a decisive and environmentally consequential stage in the production of wood–plastic composites. By isolating pre-treatment within a gate-to-gate attributional LCA, the analysis makes explicit a set of upstream impacts that are normally overshadowed by product-level

Table 5
Qualitative ranking of baseline and alternative scenarios across three impact macro-dimensions (Climate & Energy, Resources, Toxicity) and their resulting overall profile.

Scenario	Climate & Energy	Resources	Toxicity	Overall profile
SA1	High	High	High	High
SA1-alt	High	High	High	High
SA2	Low	Moderate	Moderate	Moderate
SA2-alt	Moderate	High	High	High
SA3	Moderate	Moderate	Moderate	Moderate
SA3-alt	High	High	High	High
SB	Low	Low	Low	Low
SC	Moderate	Moderate	Moderate	Moderate

considerations. The results show that chemical compatibilization, despite its well-known technical relevance, carries substantially higher environmental burdens than thermo-mechanical or thermo-physical conditioning, driven by reagent production, water purification and electricity use.

The comparison between baseline and alternative scenarios further clarifies a central point for sustainable material design: the environmental benefits of "greener" reagents cannot be assumed. While the substitution of acetic anhydride with maleic anhydride in SA1 delivered measurable improvements, the replacements tested in SA2 and SA3 produced the opposite effect, increasing burdens in land, water and ecotoxicity categories because of the upstream characteristics of the bio-based substitute. These findings show that qualitative assumptions, such as associating biological origin with environmental advantage, are insufficient for guiding material innovation. Only a multi-category life cycle perspective can reveal trade-offs and prevent burden shifting.

The energy-driven routes, particularly thermal modification and pelletization, exhibited more stable environmental profiles and, in some cases, offered competitive performance compared with chemically intensive treatments. Their relative simplicity and predictable behavior position them as credible low-impact alternatives in specific configurations (e.g. pelletization) and as robust intermediate solutions for early-stage eco-design, especially when strong interfacial modification is not strictly required.

Methodologically, the work contributes a transparent and reproducible framework for process-level LCA of laboratory-scale pre-treatments. By reconstructing inventories from harmonized literature ranges and applying a functional unit explicitly linked to conditioning, the study strengthens the interpretative clarity of LCA for bio-based composite development. This approach aligns with emerging research that emphasizes upstream process modelling as a critical foundation for material sustainability assessment.

Future work should expand the integration between environmental and mechanical performance, allowing conditioning routes to be compared not only on environmental grounds but also on their contributions to composite functionality. Improved experimental reporting, including reagent dosages, washing steps and process yields, would also strengthen inventory precision. Finally, extending the analysis to include renewable energy options and additional bio-based reagents could clarify which design pathways genuinely enhance sustainability and which simply shift burdens across impact categories.

By embedding life cycle thinking directly within the pre-treatment stage, this study provides a robust foundation for eco-design strategies that aim to reconcile environmental responsibility with material performance in wood–plastic composites.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2026.108340.

Data availability

The data that support the findings of this study are available from the corresponding author, [RL], upon reasonable request. Supplementary Material is also available with background data, methodological details, and numerical results.

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