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Life cycle assessment of wood plastic decking manufacturing: Reduction of environmental impacts based on an industrial case study in China

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ABSTRACT

Climate change has spurred global efforts to mitigate carbon emissions, presenting significant challenges for the manufacturing sector in reducing the ecological footprint of its products. This study investigates a cradle-to-grave life cycle assessment (LCA) of wood–plastic decking, focusing on a Chinese facility with an annual production capacity exceeding 20,000 tons. The results indicate that raw material acquisition and key manufacturing processes—raw material premixing, pelletizing and co-extrusion are the primary contributors to environmental impacts. Transitioning from conventional energy sources (e.g., China's electricity grid) to solar energy could reduce global warming potential (GWP) by 38.9 %. While mechanical testing confirms the viability of recycled wood plastic composites (WPCs) for partial raw material substitution, its rheological properties limit broader reuse. The recycling process, though energy-intensive due to its high energy consumption during milling, the GWP remains 84.2 % lower than incineration. Sensitivity analysis revealed that varying recycling rates from 25 % to 100 % significantly reduced marine eutrophication potential, freshwater ecotoxicity potential, marine ecotoxicity potential, and human non-carcinogenic toxicity potential by up to 8 %, while long-distance maritime transportation (up to 20,000 km) increased impacts like ozone depletion and human health ozone formation potentials. In addition, the substitution rate of RP had a relatively large effect on environmental impacts, whereas the service life showed minimal influence. This study offers actionable insights for stakeholders in the wood-plastic decking industry to reduce their environmental impact without requiring substantial modifications to existing production processes.

1. Introduction

Wood plastic composites (WPCs) have garnered significant attention from both the scientific community and various industries due to their relatively environmentally friendly production processes, ability to incorporate recycled materials, and durable end-use applications (Balla et al., 2019). These materials exhibit several advantageous properties, such as low density, cost-effectiveness, resistance to moisture, rot, insects and fungi, and enhanced durability compared to natural wood (Yeh et al., 2021), making them a viable alternative to traditional timber in construction applications, particularly outdoor decking (Turku et al., 2017). The growing demand for traditional wood products, driven by the global shortage of forest resources (Ramli, 2024) and increasing concerns over the carbon footprint of building materials, highlights WPCs' potential as a sustainable solution that reduces deforestation and promotes resource efficiency. However, the widespread adoption of WPCs also presents significant challenges for end-of-life management. Their heterogeneous composition, combining hydrophilic wood fibres with hydrophobic thermoplastic, complicates recycling efforts and often leads to degradation, contamination and reduced material quality during reprocessing. As a result, most waste is currently diverted to landfills or incineration rather than closed-loop systems, necessitating innovative strategies to minimize environmental impacts and ensure long-term sustainability.

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Although several studies have explored the recycling of waste WPCs (Burgstaller and Renner, 2023), there are currently no commercial recycling programs specifically for waste composite decking materials. As a result, these materials often end up in landfills or are used for energy recovery (Zhao et al., 2022). Recycling WPCs offers significant environmental benefits, including waste reduction, conservation of raw materials, and extended carbon storage (Zhou et al., 2022). Moreover, waste recycling and circular economy initiatives are gaining momentum globally. For instance, the European Union has set ambitious targets to achieve a 50 % recycling rate for plastic waste by 2025 and 55 % by 2030 (European Commission, 2018). Similarly, the U.S. Environmental Protection Agency (EPA) released a national recycling strategy in 2021 to promote a circular economy (U.S. EPA, 2021). In the same year, China's National Development and Reform Commission outlined the "14th Five-Year Plan" for circular economy development, aiming to achieve a 60 % utilization rate of construction waste by 2025 (NATIONAL DEVELOPMENT AND REFORM COMMISSION, 2021). These initiatives underscore the growing emphasis on reusing and recycling materials, including WPCs, rather than disposing of them in landfills.

Despite this global momentum, research on the recycling of waste WPCs remains limited. Zhou et al. (2022) recycled end-of-life (EoL) high-density polyethylene (HDPE)-based WPC window profiles to produce ultra-high-filled wood fiber/polyethylene composites via conical twin-screw extrusion. The addition of maleic-anhydride-grafted polyethylene as a compatibilizer improved the tensile and flexural properties and creep resistance of the waste WPC introduced composites. To mitigate quality fluctuations caused by variable composition in waste wood-plastic decking, the concept of an "old-for-new" service was collaboratively developed by the wood-plastic decking manufacturer and our research team. The proposed initiative aims to leverage the sales and distribution network for the recycling of obsolete or discarded wood plastic decking, consumers receive discounts on new purchases as incentive for participation. By establishing a dedicated sales-and-recycling channel, critical information including the material type, service history, and environmental exposure can be systematically recorded. This information enables targeted classification and optimization of recycling processes, ensuring consistent feedstock quality. The decking in this study features a co-extruded structure: a functional outer layer enhances durability and aesthetics, while a core layer provides mechanical strength. Currently, the core layer predominantly incorporates recycled materials, driving the manufacturer's interest in expanding the use of recycled waste WPCs to replace virgin feedstocks. However, key challenges persist, including (1) variability in the processability of recycled WPCs due to degradation and contamination, and (2) the need to quantify the environmental benefits of this closed-loop system to validate its sustainability claims.

In this study, recycled waste wood-plastic decking was blended with virgin core-layer WPC materials at varying proportions to produce composite formulations. The flexural property, rheological behaviour, and morphological features of these composites were also systematically analyzed to assess the technical feasibility of recycled material substitution, providing empirical evidence on processability (e.g., energy demands from rheological changes) and performance parity (e.g., mechanical strength and microstructural integrity) with virgin materials. A "cradle-to-grave" life cycle assessment (LCA)was then performed using industrial production data to quantify the environmental impacts of the current life cycle of wood plastic decking. The scope was expanded to assess the implications of three waste management scenarios—recycling, landfilling, and incineration—alongside an evaluation of alternative energy sources to mitigate carbon emissions and other environmental burdens. By integrating material performance data with LCA outcomes, such as using rheological data to refine energy consumption estimates in recycling scenarios and mechanical/morphological findings to validate assumptions on product durability and replacement rates, this study aims to provide actionable insights for manufacturers to reduce the environmental footprint of wood-plastic decking through optimized recycling strategies and energy transitions.

2. Materials and methods

2.1. Raw materials

The recycled polyethylene-based WPC scrap (denoted by RP), sourced from co-extruded WPC deckings after 2–7 years of outdoor exposure (Fig. 1 (a)), has a density of 1.26 g/cm^3. The original core layer WPC material (denoted by WP), shown in Fig. 1 (b), has a density of 1.33 g/cm^3. Both materials were provided by Ningbo Helong New Material Co., LTD, Zhejiang Province, China.

The composition of the raw materials was determined based on data provided by the supplier, as detailed in Table 1. Because both the RP and WP materials were provided by the same supplier, it was assumed that all RP materials shared identical compositions. For the co-extruded WPC decking, the outer layer constituted 9 wt% of the total weight, while the core layer accounted for the remaining 91 wt%.

2.2. Sample preparation

Prior to mixing, the RP and WP materials were oven-dried at 80 °C for 12 h to remove residual moisture. Each formulation was then blended in the internal mixer of a torque rheometer (RM-200C, Harbin Hapro Electric Technology Co., Ltd, China) at a temperature of 190 °C for 10 min. The internal mixer is a chamber equipped with counter-rotating blades to achieve enhanced mixing of the composite materials, thereby simulating the mixing effect of an industrial-scale twin-screw extruder. Following mixing, the homogenized material was compression molded into 2 mm thick plates using a hydraulic press (GT-7014-H10C, Gotech Testing Machines Inc., China). The compression molding process involved maintaining the hot plates at 190 °C and subjecting the materials to a three-step procedure: pre-heating at 1 MPa for 6 min, pressing at 3 MPa for 4 min, and cooling under pressure at 3 MPa for 3 min. The molded plates were cut into 80 × 10 × 2 mm specimens for flexural testing. The compositions of the prepared samples are summarized in Table 2.

2.3. Formulation characterization

The inclusion of flexural strength/modulus, torque rheometry, and morphological analysis in this LCA is critical to holistically evaluate the viability of recycled WPC decking. Flexural properties directly determine structural performance and product longevity, where degradation from recycled materials could shorten service life, increasing replacement rates and lifecycle environmental impacts. Torque rheometry quantifies processability, as altered melt behavior in recycled feedstocks (e.g., degraded polymers or contaminants) elevates energy demands during manufacturing, directly linking material recyclability to production-phase emissions. Morphological studies (e.g., Scanning Electron Microscope/Transmission Electron Microscope) reveal microstructural flaws like poor fiber-matrix adhesion or filler agglomeration, which compromise mechanical durability and may necessitate additives or excess material use to meet standards, indirectly inflating environmental burdens. Collectively, these tests validate whether recycled WPCs achieve performance parity with virgin materials, ensuring environmental claims in the LCA are grounded in technical reality.

2.3.1. Flexural property

Flexural strength and modulus of the composites were evaluated in accordance with ISO 178 standard using a universal testing machine (TCS-2000NE, Gotech Testing Machines Inc., China). Tests were conducted under three-point bending mode at a crosshead speed of 2 mm min^{-1} and span of 64 mm. Ten specimens were tested per formulation to ensure statistical reliability; from these, the five closest data points were

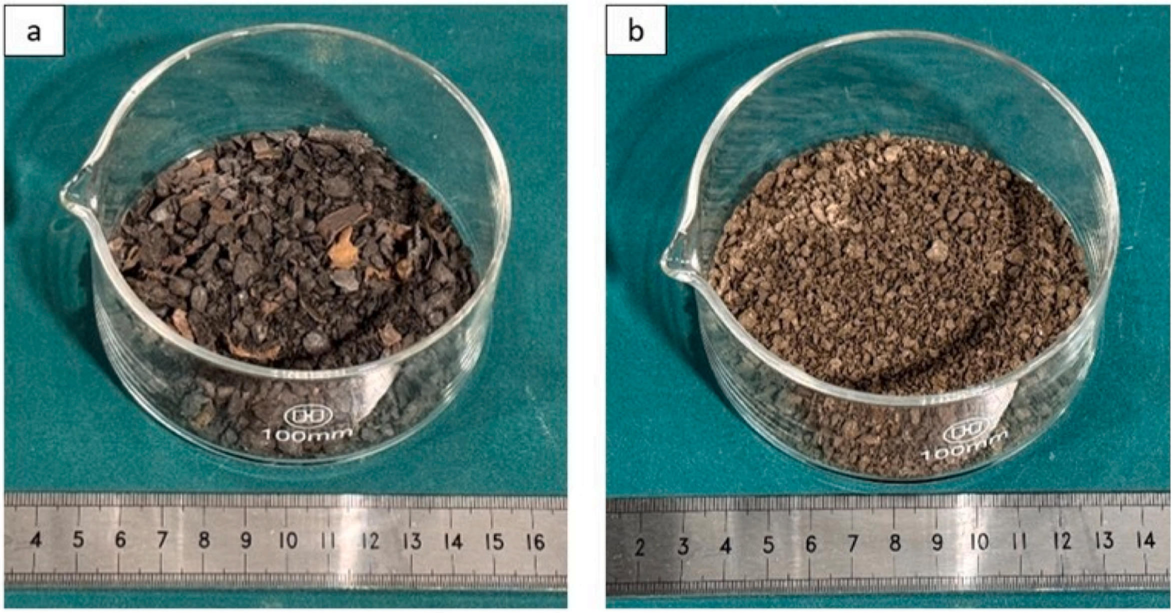

Fig. 1. a) recycled polyethylene-based WPC scrap (RP); b) core layer WPC material (WP).

Table 1
Composition of the outer layer and core layer materials.

Outer layer		Core layer	
Content	Weight fraction	Content	Weight fraction
High-density polyethylene (HDPE)	79.4 %	Recycled high-density polyethylene (RHDPE)	24.5 %
ultra-high molecular weight polyethylene (UHMWPE)	4.3 %	Maleic anhydride grafted polyethylene (MAPE)	4.5 %
Hollow glass beads (HGB)	8.6 %	Wood powder	63.1 %
UV absorber	4.0 %	Lubricant	3.2 %
Pigment	3.7 %	Talc	4.4 %
		Anti-oxidant	0.3 %

Table 2
The compositions of the blends.

Sample number	Sample code	WP (wt.%)	RP (wt.%)
1	WP_{100}	100	0
2	$WP_{75}RP_{25}$	75	25
3	$WP_{50}RP_{50}$	50	50
4	$WP_{25}RP_{75}$	25	75
5	RP_{100}	0	100

selected—with the coefficient of variation (CV) verified to be below 5 %—and used to generate error bars.

2.3.2. *Torque rheometry*

A torque rheometer (RM-200C; Harbin Hapro Electric Technology Co., Ltd., China) was used to determine the rheological property and extrusion ability of polymers of the composites. The mixed composite powder was fed into the internal mixer chamber and heated to 190 °C. The rheological behaviour of composite formulation was recorded at a constant rotor speed of 50 rpm for 10 min. Data acquisition commenced immediately following material loading to capture the complete melt-blending profile, encompassing torque variations and thermal stability. Three replicates per formulation were tested to ensure reproducibility, with results averaged to account for minor batch inconsistencies.

2.3.3. *Morphological study*

The morphology of the fracture surfaces of the composite was characterised by scanning electron microscope (SEM) (GeminiSEM360, ZEISS, Germany) in accordance with ASTM E986 guidelines. The acceleration voltage was set to 1.00 kV, the magnifications are 500×, 1000X and 2000X. The WPC samples were sputter-coated with 5 nm of gold before the SEM analysis to mitigate surface charging during imaging.

2.4. *Life cycle assessment*

2.4.1. *Methodology*

In this study, LCA was performed according to the ISO 14040 standard, which includes four parts: goal and scope, inventory analysis, life cycle impact assessment, and life cycle interpretation. The LCA is modeled by using the software SimaPro Power User, with the support of lifecycle inventory (LCI) databases of Ecoinvent 3 - allocation, cut-off by classification-system.

2.4.2. *Goal and scope*

The goal of this study was to perform a quantitative evaluation of the environmental burdens associated with industrial-scale wood plastic decking manufacturing through a cradle-to-grave LCA. The system boundary of the LCA is presented in Fig. 2.

This study employs a cradle-to-grave LCA framework to evaluate the environmental impacts of WPC decking production, segmented into three manufacturing phases (I, II and III), and explores the use stage (Phase IV) and post-consumer waste management strategies (Phase V). The functional unit (FU) defined for this study was 1 ton of wood plastic decking for a service life of 25 years to align with product warranty duration and requirements following both domestic and international standards (China, 2024, E.V.I. I. C. A. E., 2015).

To identify emission reduction opportunities, the energy demand of these phases was analyzed under three scenarios: reliance on China's conventional electricity grid, and transitions to wind or solar power. Phase V extends the analysis to EoL management, comparing three disposal pathways: landfill, incineration, and mechanical recycling (size reduction, reprocessing, and partial reintegration into production). Each pathway's environmental burden was quantified, with particular attention to energy consumption, global warming potential (GWP), and technical constraints such as rheological degradation in recycled

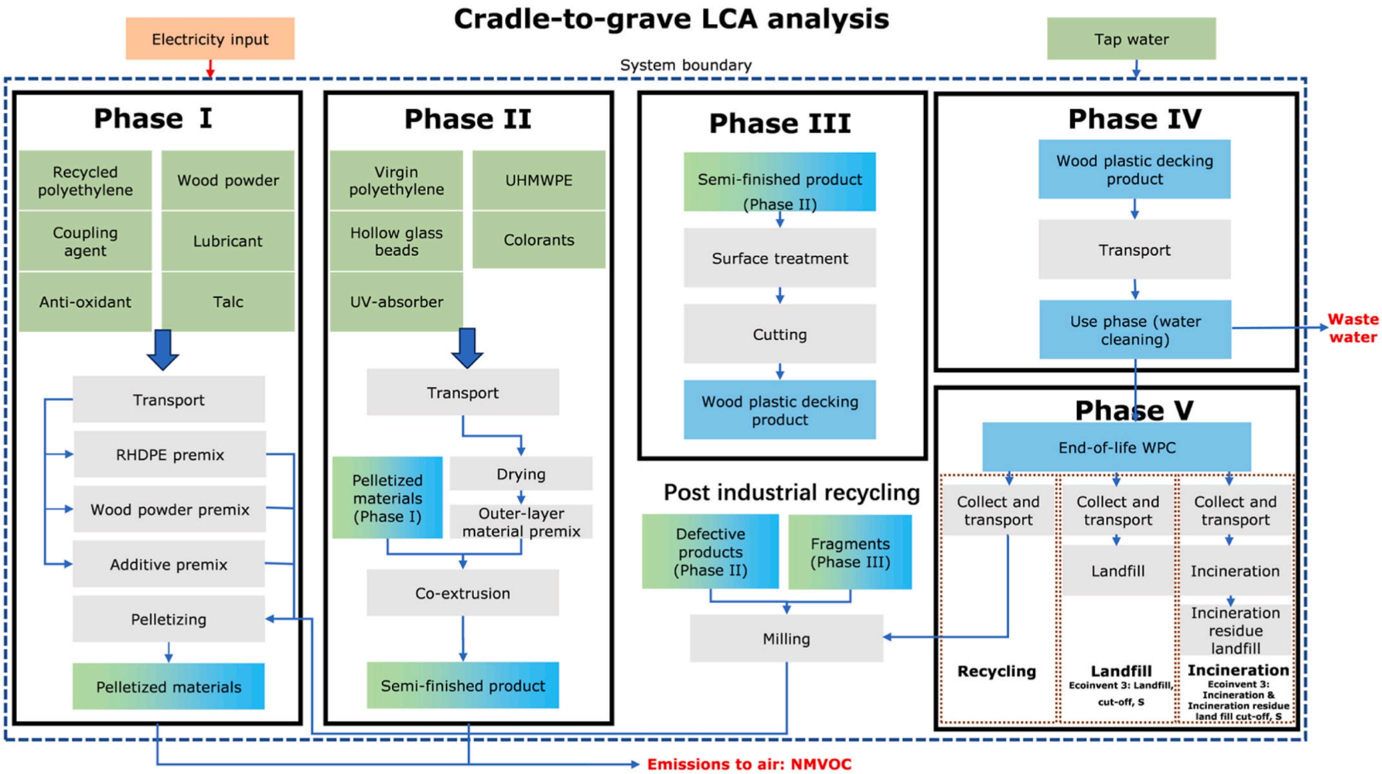

Fig. 2. The system boundary of the life cycle assessment (Green represents raw material inputs, blue represents final products, transition colour from green to blue represents intermediate product, orange represents energy input, grey represents process, brown represents waste disposal and red represent emission. Blue arrows illustrate material flow in the process and red arrow marks the energy flow.).

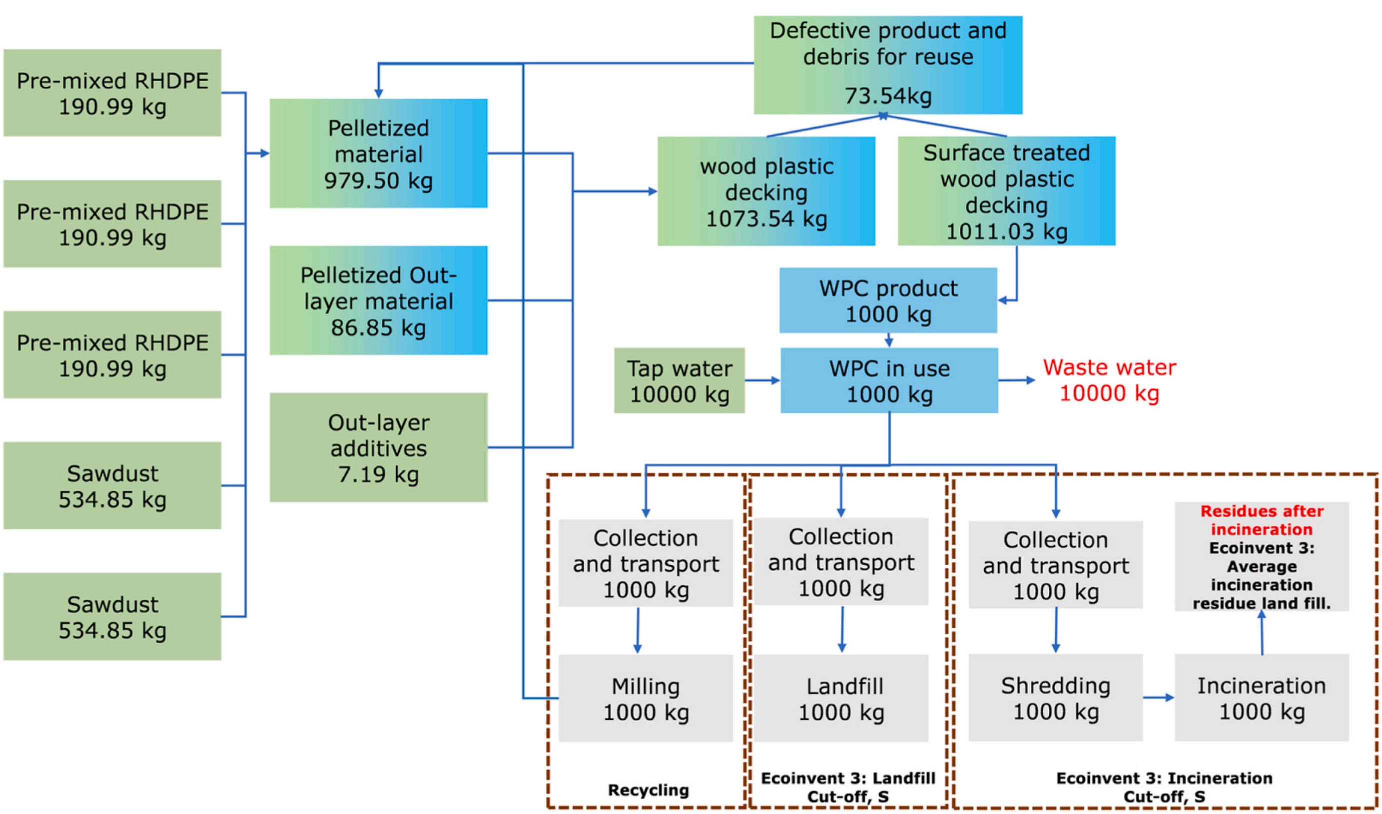

Fig. 3. Mass balance flowchart of wood plastic decking manufacturing process.

materials. This integrated approach enables a holistic assessment of sustainable strategies for WPC production and waste valorization.

Cradle-to-grave stages

- Phase I Raw materials were premixed to ensure uniform dispersion and pelletized to form the core layer materials for co-extrusion.
- Phase II The outer layer materials were dried and premixed, then it was co-extruded with the core layer materials prepared in Phase I to form semi-finished products.
- Phase III The semi-finished products were surface-treated to achieve a wood-like texture and cut into the desired dimensions to produce the final product.
- Phase IV The final product was transported from Ningbo to Taizhou. During the use phase, only tap water for cleaning was considered.
- Phase V Waste Treatment – Three EoL waste treatment scenarios were evaluated: landfill, incineration, and recycling. Landfill is set as the default disposal scenario. The recycling scenario is based on the existing industrial recycling system, which assumes that the EoL WPC can be milled and recycled as raw materials for new WPC manufacturing.

2.4.3. *Inventory analysis*

In this study, both primary and secondary data were utilized. Primary data for each stage of the wood plastic decking manufacturing process were collected through direct questionnaires administered to the manufacturer. The overall mass balance of the studied process was calculated based on 1 ton of wood plastic decking for a service life of 25 years, as shown in Fig. 3. The recycling modeling follows a cut-off allocation approach (Ekvall et al., 2020), with only the burdens of recycling processes being considered. No credits for avoided virgin material production are applied under this approach. Technical substitutability is limited by degradation risks (Antonopoulos et al., 2021), while market substitutability assumes partial displacement of virgin inputs in China's WPC sector, supported by initiatives like those in the EU JRC report (Garcia-Gutierrez et al., 2023) for formal recycling systems.

The secondary data is obtained from the database Ecoinvent 3.7.1–allocation, cut-off by classification–system. Recycled WPC is treated as a secondary raw material, entering the system burden-free from prior life cycles. Only the environmental impacts associated with the recycling processes are included, and no credits are given for avoided virgin material production. The specific details of these data are presented in Table 3. The details of the raw material source, composition, dataset selection in SimaPro and energy consumption in each phase are presented in supplementary data, Table S1–S3.

2.4.3.1. Mixing of the raw materials (Phase I). In Phase I, the recycled raw materials undergo a pre-mixing process to enhance material homogeneity before being extruded using a twin-screw extruder and subsequently pelletized. This process integrated three primary pre-mixed streams: pre-mix of recycled HDPE sourced from various origins, pre-mix of sawdust blended with lubricants, and a pre-mix of additives. The materials are stored in tanks and then pneumatically conveyed to the downstream stages. Material flows, energy inputs, transportation, and emissions are listed in Table 3.

2.4.3.2. Co-extrusion processes (Phase II). In Phase II, virgin HDPE and hollow glass beads are extruded to form the outer-layer material. Following pelletization, the materials were blended with pigments and anti-oxidant resin, dried, and co-extruded with Phase I pellets to produce wood plastic decking. During this process, air pollution primarily results from the emission of volatile organic compounds (VOCs), attributed solely to melt-processing. It was assumed that all air pollution

Table 3
Inventory data for producing 1 ton of wood plastic decking.

Phase I		
Inputs from technosphere	Amount	Unit
Polyethylene, high density, granulate, recycled	245.97	kg
Polyethylene, high density, granulate	44.66	kg
Maleic anhydride	0.45	kg
Sawdust, wet, measured as dry mass	609.73	kg
Palm oil, refined	31.91	kg
Tris(2,4-ditert-butylphenyl)phosphite	2.45	kg
Magnesium oxide	29.57	kg
Silica sand	14.76	kg
Electricity, low voltage	208.21	kWh
Transport		
Transport, freight, lorry >32 metric ton, EURO6	85.14	tkm
Transport, freight, lorry 16–32 metric ton, EURO6	188.49	tkm
Transport, freight, lorry 3.5–7.5 metric ton, EURO6	1.84	tkm
Emissions to air		
NMVOC, non-methane volatile organic compounds	0.005	kg
Phase II		
Inputs from technosphere		
Polyethylene, high density, granulate	78.71	kg
Foam glass	4.88	kg
Polypropylene, granulate	3.171	kg
Maleic anhydride	0.0033	kg
Palm oil, refined	0.08	kg
Polyethylene, linear low density, granulate	4.80	kg
Chemical, inorganic	1.54	kg
Chemical, organic	0.85	kg
Electricity, low voltage	352.17	kWh
Transport		
Transport, freight, lorry 16–32 metric ton, EURO6	3.73	tkm
Transport, freight, lorry 3.5–7.5 metric ton, EURO6	3.89	tkm
Emissions to air		
NMVOC, non-methane volatile organic compounds	0.008	kg
Outputs to technosphere: waste treatment		
Post industrial recycling-milling	51.48	kg
Inputs during waste treatment: Electricity, low voltage	7.32	kWh
Phase III		
Inputs from technosphere		
Electricity, low voltage	107.26	kWh
Outputs to technosphere: waste treatment		
Post industrial recycling-milling	22.06	kg
Inputs during waste treatment: Electricity, low voltage	3.14	kWh
Phase IV		
Inputs from technosphere		
Transport, freight, lorry 7.5–16 metric ton, EURO6	200	tkm
Tap water	10000	kg
Emissions to water		
Waste water	10000	kg
Phase V		
Scenario 1: Landfill	**Amount**	**Unit**
Municipal waste collection service by 21 metric ton lorry	50	tkm
Waste polyethylene, treatment of waste polyethylene, sanitary landfill	34 %	
Waste wood, untreated, treatment of, sanitary landfill	66 %	
Scenario 2: Incineration		
Municipal waste collection service by 21 metric ton lorry	50	tkm

(*continued on next page*)

Table 3 (*continued*)

Phase I		
Inputs from technosphere	Amount	Unit
Waste polyethylene, treatment of waste polyethylene, municipal incineration	34 %	
Waste wood, untreated, treatment of waste wood, untreated, municipal incineration	66 %	
Scenario 3: Recycling		
Transport, freight, lorry >32 metric ton, EURO6	200.00	tkm
Mechanical recycling, based on the post industrial recycling-milling	100 %	
Electricity, low voltage	142.13	kWh/ton recycling input

Note.
1. For Phase V, scenario 1 and 2, the percentage is calculated based on the content of wood plastic decking, the recycled HDPE, virgin HDPE, UHMWPE, and MAPE are classified as "waste polyethylene", the rest materials are classified as "waste wood".
2. Scenario 2: Incineration: energy recovery and the associated footprints of substituted electricity and heat were considered in this Ecoinvent datasets.
3. NMVOC emissions for Phases I and II were measured by a third-party certification body in the partner's phase-specific production buildings during routine certification checks.

originated from the melt-processing stage. VOCs emission data is derived from manufacturer emission testing reports: 0.005 kg/ton (Phase I) and 0.008 kg/ton (Phase II) of decking produced. NMVOC emissions for Phases I and II were measured by a third-party certification body in the partner's phase-specific production buildings during routine certification checks.

2.4.3.3. Post-treatment process (Phase III). In Phase III, the extruded wood plastic decking undergoes a two-stage surface treatment process with steel brush and sandblasting to achieve a rough texture resembling natural wood. Following the surface treatment, the final product was trimmed to the specified dimensions. Residual polyethylene from sandblasting and trimming is collected for recycling. This phase includes energy consumption from auxiliary systems, such as electrostatic and pulse dust removal, as well as cooling water treatment.

2.4.3.4. Distribution and use (Phase IV). While the products are generally marketed globally, this study focuses on a specific regional scenario for detailed analysis. The WPCs decking is manufactured in Cixi, Ningbo, with the target market in Taizhou, approximately 200 km away. Taizhou was strategically selected for its established sales and distribution network, which also offers a valuable opportunity to pilot the return of EoL WPC products to the manufacturing facility for recycling, supporting a circular economy model.

During the use phase, the WPC decking requires no external energy supply for its functionality, with the primary input being water for cleaning. Based on EPD International AB (2023) (ANHUI HONGSHANLIN et al., 2023), it is assumed that the decking is cleaned once per quarter, with each cleaning event for 1 ton of WPC (the functional unit) requiring 100 kg of tap water. Assuming a product lifespan of 25 years, the total tap water consumption over the entire use phase is calculated to be 10 tonnes per functional unit.

2.4.3.5. Disposal scenarios (Phase V). Three EoL scenarios, landfills, incineration, and recycling were modeled to represent potential disposal pathways for wood plastic decking. Landfill is set as the default disposal option. Specific Life Cycle Inventory (LCI) datasets for the treatment of WPC waste are not readily available in common databases. Therefore, modelling approaches based on the material's composition and available process data were adopted. The recycling process modeled in this study is based on the “Taizhou to Ningbo” collection and recycling scenario, waste WPC was collected in Taizhou and milled in Ningbo for recycling. This recycling process primarily involves shredding/milling the WPC, and the associated energy consumption for these operations has been included in the assessment. For the baseline scenario, a 100 % collection and milling rate for the received waste WPC was assumed, reflecting an idealized technical potential based on the internal system. The implications of varying recycling rates were explored in the sensitivity analysis.

A key challenge in adopting recycled HDPE is that recyclates are often more expensive than virgin materials due to collection, sorting, and reprocessing costs, which can limit market substitutability and hinder widespread implementation. However, WPC decking represents a promising application area for recycled HDPE, where these economic barriers are mitigated. The cost advantage of recycled HDPE used in WPC decking arises from two main factors: (1) the quality requirements for recycled HDPE in WPC decking are less stringent, as mechanical strength is bolstered by wood fiber fillers and the high-pressure extrusion process, allowing for the use of lower-grade recyclates without compromising final product performance; and (2) the wood powder premixing step enables recycled HDPE to be incorporated as shredded pieces or flakes, bypassing the energy-intensive pelletizing required in conventional HDPE recycling, thereby reducing processing costs. The proposed "old-for-new" take-back scheme further lowers expenses by facilitating the collection of end-of-life decking with minimal preprocessing (e.g., washing and shredding), incurring only dismantling and transportation costs and no material purchase costs, as the collected waste directly serves as feedstock, enhancing the economic viability of closed-loop recycling in this context.

2.4.4. Impact assessment

In this study, the ReCiPe method was utilized to evaluate environmental impacts at the midpoint level. The ReCiPe method is well-established and has been widely applied in LCA studies involving natural fiber-filled composites, plastic recycling, and composite waste treatment (Vassallo and Refalo, 2024; Gu et al., 2018). This assessment quantifies the effects of different waste management strategies and energy sources on the environmental footprint of wood plastic decking.

To explore potential reductions in environmental impacts, the energy source for the manufacturing process was modeled using both conventional energy (representing the current electricity mix in China) and renewable alternatives, specifically solar and wind power.

The contributions of the different processes to the environmental impacts are expressed using selected characterisation factors from the ReCiPe method. The following environmental labels are included in this study: global warming potential (GWP), stratospheric ozone depletion (ODP), ionizing radiation potential (IRP), ozone formation potential (OFP), Human health (HOFP), fine particulate matter formation (PMFP), terrestrial ecosystems (EOFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), terrestrial ecotoxicity potential (TETP), freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP), human carcinogenic toxicity (HTPn), human non-carcinogenic toxicity (HTPnc), land use potential (LOP), mineral resource scarcity (SOP), fossil resource scarcity (FFP) and water consumption potential (WCP).

2.4.5. Sensitivity analysis

The results of the LCA can be influenced by uncertainties and variations in input parameters. Therefore, a sensitivity analysis was conducted in accordance with ISO/TR 14049 (2012) guidelines to evaluate the robustness of the results within the defined system boundary. This analysis focused on the potential impacts of variations in key parameters including the recycling rate of waste wood plastic decking and the transportation distance for waste treatment. These parameters were selected due to their potential variability in real-world scenarios and their expected influence on the environmental profile.

National standard for green WPCs mandates a material recycling efficiency exceeding 98 %. In the baseline scenario, a 100 % collection and milling rate for the received end-of-life WPC was assumed, reflecting an idealized technical potential enabled by the take-back scheme organised by the producer. To evaluate the influence of recycling rates, sensitivity analysis was performed at recycling rates of 25 %, 50 %, 75 %, and 100 %. It is important to note that the 'recycling rate' analyzed here refers to the proportion of end-of-life WPC decking collected through the proposed 'old-for-new' take-back scheme, assuming non-recycled waste is landfilled. This simple ratio approach was employed because the scheme was piloted at a small scale, providing limited data to predict realistic collection rates; thus, exploratory variations (25–100 %) were used to broadly assess potential impacts. This collection rate determines the volume of available recycled feedstock but is distinct from the 'material substitutability'—the feasible blending ratio of recycled WPC in new formulations—which is constrained by technical properties evaluated in our experiments. The recycling scenario in this case study is based on the established trial program involving the collection of EoL WPC decking in Taizhou and its subsequent road transportation approximately 200 km back to the manufacturing facility in Ningbo. However, a substantial volume of WPC products manufactured in this facility is exported to international markets, include Europe, USA, Australia and the Association of Southeast Asian Nations (ASEAN). To assess the environmental implications of potential global take-back and recycling schemes for these exported products, a sensitivity analysis was conducted. This analysis specifically investigates the effect of long-distance maritime transportation on the overall environmental performance of the recycling scenario. To this end, the return transportation distance for EoL WPC decking from overseas markets to the Ningbo recycling facility was varied in the analysis. The distances selected for this sensitivity analysis are 0 km, 5000 km, 10,000 km, and 20,000 km, using maritime freight as the mode of transport. The dataset selected for transportation is "Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship". This exploration aims to understand the extent to which transportation impacts might offset the benefits of recycling EoL products from distant markets.

Based on the torque rheometry results, it can be observed that replacing WP with RP leads to a corresponding increase in torque during the extrusion process. The relationship between torque and power consumption can be expressed as:

$$P = \tau \cdot \omega$$

where P is the motor power (W), τ is the torque (N·m), and ω is the rotational speed (rad·s^{-1}) (Deng et al., 2012). Under steady operating conditions, the supply voltage is approximately proportional to the rotational speed, while the current is proportional to the developed torque. When the rotational speed remains constant, power consumption increases proportionally with torque (Deng et al., 2014; Godavarti and Karwe, 1997), resulting in higher electricity demand and consequently greater environmental impacts. To evaluate this effect, a sensitivity analysis was conducted for RP substitution ratios of 0 %, 25 %, and 50 %. In addition, to account for the potential durability reduction arising from the use of recycled materials, a sensitivity analysis was performed with assumed service lives of 5, 15, and the standard 25 years, in order to assess the influence of WPCs service life on the overall environmental impacts.

2.4.6. Uncertainty analysis

Due to the uncertainties that may arise from the complex supply chain for recycled HDPE, for the stages involving the use of recycled HDPE. A Monte Carlo simulation (5000 runs) was conducted in SimaPro to account for variability in key parameters. Uncertainty distributions were assigned to reflect data quality fluctuations in recycled materials and process energy demands. Specifically, the effective content of recycled HDPE was modeled with a triangular distribution (Min = 0.8 Mass, Mode = 1Mass, Max = 1.2 Mass) to represent ±20 % purity variation. For electricity and thermal energy consumption during processing, a lognormal distribution with ±30 % variability was applied to capture the influence of impurities on processability. This range is based on empirical data from industrial production. The simulation results are reported as mean values with 95 % confidence intervals, thereby providing a more robust comparison between recycling and disposal scenarios.

3. Results and discussion

3.1. Flexural properties

The flexural properties of the WP/RP composites are shown in Fig. 4.

The incorporation of RP content enhanced both the flexural modulus and flexural strength of wood plastic decking. Specifically, the flexural modulus and flexural strength of RP100 were 23.1 % and 53.6 % higher, respectively, than WP100. The primary distinction between RP and WP lies in their composition: RP comprises both the outer and core layer materials of wood-plastic composites (WPCs), whereas WP consists solely of core layer materials. The outer layer primarily consists of polyethylene (>83 wt%), along with colorants, UV absorbers, and antioxidants. The superior flexural performance of RP100 likely results from the high resin content, as the outer layer is mainly consists of high-performance polyethylene, which is miscible with the core layer polyethylene. Due to the high content of wood powder in WP100, the incompatibility and immiscibility between the polyethylene matrix and wood powder lead to the low flexural performance (Turku et al., 2017). Previous studies have reported that the volume of voids within the matrix is positively correlated with fiber content (Gu et al., 2018). Higher void content in WP-rich formulations, driven by increased fiber content, correlates with mechanical failure under flexural stress. These findings confirms that recycled polyethylene-based WPC scrap is a viable substitute for virgin core layer materials, supporting closed-loop recycling in WPC manufacturing with minimal environmental impact, as it reduces the need for virgin polyethylene production. It should be noted that the superior flexural properties observed in RP100 blends may not persist after installation and during the decking's service life. The inclusion of recycled components could accelerate aging due to weathering (e.g., UV exposure and moisture cycling) and in-use conditions (e.g., creep or impact loading), potentially compromising long-term performance.

3.2. Torque rheometry

Torque rheometry, which measures melt behavior during processing, is critical for assessing the energy demands of WPC manufacturing, a key factor in life cycle emissions. Rheological property of WPC composites is closely associated with particle rigidity and size (Mu et al., 2021). Torque and temperature profiles are shown in Fig. 5. Results for equilibrium melt temperature (T_e) and equilibrium torque (M_a), averaged between 9 and 10 min, are recorded in Table 4.

As illustrated in Fig. 5, both T_e and M_a at steady state increased with

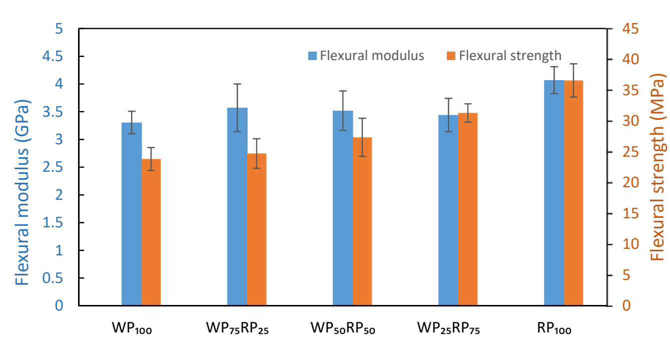

Fig. 4. The flexural properties of the WP/RP composites.

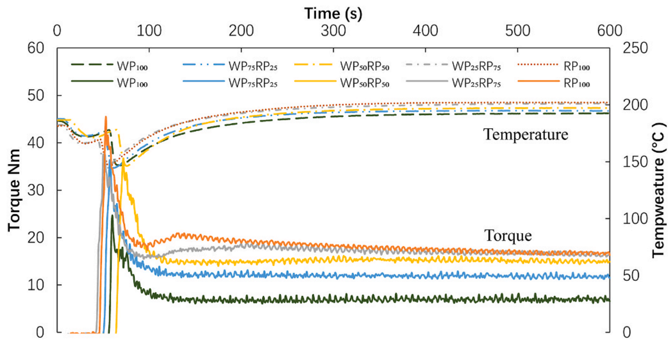

Fig. 5. Torque and temperature curves of the WP/RP composites.

Table 4
Equilibrium torque and equilibrium melt temperature of WP/RP blends.

Sample number	Sample code	M_a (Nm)	T_e (°C)
1	WP_{100}	7.0	192.5
2	$WP_{75}RP_{25}$	11.8	194.7
3	$WP_{50}RP_{50}$	14.9	197.3
4	$WP_{25}RP_{75}$	16.4	201.1
5	RP_{100}	16.7	202.1

higher RP content. The rise in T_e with increasing RP content reflects increased shear heating from friction between the molten WP/RP composites, the chamber wall, and the rotor, driven by the composition of each formulation (Feng et al., 2017; Saddem et al., 2018). For wood flour/HDPE composites, equilibrium torque normally increases with higher wood flour and lower lubricant content (Feng et al., 2017). Despite the wood powder content in WP being 18 % higher than that in RP due to the presence of an outer layer, the equilibrium torque of RP was observed to be 139 % higher than that of WP. Elevated equilibrium torque likely stems from degraded or absent lubricants in the recycled composites and the presence of UHMWPE from the outer layer of the decking. The reduced lubricant content in WPC formulations has been shown to increase melt torque and viscosity (Bettini et al., 2013; Saddem et al., 2019; Dai et al., 2019), while UHMWPE presence elevates processing resistance due to its high viscosity, even in blends with HDPE or PP (Rice et al., 2025; Liu et al., 2015). Molecular weight degradation is also a common factor in recycled WPCs, leading to altered rheological behaviour (Ramırez-Vargas et al., 2004; Petchwattana et al., 2012). These findings highlight a trade-off: while RP supports recycling, its higher energy requirements during processing elevate production-phase emissions, necessitating optimized formulations or lubricant restoration to align with carbon reduction goals.

3.3. Morphological analysis

Micrographs of the flexural fracture surfaces of the WP/RP composites are shown in Fig. 6.

As illustrated in Fig. 6, the SEM micrographs of the fracture surfaces of WP_{100}, $WP_{50}RP_{50}$, and RP_{100} reveal consistent microstructural characteristics. All samples exhibit gaps and voids on the fracture surfaces, resulting from the pull-out of wood fibers, indicating weak interfacial bonding between the polyethylene matrix and wood powder. This poor adhesion, a primary cause of reduced mechanical performance, aligns with the lower flexural strength of WP100 observed in flexural property testing. To enhance the mechanical properties, the incorporation of a coupling agent into the matrix could be considered as a potential solution (Ramli, 2024). These microstructural defects increase the likelihood of premature failure, potentially shortening product lifespan and elevating lifecycle environmental impacts through higher replacement rates. Incorporating coupling agents could enhance fiber-matrix adhesion, improving durability and reducing material waste. For recycled WPC, addressing these flaws is critical to achieving performance parity with virgin materials, ensuring that recycling reduces environmental impacts without compromising product quality in closed-loop manufacturing.

The experimental analyses provide critical empirical support for the LCA by quantifying the technical viability of recycled WPC substitution and its environmental trade-offs. Flexural testing demonstrates that recycled blends (RP) can enhance initial mechanical performance, with RP100 exhibiting 23.1 % higher modulus and 53.6 % higher strength than virgin WP100, supporting acceptable substitution fractions up to 50 % (e.g., WP50RP50) for decking applications without compromising structural integrity. However, rheological results reveal a derived technical substitutability limit of approximately 50 %, as higher RP ratios (e.g., 100 %) increase equilibrium torque by 139 %, implying elevated processing energy demands (e.g., 20–30 % higher in LCA Phases I/II due to shear heating and lubricant degradation). Morphological insights further identify restrictions, such as voids indicating weak fiber-matrix adhesion, which may accelerate weathering and reduce service life, potentially offsetting recycling benefits through increased replacement rates not fully modeled here. Overall, these findings refine LCA assumptions on energy consumption and durability, emphasizing the need for additives to expand substitutability while maintaining sustainability gains.

3.4. Life cycle assessment

3.4.1. Cradle-to-grave results

Fig. 7 presents the contribution of Phase I to Phase V in the “cradle-to-grave” analysis of 1 ton of wood plastic decking, the default disposal scenario is landfill.

Among the process stages, Phase I is identified as the predominant contributor to the overall environmental impact, representing 52.4 % on average across all environmental impact categories. This phase exhibits notably high values in terms of FEP and LOP. The energy-intensive processing activities, including raw material premixing and pelletizing, are primarily responsible for the elevated FEP due to emissions associated with fossil fuel-derived emissions from China’s electricity mix. Additionally, the high LOP can be attributed to the long-distance transportation of materials, the land use required for infrastructure such as roads, and the volume of materials occupying land resources (Gu et al., 2018). Phase II, which encompasses the acquisition of outer layer materials and the energy-intensive co-extrusion process, also constitutes a significant source of environmental burden. Collectively, Phases I and II account for over 75 % of the total environmental impact across all assessed impact categories. In contrast, Phase III, which involves low-energy post-treatment processes, has negligible impacts due to minimal resource use and emissions. TETP is the most significant impact on Phase IV, which is mainly because of the emission during the transportation from the manufacturer to end user. For Phase V, the landfill has the highest impacts on MEP, FETP, METP and HTPnc, it is mainly caused by landfill leachate and gas (Postacchini et al., 2018; Melnyk et al., 2015).

To mitigate environmental impacts in the future, prioritized strategies include: (1) substituting raw materials with alternatives that exhibit lower environmental footprints, (2) sourcing materials locally to shorten transport distances, and (3) improving the energy efficiency of the extrusion process. A feasible strategy to achieve these objectives involves sourcing raw materials from local suppliers and advancing rapid prototyping technologies to optimize material utilization and processing efficiency. However, the implementation of these improvement measures is heavily contingent on the existing supply chain structure of wood-plastic manufacturing, which limit short-term feasibility. In this context, transitioning the current energy source (e.g., China’s electricity mix) to cleaner alternatives, such as solar or wind power, offers a more immediate solution to lower GWP and other impacts, as detailed below.

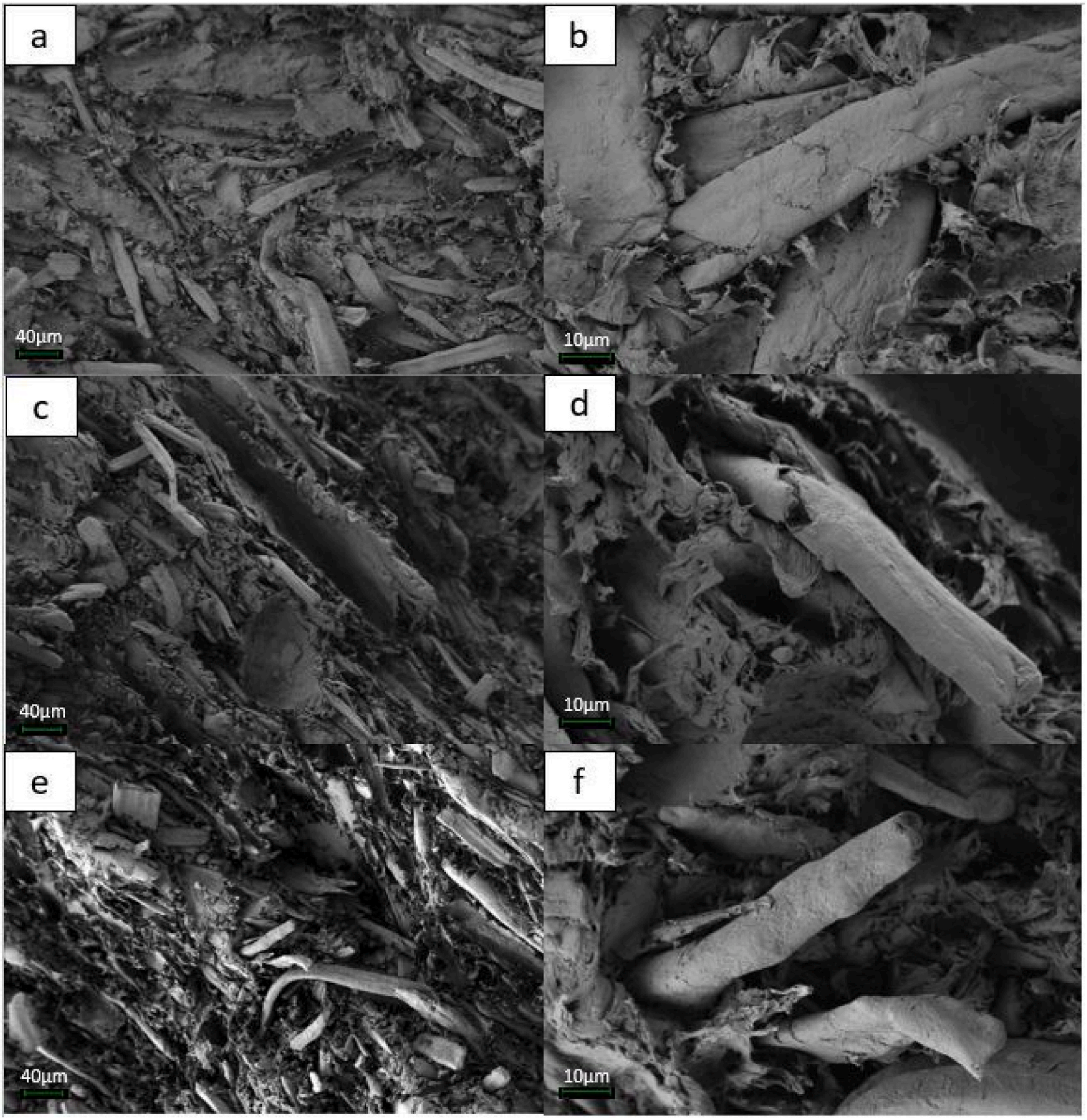

Fig. 6. SEM micrographs of the flexural fracture surfaces of a,b)WP_{100}; c,d)$WP_{50}RP_{50}$; and e,f) RP_{100} composites.

3.4.2. Effect of energy source

Wind and solar energy are among the most promising renewable alternatives to fossil fuels for achieving carbon neutrality in China (Liu et al., 2022). With the rapid advancement of solar panel and wind turbine technologies, the transition to sustainable energy sources in wood-plastic decking manufacturing has become increasingly feasible. Fig. 8 illustrates the environmental impact of replacing conventional energy sources with either solar or wind power.

The results indicate that switching from conventional energy (electricity mix, China) to solar energy reduces GWP by 38.9 %, driven by minimal emissions over solar panels' service life compared to continuous fossil fuel combustion. Solar energy outperforms conventional energy across most impact categories but shows elevated TETP and stratospheric ozone depletion potential (SOP) due to mineral extraction for glass components in panel manufacturing (Zahedi et al., 2022). In the case of wind energy, the GWP is 24.5 % lower compared to conventional energy, though it is 23.5 % higher than solar. In addition, wind energy exhibited the lowest environmental impact in MEP, TETP, HTPc, HTPnc, and LOP. Despite these advantages, wind power recorded the highest FETP, METP, FFP, and WCP among the three options. This can be attributed to the complex manufacturing process of wind turbine blades, which involves chemical treatments for blade sealants, material-intensive tower construction, and fossil fuel usage in the welding process (Alsaleh and Sattler, 2019). Solar energy thus offers the

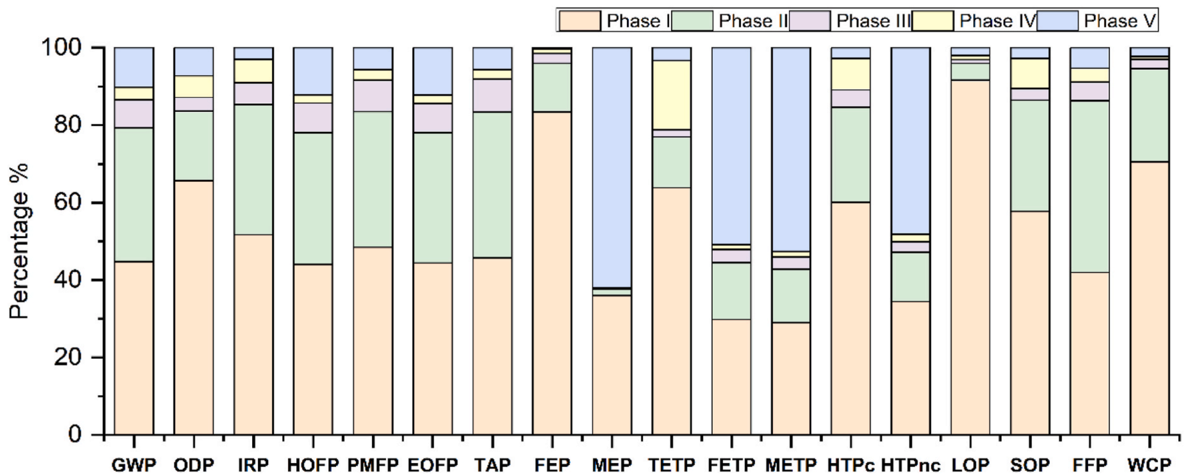

Fig. 7. Inventory contributions to the normalized results at midpoint level (ReCiPe) for wood plastic decking manufacturing process, per functional unit.

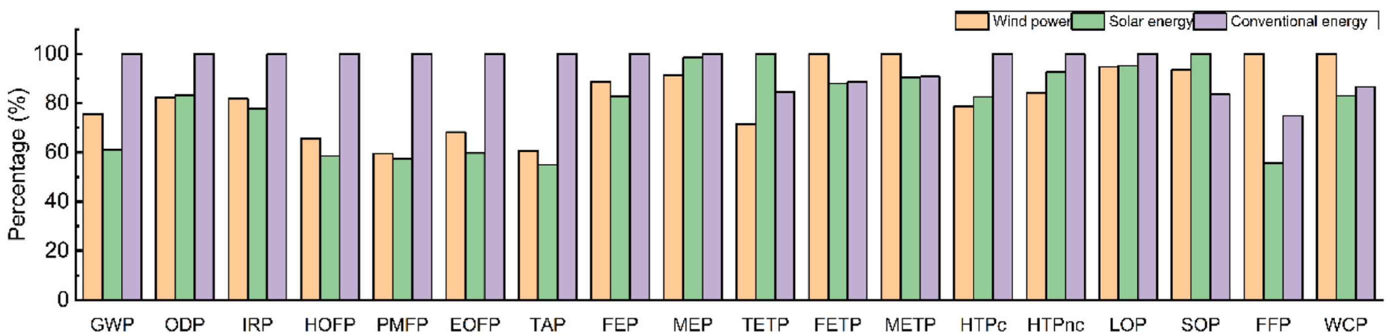

Fig. 8. Environmental impacts associated with the three energy sources (Phase I, II and III).

greatest GWP reduction potential for WPC manufacturing, aligning with China's carbon neutrality goals. Since all manufacturing phases currently rely on the same conventional energy mix (China's electricity grid), substituting renewables (solar or wind) across the process results in proportional reductions in environmental impacts, scaled by each phase's energy consumption share. Thus, the overall GWP reduction distributes linearly without phase-specific variations, avoiding redundant differentiation in the main analysis.

3.4.3. Effect of disposal scenarios

End-of-life scenarios—landfill, incineration, and recycling—were assessed for environmental impacts. Landfill remains one of the most commonly employed waste management strategies for wood-plastic composites (Shahani et al., 2021). However, increasing environmental awareness has led to greater complexity in selecting appropriate landfill sites, posing significant challenges for decision-makers. The selection process must account for a range of environmental, economic, and social factors to ensure sustainable landfill placement (Rezaeisabzevar et al., 2020). Fig. 9 presents the environmental impact results of landfill, incineration and recycling.

Landfill scenario shows remarkable high impact on MEP and non-carcinogenic human toxicity potential (HTPnc). Landfill leachate can contribute to nitrogen enrichment in seawater, thereby increasing MEP (Postacchini et al., 2018). In addition, persistent organic pollutants (POPs) may be released to the environment through landfill gases and leachates (Melnyk et al., 2015). Its high LOP reflects significant land use requirements.

Incineration scenario has remarkable high impact on GWP, ODP,

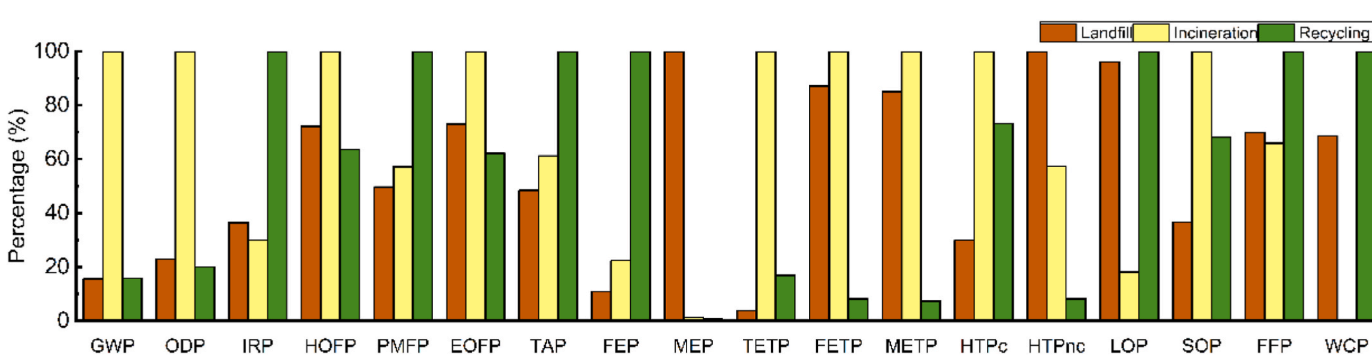

Fig. 9. Environmental impacts at midpoint level (ReCiPe) for three wood plastic decking disposal scenarios (landfill, incineration and recycling), per functional unit (Phase V).

TETP, FETP, METP, HTPc, and SOP, driven by high carbon dioxide emissions associated with plastic incineration (Khan et al., 2021). The combustion process not only releases greenhouse gases and ozone-depleting substances but also contributes to terrestrial and freshwater ecotoxicity, leading to the high ODP, TETP, FETP and METP. The high OFP related HOFP and EOFP may be attributed to the transportation emissions (Guzman et al., 2025). Moreover, the incineration of certain halogenated organic compounds as additive can lead to the formation of hazardous byproducts particularly in cases where filtration systems are inadequate (Sommerhuber et al., 2017). This hazardous gas contributes to the high HTPc. The high SOP can be explained due to the low calorific value of the municipal solid wastes, a certain amount of auxiliary fuel are required to be added to improve the incineration (Bujak et al., 2018).

Recycling, while energy-intensive due to milling (43.7 % higher GWP than landfill), achieves an 85 % lower GWP than incineration. High energy consumption in recycling, reliant on China's fossil-based grid, elevates IRP, HOFP, PMFP, EOFP, FEP, FFP and WCP. Nevertheless, since the recycling process repurposes all waste wood-plastic decking, it preserves raw manufacturing materials and avoids the production of secondary pollutants. As a result, this method presents a more sustainable waste treatment alternative compared to landfill and incineration.

3.4.4. Sensitivity analysis

The influence of varying recycling rates (25 %, 50 %, 75 %, and 100 % of waste wood-plastic decking directed to recycling instead of landfill) on environmental impacts is presented in Fig. 10 (a).

The model evaluation results indicate that the recycling rate significantly affects MEP, FETP, METP, and HTPnc. The influence on the remaining environmental indicators was below 8 %. This finding is consistent with the EoL modelling, where landfill (the alternative to recycling in this analysis) demonstrates a more pronounced impact on aquatic ecosystems and certain human toxicity endpoints, contributing to elevated eutrophication and ecotoxicity potentials.

The effects of varying maritime transportation distance (0 km, 5000 km, 10000 km, and 20000 km) on environmental impacts are shown in Fig. 10 (b). The results indicate that ODP, HOFP, PMFP, EOFP, TAP, HTPc and SOP is very sensitive to the long-distance maritime transportation. Fuel consumption and materials consumption are the major factors contribute to the environmental impact of maritime transportation (Dong and Cai, 2019). The primary emissions from the ship are released exhaust gases, which include CO_2, PM, CH_4, NO_x and N_2O (Dong et al., 2023).

The evaluation of effects of RP substitution rate are shown in Fig. 11 (a). It shows that increasing RP content leads to higher electricity consumption. This significantly affects most environmental indicators, while the impacts on FEP, MEP, TETP, LOP, and WCP are relatively minor. This trend can be attributed to the higher equilibrium torque observed in experiments. Higher torque implies greater energy demand during both pelletizing and product extrusion stages. However, as shown in Fig. 9, recycling also provides environmental benefits that can partially offset this effect. A balanced recycling strategy should focus on reducing extrusion energy demand. This can be achieved by improving material compatibility, optimizing formulation design, or adopting more energy-efficient extrusion systems.

The sensitivity analysis for different service lives indicates that variations in product service life have little effect on most environmental impact indicators, with differences of no more than 5 % observed only in IRP, HTPc, and SOP. These effects are primarily associated with the use phase of WPCs, while differences during the manufacturing phase are negligible. Therefore, products manufactured with RP can substitute for virgin products without causing significant environmental impacts.

In the sensitivity analysis, it is presumed that waste wood-plastic decking is transported back to Ningbo for recycling, which would elevate both the economic and environmental costs of the process. However, in practice, manufacturers could leverage existing sales networks and 'old-for-new' programs to collect discarded wood-plastic decking while forming partnerships with local wood-plastic producers to facilitate recycling. This approach would enable localized recycling of wood-plastic decking, reducing logistical and sustainability impacts.

3.4.5. Uncertainty analysis

Monte Carlo simulations were performed for each disposal scenario,

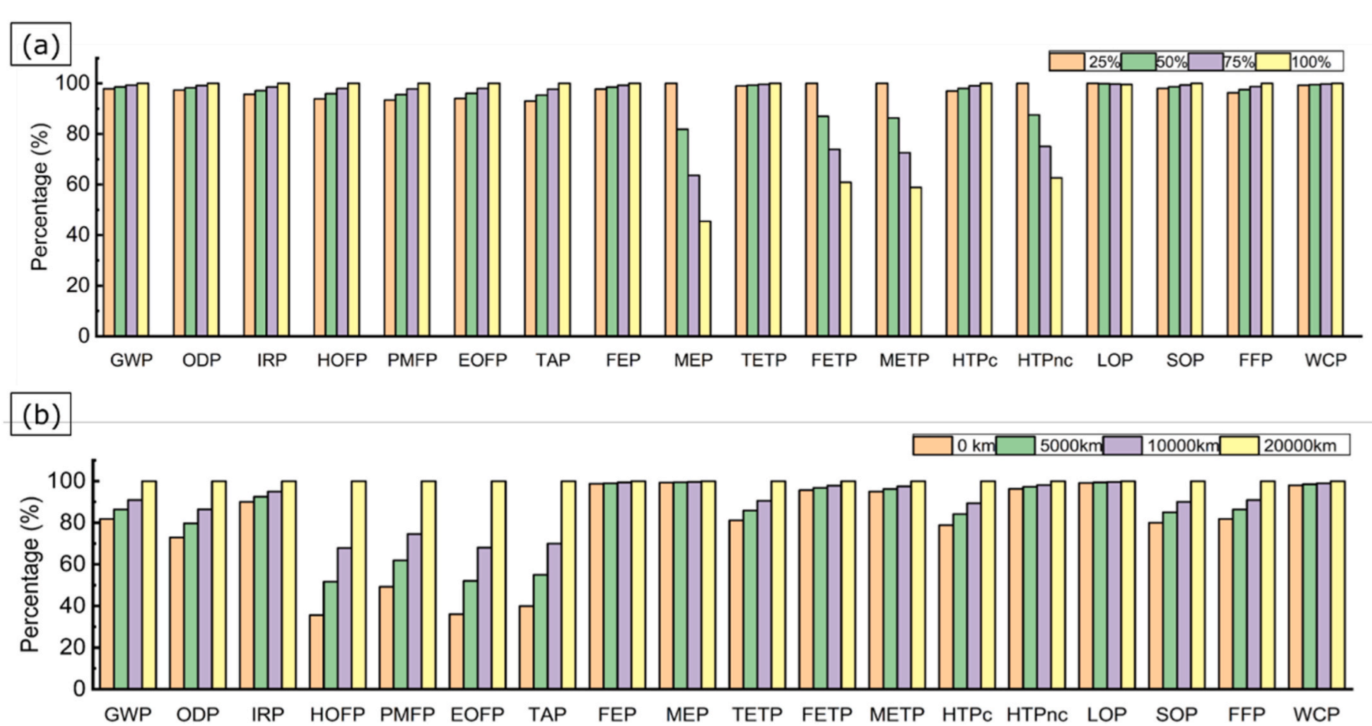

Fig. 10. Environmental impacts associated with (a) different recycling rates; (b) four transportation distances.

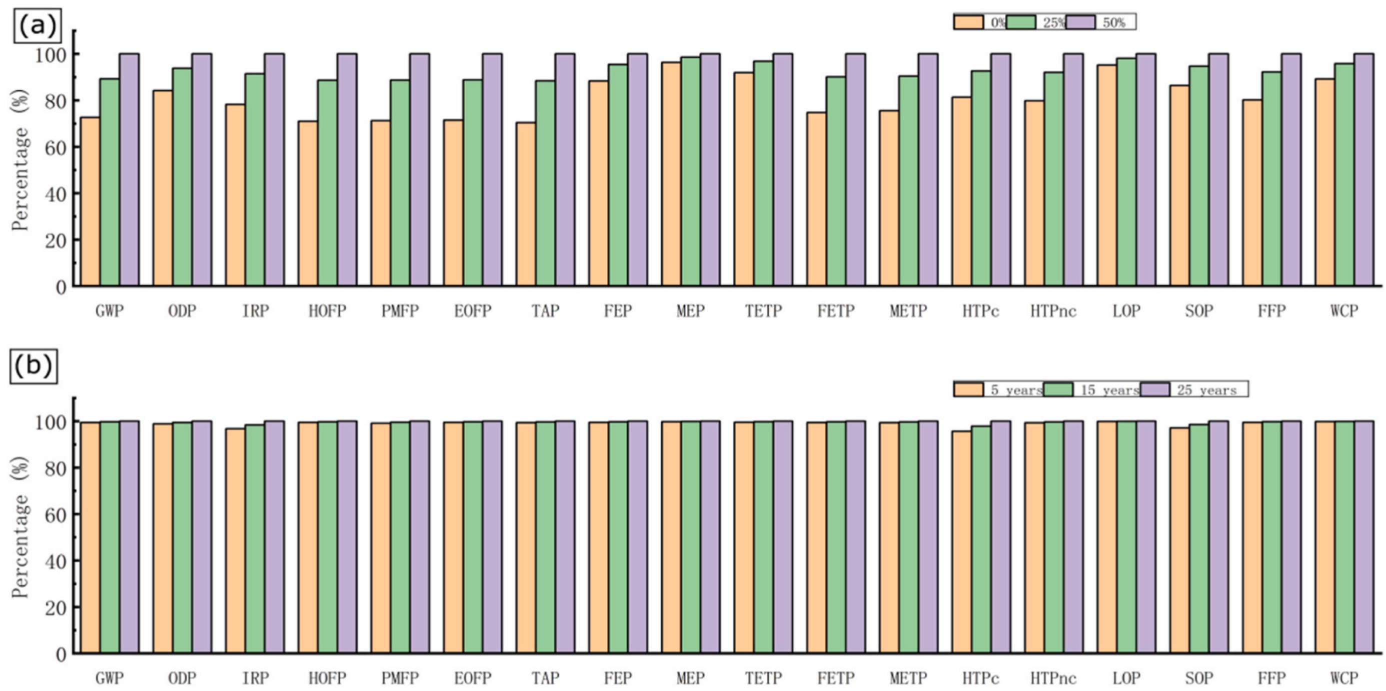

Fig. 11. Environmental impacts associated with (a) different RP substitution rate; (b) different service life.

and the resulting 95 % confidence intervals (CI) of GWP are presented in Fig. 12. Despite the presence of uncertainties, the results consistently indicate that GWP for the recycling scenario is approximately equal to that of the landfill scenario, and both are lower than the GWP for the incineration scenario. These findings align with those based on point estimates, suggesting that variations in the quality of recycled HDPE do not significantly affect on the comparative results across the disposal scenarios.

4. Limitation of the study

This LCA is based on specific operational data from an industrial-scale facility producing over 20,000 tons of wood-plastic decking annually, with processing data collected for year 2023. While this provides a robust basis for a case-specific LCA, several limitations should be acknowledged:

A primary limitation relates to the LCI data for recycled polyethylene (PE), a key raw material. The supply chain for recycled plastics is inherently complex, characterized by diverse sourcing and inconsistent material quality. Unlike virgin plastics, recycled plastics are sourced from various collection sites, often small-scale recycling facilities, and originate from diverse sources. Additionally, the quantity of reprocessed plastics available from suppliers fluctuates across different months. Due to these inconsistencies, manufacturers are often required to procure recycled polyethylene from multiple suppliers. In this study, the generic Ecoinvent dataset “Polyethylene, high density, granulate, recycled (Deng et al.)| market for polyethylene, high density, granulate, recycled| Cut-off, S” was used to represent the average conditions, particularly aiming to reflect circumstances in developing countries. This choice, however, introduces uncertainty, as discrepancies may exist between this global dataset and the specific regional supply chain characteristics encountered by the manufacturer in China. While it was posited that a lack of technological advancements in the mechanical recycling sector over an extended period might lead to a degree of convergence between dataset characteristics and typical real-world operations, this remains an assumption and the uncertainty associated with regional specificity persists.

The second limitation arises from the scarcity of specific LCI datasets for the waste treatment options for wood-plastic composites. To address this, proxy modelling based on the WPC’s primary composition (34 % polyethylene and 66 % wood fiber by weight) was employed for landfill and incineration scenarios. Correspondingly, Ecoinvent datasets for "waste polyethylene" and "untreated waste wood" were used in these weighted proportions for both landfill and incineration scenarios. This approach, while common in LCA for composite materials, is less precise than using data from facilities specifically processing WPC waste.

Additional constraints stem from the selection of energy sources and sensitivity analysis. The assessment of renewable energy substitution utilized a wind power dataset from SimaPro specified for "high voltage" (>24kv) supply. This may not accurately capture the environmental profile of wind-generated electricity supplied directly to a manufacturing facility at a lower voltage, potentially omitting certain grid interaction effects or different infrastructure requirements. In terms of the scope of recyclability assessment, the primary data for the WPC recycling process were based on the manufacturer’s trials using a limited quantity of collected WPC waste. While these trials indicated that incorporating small proportions of this recycled material into the polymer matrix did not significantly impair the mechanical properties of the final product (consistent with the abstract’s note on rheological limitations for broader reuse), the assessment of recyclability at higher incorporation rates or after multiple recycling loops requires further investigation. A further limitation is the uniform assumption of a 25-year service life for the functional unit across all scenarios, which may not accurately reflect real-world usage, particularly for products incorporating recycled content from the take-back scheme. As the recycled material includes a mix of HDPE-based decking from various manufacturers with different service times, acquiring accurate service life information was not feasible, and thus the LCA model did not integrate impacts from potential higher replacement rates. Although our rheological and flexural tests verified that recycled polyethylene-based WPC (RP) can replace virgin core layer material (WP) with superior initial performance, future studies should incorporate sensitivity analyses on varying lifespans and long-term durability testing for more robust evaluations.

These limitations highlight areas where further research would be beneficial. Specifically, developing regionalized LCI data for recycled

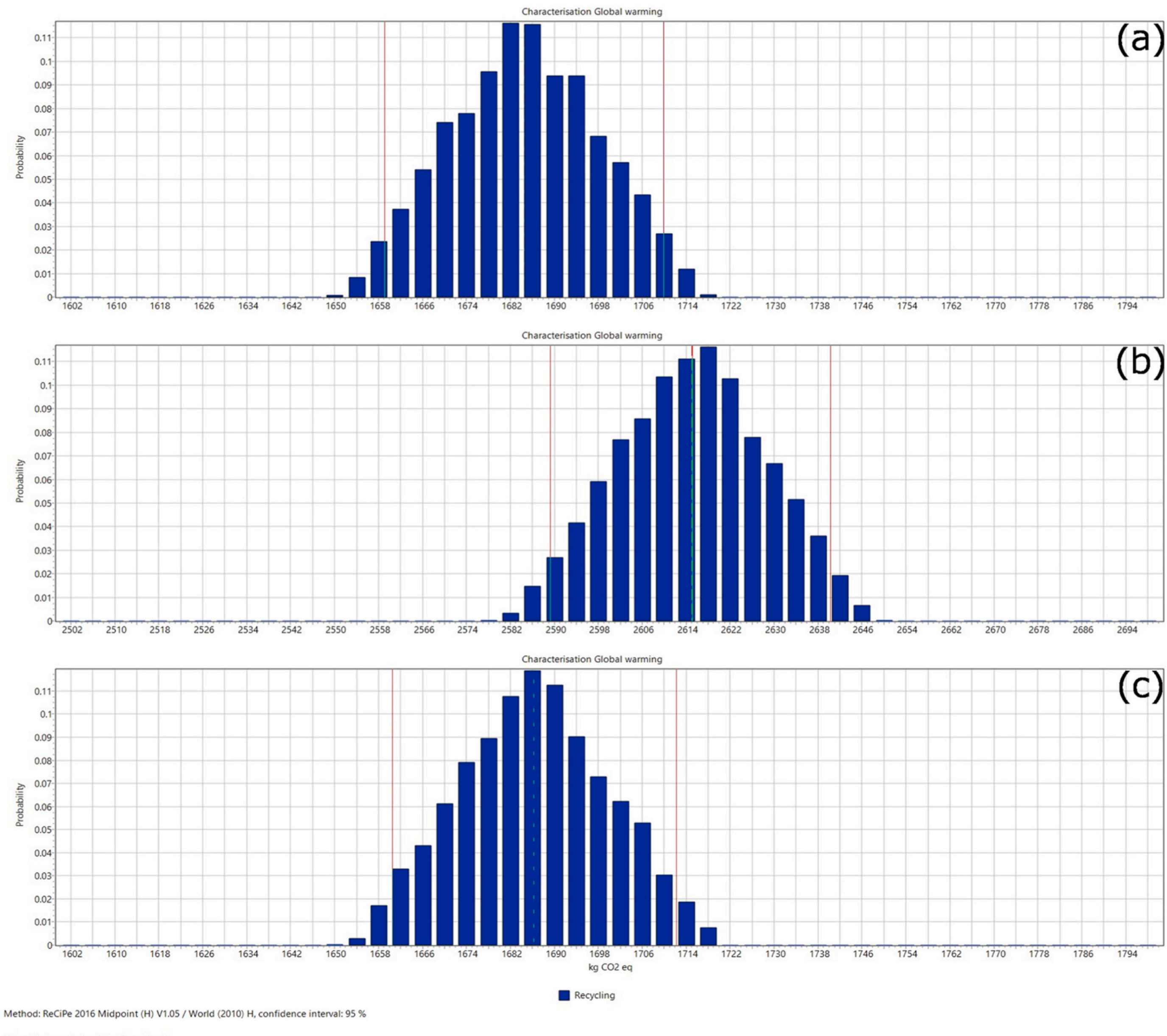

Fig. 12. GWP with Monte Carlo Simulation for different disposal scenario (a) landfill; (b) Incineration (c) Recycling.

materials and specific EoL treatment pathways for WPCs, alongside more extensive research into the technical and economic feasibility of high-volume WPC recycling, would enhance the accuracy and applicability of future LCA studies in this sector.

5. Conclusion and recommendations

This cradle-to-grave LCA of WPC decking, conducted at an industrial facility in China with an annual capacity exceeding 20,000 tons, quantifies the environmental impacts of production and waste management strategies. Using the ReCiPe 2016 method and SimaPro with Ecoinvent 3 data, the study identifies raw material acquisition, premixing, pelletizing, and co-extrusion (Phases I and II) as the primary contributors to environmental impacts, accounting for over 75 % of the burden across categories like global warming potential (GWP), freshwater eutrophication potential (FEP), and terrestrial ecotoxicity potential (TETP). Transitioning from China's fossil-heavy electricity mix to solar energy reduces GWP by 38.9 %, offering a practical pathway to lower environmental impacts without major process modifications. Among disposal scenarios, recycling achieves an 84.2 % lower GWP than incineration. Sensitivity analysis reveals that higher recycling rates and shorter transport distances further mitigate impacts, particularly for TETP. The substitution rate of RP has little impact on TETP, but significantly affects other environmental impact indicators. In contrast, the service life has minimal influence on overall environmental impacts.

These findings provide actionable insights for WPC manufacturers to enhance sustainability. To reduce environmental impacts, we recommend: (i) adopting low-impact raw materials, such as locally sourced recycled polyethylene, to minimize transport emissions; (ii) improving energy efficiency in extrusion and pelletizing through advanced process controls; and (iii) transitioning to renewable energy sources, with solar power prioritized for its superior GWP reduction. For waste management, recycling should be prioritized over incineration and landfilling, but its energy intensity necessitates renewable energy adoption to maximize benefits. Additionally, the recycling process should maintain flexibility in choosing recycling facilities, with preference given to local enterprises to avoid long-distance transport and reduce associated economic and environmental burdens. Enhancing the rheological properties of recycled polyethylene-based WPC (RP) through additives like lubricants or compatibilizers can improve processability, ensuring performance parity with virgin materials and supporting closed-loop systems. Standardizing quality criteria for recycled WPC will further promote consistent reprocessing outcomes.

Future research should focus on: (i) the development of scalable recycling systems for post-consumer WPC decking, utilizing initiatives such as 'old-for-new' programs to optimize material collection, while fostering collaboration with local WPC manufacturers to facilitate material reuse; (ii) optimizing rapid prototyping techniques to reduce energy use in manufacturing; and (iii) conducting region-specific LCAs to account for variations in energy grids and supply chains. By implementing these strategies, the WPC industry can advance toward carbon neutrality and circular economy goals, balancing environmental benefits with technical and economic feasibility.

CRediT authorship contribution statement

Hongxun Cui: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yitao Zheng:** Writing – original draft, Methodology, Investigation, Conceptualization. **Zheng Wang:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Zeping Wang:** Validation, Methodology, Investigation. **Guozhen Li:** Validation, Resources, Methodology. **Kok Hoong Wong:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jiawei Wang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yun Zhou:** Resources, Methodology, Funding acquisition, Conceptualization. **Philip Hall:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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.envres.2025.123147.

Data availability

I have shared my data as supplymentary data at the attached file.

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