Advancing circular economy of pallets: a comprehensive evaluation framework

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Abbreviations

CE	circular economy
CEP	circular economy performance
CEPI	circular economy performance index
CF	carbon footprint
CFLP	Pallet Professional Committee of China Federation of Logistics and Purchasing
EoL	end-of-life
ERRI	energy recovery rate index
FC	freshwater consumption
FD	fossil depletion
FE	freshwater eutrophication
FPMs	fine particulate matters
FU	functional unit
FUI	frequency of use index
GHG	greenhouse gas
GWP	climate change
HT	human toxicity

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LCA	life cycle assessment
LSI	lifespan sustainability index
MERI	material efficiency ratio index
MFA	material flow analysis
MIPS	material inputs per unit of service
Mt	million tonnes
PCI	production cost index
POF	photochemical ozone formation
REUI	renewable energy usage index
RI	repairability index
RMI	proportion of recycled materials input index
RRI	recycling rate index
Sinopec	China Petroleum & Chemical Corporation
WRI	waste reduction index
WWRI	waste-to-weight ratio index

Abstract

The pursuit of sustainable development highlights the circular economy (CE) as a viable approach. Pallets, transporting over 80% of global trade, lack CE performance (CEP) evaluation, hindering sustainability efforts in logistics. This study develops a comprehensive framework comprising 17 indices across the pallet lifecycle to evaluate CEP in China, based on literature review, field studies, and integration of material flow analysis and life cycle assessment. Results reveal significant variation in CEP across pallet types. Wooden pallets generate substantial waste, with a high waste-to-weight ratio of 58.60%, due to inefficient processing. Plastic pallets exhibit high material efficiency (99.88%), but face environmental challenges due to non-renewable resources reliance.

Steel pallets demonstrate exemplary waste management but are underutilised. Paper pallets need better durability and fly ash pallets have environmental concerns due to adjuvants. The proposed framework offers an effective tool for promoting sustainability in logistic carrier industries, with applicability extending beyond pallets.

Keywords: Pallet waste management; Comprehensive evaluation framework; Circular economy performance index; Material flow analysis; Life cycle assessment

1. Introduction

Human society's pursuit of sustainable development necessitates exploring pathways such as the CE (Saidani et al., 2019), with its ultimate goal of achieving sustainability (Linder et al., 2017). Trade, as a fundamental aspect of human activity, plays a crucial role in economic activity but also contributes to resource consumption and environmental impacts. Therefore, aligning trade with CE principles is essential for sustainable development. Pallets are the primary logistics carriers, facilitating over 80% of global trade. They play a key role in the supply chain (Zhang et al., 2024).

The United States is recognised as the largest pallet-holder globally, with about 1.8 billion pallets (Alanya-Rosenbaum et al., 2021). China held over 1.55 billion pallets, with an annual growth rate of 6.9% in 2020. This represented about 25% of the global pallet inventory, making it the second-largest pallet holder worldwide (Zhang et al., 2023). However, this expansion brings challenges such as increased resource consumption, waste generation, and environmental burdens (Alanya-Rosenbaum et al., 2021). To tackle these challenges and foster circularity in trade, the pallet industry needs to adopt CE principles. Nevertheless, assessing the progress of CE initiatives within the pallet industry requires a comprehensive set of indices tailored to its unique characteristics (Blomsma and Brennan, 2017; Bocken et al., 2017). In the absence of an assessment framework or backing from the industry, CE initiatives within the pallet industry are not sustained (Saidani et al., 2019). However, the existing CE indices, such as MIPS and CF, are often generic which lack consideration of differences between sectors (Rousseaux et al., 2017) or product categories (Linder et al., 2017), limiting their application in the pallet industry in China (Elia et al., 2017). For instance, the MIPS indicator calculates all material inputs required for a specific type of material flow, encompassing the entire lifecycle of a product, service, or process from cradle to cradle. These inputs are related to the unit of the product or service provided. However, MIPS only measures a product or service' s material intensity, which helps with the study of one CE requirement. It does not provide information on the associated emissions, the utilisation of recyclable resources, or material losses, which are key aspects in the pallet industry. Besides, the CF is a widely recognised environmental performance indicator that measures the impact of human activities on the global climate. It is expressed in terms of the GHG emissions produced by a system. However, its primary limitation is its exclusive focus on the global warming potential, overlooking other impact categories present throughout the entire lifecycle of pallets. Therefore, these generic indices are not sufficient because they do not consider the specific needs of individual sectors or product types (Elia et al., 2017). The pallet industry in China may have unique material flows, product lifecycles, recycling potentials and environmental impacts that are not well-reflected by a one-size-fits-all approach. The lack of sector-specific considerations can lead to an inadequate assessment of CE, which in turn may not effectively guide industry practices toward more circular models.

Furthermore, there are currently four main types of pallet varieties (wood, plastic, paper, and steel pallets), along with an emerging type: fly ash pallets in

China. The waste generation and environmental impacts of each pallet variety differ, necessitating a detailed analysis at product level. Tailored policies for the pallet industry are required to be formulated to enhance the CEP of each pallet type, thereby effectively advancing the progress of the CE. Recent studies provide valuable insights into the environmental sustainability hotspots along the pallet lifecycle. For example, Carrano et al. (2014) found that the manufacturing stage of wooden pallets significantly contribute to carbon emissions, highlighting the need for efficient material and energy use. Alanya-Rosenbaum et al. (2021) considered more environmental impact categories and identified the manufacturing stage as the most significant contributor, followed by the raw material supply stage. Weththasinghe et al. (2022) compared the carbon footprint of wooden and plastic pallets in Australia, revealing that plastic pallets have a 1.5 times higher carbon footprint than wooden pallets from a cradle-to-grave perspective. Kočí (2019) expanded the environmental impact categories and found that wooden pallets generally have lower environmental impacts than plastic pallets, especially when wood is used for energy recovery at the end of its lifecycle. Current research highlights that different types of pallets have different environmental hotspots, and the environmental impacts exist during the entire lifecycle. These insights justify the focus on the pallet industry and underscore the potential benefits of adopting CE measures to mitigate environmental impacts.

However, the existing research predominantly focuses on the environmental impacts of different pallet products, neglecting other aspects of CE, thereby resulting in a lack of comprehensive CEP assessment for pallets. For instance, pallets made from materials such as wood or plastics can be recycled at the end of their lifecycle. By reprocessing these materials, they can be reintroduced into the production of new pallets, thereby extending their useful life and reducing the need for virgin materials. The inclusion of a recycling rate would allow for the quantification of how effectively materials are reintroduced into subsequent life cycles, thus operationalising circularity performance. MFA and LCA stand as two commonly used methods for CE indicator development (Figge et al., 2018; Haas et al., 2015). MFA depicts the pathways of pallet streams, identifying the hotspots for waste prevention and reduction (Franklin-Johnson et al., 2016). However, MFA fails to assess pallets in view of the environmental impacts (Allesch and Brunner, 2015). LCA allows evaluating the environmental effects, while fails to consider the total mass flow (Wang et al., 2022). Besides, the detailed mass flow and balance in the MFA model also serve as life cycle inventory for LCA (Brunner and Rechberger, 2016). Therefore, integrating MFA and LCA can provide a more holistic sets of indicators including the environmental implications and the sources of impacts of the pallet industry in China, since these two methods are complemented by each other (Liang et al., 2023). However, only very little research has provided the waste disposal rates of pallet market in the US through questionnaires (Buehlmann et al., 2009; Gerber, 2018), without covering other aspects of pallet life cycle, such as raw materials input, production volume, consumption and inventory. Current knowledge of anthropogenic material cycles, such as material compositions, quantities, consumption patterns, and waste treatment of pallets, is lacking. This gap hinders research on the MFA of the Chinese pallet market. Consequently, it impedes the ability to understand the circularity of the pallet industry and formulate CE policies for this sector. Present policies in China, such as the 14th Five-Year Plan for Logistics (General Office of the State Council of China, 2022), aimed at promoting CE development primarily emphasise enhancing pallet reuse due to a lack of clarity regarding the circularity of each pallet type. As a result, these policies lack specificity, contributing to the sluggish progress of the pallet industry in achieving CE objectives.

Therefore, the two research questions proposed in this study are: (1) How to assess the CEP among various types of pallets (wooden, plastic, paper, steel, and fly ash) in the pallet industry in China, and what potential areas for improvement can be identified? and (2) How can MFA and LCA be integrated to provide comprehensive evaluation indices of the CEP of pallets? In order to answer the two research questions, this study proposes a framework comprising a comprehensive set of evaluation indices for measuring the CEP of five pallet types. This framework takes the characteristics of the Chinese pallet industry into consideration and is based on the evaluation on the circularity and environment impacts with the aid of MFA and LCA. The framework involves a dual approach: MFA is employed to first identify the current state of the supply chain, including the waste generation and material flows for different pallet types; subsequently, LCA is used to evaluate the environmental impacts associated with each pallet type within the context of the Chinese pallet industry based on the data inventory provided by MFA. The analysis covers five types of pallets: wood, plastic, paper, steel, and the emerging fly ash pallets, each with distinct waste generation and environmental impact profiles. The MFA identifies critical points for waste prevention and resource optimisation, and the LCA quantifies the environmental impacts across various categories, providing a comprehensive view of each pallet type's environmental performance. 17 indices that capture the multifaceted aspects of pallet lifecycle are derived from the integration of these methods, forming a comprehensive CEPI framework. By identifying the finely tailored recommendations, this study offers crucial insights for advancing CE initiatives in the Chinese pallet industry and contributes to the broader goal of fostering sustainable development in global logistic carrier industries.

2. Method and materials

2.1 Material flow analysis

MFA is one methodology based on the framework of social metabolism, which systematically evaluates the movement and storage of materials in a specific time and space system (Brunner and Rechberger, 2016). It relies on the principles of the material balance, which states that the total inputs and outputs of a system, plus the net accumulation of materials in the system, must be equal (Hinterberger et al., 2003).

The system boundary is China, covering the production, manufacturing, use, recycling and waste management phases (Fig. 1). Four types of pallets, including wooden pallet, plastic pallet, paper pallet, steel pallet, contributing for 99% of market share in 2020 are considered separately. The remaining types of pallets including fly ash pallets, which together accounting for 1% of market share are included in other pallets in the manufacturing stage. Six types of materials are considered in the production stage, eight sectors in the use stage and four EoL treatment methods are considered in the EoL stage. The scope of the system analysis excludes the initial extraction and production of primary materials (Hsu et al., 2021). The temporal boundary of the study is 2020. Pallets that are used as packaging materials for import or export, and not sold as products are not considered in this study, because they are not recorded in the customs data and thus unavailable. The data for this study were sourced primarily from field studies conducted to the CFLP, which includes more than 50% of the pallet market in China. These studies included various pallet companies across different regions and production scales. Additionally, secondary sources such as academic papers (e.g., Alanya-Rosenbaum et al., 2021; Anil et al., 2020) reporting raw material consumption data for pallets in other regions were used to cross-check and confirm the primary findings. The data collection process was reviewed by experts from CFLP to gather feedback and insights on the data's accuracy and representativeness (Zhang et al., 2023), considering the data quality evaluation criteria, namely, reliability, completeness, temporal correlation, geographical correction and other correlation (Laner et al., 2016). Detailed data collection process, data sources and data quality evaluation criteria explanations are provided in supplementary materials.

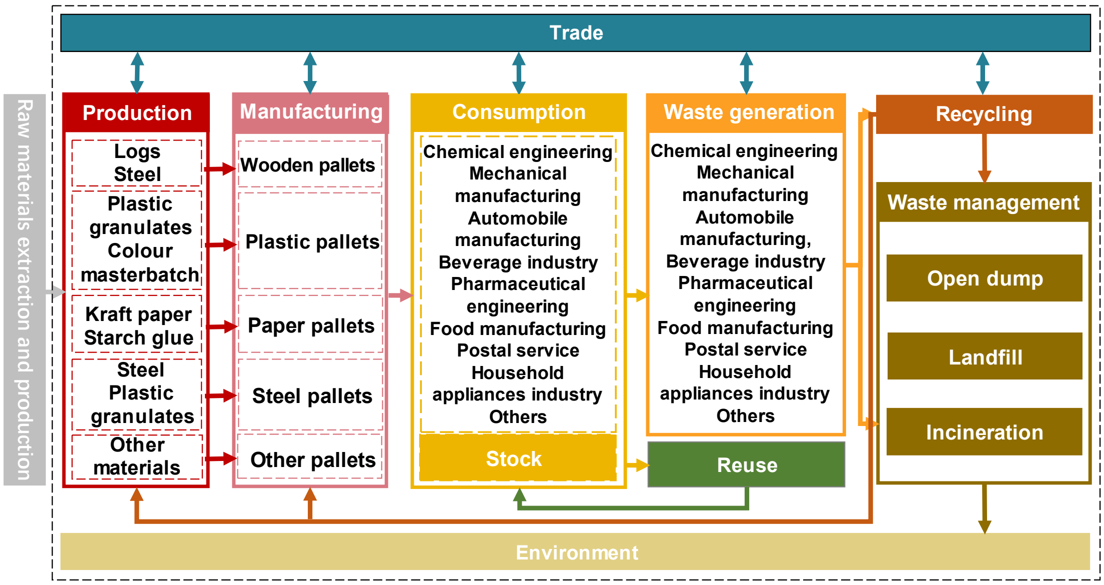


Fig. 1. Schematic diagram of pallet flows and stocks in China. Stages are represented by boxes, and flows are shown by arrows. The system boundary is depicted as a black dotted box.

2.1.1 Flows and stocks

2.1.1.1 Inflow of pallets

The apparent consumption ($A_{p,n}$) of pallet *p* in the year n equals the sum of domestic production ($P_{p,n}$), the last-year stock ($S_{p,n-1}$) and the imports ($I_{p,n}$) of pallet *p* in the year while deducting the exports ($E_{p,n}$). The equation assumes that all last year's stock becomes a flow in the current year. It is described in formula 1:

$$A_{p,n} = P_{p,n} + S_{p,n-1} + I_{p,n} - E_{p,n} \quad (1)$$

2.1.1.2 Lifetime distribution

Pallet products have a limited lifespan and are eventually discarded. Some of the discarded pallets are recycled, while others are disposed. The duration of pallet products in the use inventory stage and their final elimination depends on the lifespan of the end-use products. The EoL distribution of each type of pallets is needed to estimate the amount of pallet waste and the changes in the social stock of pallets at each stage. Previous studies have shown that the EoL patterns of products follow the Weibull distribution (Dong et al., 2020; Glöser et al., 2013). Therefore, the material flow method which uses a lifetime distribution to perform is adopted to calculate the social stock of each type of pallets for each target year. The social stock of pallets has a lifetime distribution that follows the Weibull function: The parameters and data processing are as follows:

$$C(x) = \int_{n-1}^{n} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)} dx \tag{2}$$

where $C(x)$ is the change in the scrap rate in No. x year. k is the shape parameter, λ is the proportion parameter.

Consumption

$$ChE_{p,n} = c_i \times A_{p,n} \tag{3}$$

$$MeM_{p,n} = m_i \times A_{p,n} \tag{4}$$

$$AuM_{p,n} = a_i \times A_{p,n} \tag{5}$$

$$BeI_{p,n} = b_i \times A_{p,n} \tag{6}$$

$$PhE_{p,n} = p_i \times A_{p,n} \tag{7}$$

$$FoM_{p,n} = f_i \times A_{p,n} \tag{8}$$

$$PoS_{p,n} = s_i \times A_{p,n} \tag{9}$$

$$HoA_{p,n} = h_i \times A_{p,n} \tag{10}$$

$$Oth_{p,n} = t_i \times A_{p,n} \tag{11}$$

Where $ChE_{p,n}$, $MeM_{p,n}$, $AuM_{p,n}$, $BeI_{p,n}$, $PhE_{p,n}$, $FoM_{p,n}$, $PoS_{p,n}$, $HoA_{p,n}$, and $Oth_{p,n}$ refer to the amounts of pallet use flowing into the chemical engineering, mechanical manufacturing, automobile manufacturing, beverage, pharmaceutical engineering, food manufacturing, post services, household appliance and other industries, respectively; c_i, m_i, a_i, b_i, p_i, f_i, s_i, h_i, and t_i refer to the corresponding flow ratios.

2.1.1.3 Recycling and waste management

Without considering the import and export conditions, let the production of each type of the pallets in No. (x-n) year be P_{x-n}, and the corresponding scrap rate in year n be C_n, then the scrap function of each type of the pallets can be obtained as follows:

$$W(x) = \sum_{n=n_{min}}^{n=n_{max}} \left(P_{p,x-n} \times C_{p,n}\right) \tag{12}$$

Waste management

$$INC = \sum_{n=n_{min}}^{n=n_{max}} \left(P_{p,x-n} \times C_{p,n}\right) \times n_i \tag{13}$$

$$LAN = \sum_{n=n_{min}}^{n=n_{max}} \left(P_{p,x-n} \times C_{p,n}\right) \times l_i \tag{14}$$

$$OPE = \sum_{n=n_{min}}^{n=n_{max}} \left(P_{p,x-n} \times C_{p,n}\right) \times o_i \tag{15}$$

$$REC = \sum_{n=n_{min}}^{n=n_{max}} \left(P_{p,x-n} \times C_{p,n}\right) \times r_i \tag{16}$$

where *INC*, *LAN, OPE* and REC refer to the amounts of pallet waste flowing into the incineration, landfill, open dump and recycling, respectively; n_i, l_i, o_i, and r_i refer to the ratios of incineration, landfill, open dump and recycling for pallet waste.

2.1.1.4 After-use stocks

The after-use stock refers to pallets after the active use status that are providing services to the society. The after-use pallets are acquired as an accumulation within the economy, which are determined by the disparity between the inflow and outflow entering or leaving the sectors within a specified period. This calculation can be expressed as follows:

$$S_{p,n} = P_{p,n} + S_{p,n-1} + I_{p,n} - E_{p,n} - \sum_{n=n_{min}}^{n=n_{max}} \left(P_{p,x-n} \times C_{p,n}\right) \tag{17}$$

2.1.2 Sensitivity analysis

This study employs MFA to model the flows and stocks of pallets in China, which is based on a substantial quantity of statistics and coefficients as the input data. These data may entail uncertainties in the model results, which need to be assessed and validated. Therefore, a sensitivity analysis, aiming to assess the robustness and reliability of the model results by examining how they are affected by the variations in the model parameters, has been performed following the method of Augiseau and Barles (2017). The parameters that are subject to uncertainty include: the product split ratios in the manufacturing phase and the sector split ratios of the top-down method in the consumption stage. The sensitivity analysis involves changing each parameter by ±10% and calculating the variance in the final results (Jiang et al., 2020).

2.2 Life cycle assessment

The environmental implications of five types of pallets are assessed by LCA approach using ReCiPe 2016 Midpoint (H) method in Gabi software to obtain the environmental impact index. The system boundary is from cradle to grave (Chen et al., 2022; Miah et al., 2017). The construction of infrastructure and the transportation of raw materials and waste disposal facilities are not considered in this research (Zhang et al., 2023). Six impact categories: GWP, POF, FE, FC, FD, and HT are included. “One tonne of cargo delivered using pallets” is used as FU (Table S9). The FU is based on our previous research which considers the load carrying capacity and reference service life of pallets, with the "racked across the length" support condition (Zhang et al., 2023). The system expansion approach is employed to account for the avoided burden from material recycling and energy recovery (Eriksson et al., 2010; Frischknecht, 2010). The evaluation is consistent with international LCA standards (ISO, 2006a, 2006).

3. Results

3.1 Material flow analysis

3.1.1 Pallet flows

The consumption of raw materials for manufacturing pallets amounted to 12.51 Mt in 2020 (Fig. 2), including 10.69 Mt of logs (85% of the total flows), 1.08 Mt of plastic granulates (9%), 0.49 Mt of steel (4%) and 0.11 Mt of paper (1%). At the pallet manufacturing stage, the wooden pallet products reached 6.29 Mt, while 41% of raw materials were by-products during the production process, indicating the huge amount of waste generated. The production of plastic, paper and steel pallets was 1.09, 0.13 and 0.41 Mt, respectively. The loss rates for paper pallets and steel pallets were 16% and 12%. The total pre-consumer waste generated was 4.53 Mt, accounting for 36% of the total material inputs.

3.1.2 Pallet stocks

In terms of pallet consumption by industry sectors, the chemical engineering sector was the largest user of pallets in China, accounting for 46% of the total pallet stock (19.30 Mt) in 2020. Within this sector, wooden pallets dominated the market with a share of 86% (16.53 Mt), followed by steel pallets and plastic pallets with shares of 7% (1.29 Mt) and 6% (1.15 Mt) respectively. The second largest user of pallets in China was the mechanical manufacturing sector, which accounted for 28% of the total pallet stock (11.57 Mt) in 2020. Similar to the chemical engineering sector, wooden pallets were the most preferred type of pallets. The automobile manufacturing sector was the third largest user of pallets in China, accounting for 8% of the total pallet stock (3.52 Mt) in 2020. This sector mainly used wooden pallets and steel pallets. The household appliances industry consumed 0.34 Mt, with a different consumption pattern that it mainly uses paper pallets, because paper pallets are especially suitable for products that have irregular shapes or structures that need customised packaging. Among different types of pallets, wooden pallets had the largest market share of 74% in 2020. However, it faces limitations in industries that require high hygiene standards, due to drawbacks, such as being susceptible to moisture absorption, insect infestation, fire hazard, and splintering, which has resulted in a decline in market share from 80% in 2012. Plastic pallets, on the other hand, gained more popularity in these industries, such as food and pharmaceutical sector, leading to an increased market share from 12% in 2012 to 16% in 2020.

3.1.3 Pallet recycling and waste management

The amount of pallet waste was 10.92 Mt in 2020. 70% of post-consumer waste was incinerated (7.63 Mt). 25% was recycled to be served as materials to replace raw materials input in the next-round production (2.70 Mt). 5% was landfilled (0.53 Mt), and 0.01 Mt of waste were open dumped. Pre-consumer waste accounts for 41% of total waste.

The chemical engineering industry generated the most waste (2.96 Mt), in addition to 85% of the pallets (16.34 Mt) that were used in the chemical engineering industries and went to in-use stock. 52% (1.53 Mt) of the waste pallets were incinerated, 44% (1.29 Mt) were recycled, and 4% (0.13 Mt) were landfilled. The mechanical manufacturing industry generated the second most waste (1.93 Mt), in addition to 9.64 Mt of pallets that went to in-use stock. Of the waste pallets, 53% (1.03 Mt) were incinerated, 45% (0.86 Mt) were recycled, and 2% (0.04 Mt) were landfilled. The automobile manufacturing sector generated the third most waste (0.55 Mt), in addition to 2.97 Mt of pallets that went to in-use stock. Of the waste pallets, 53% (0.29 Mt) were incinerated, 45% (0.25 Mt) were recycled, and 0.01 Mt were landfilled. The beverage industry generated the fourth most waste (0.28 Mt), in addition to 1.38 Mt of pallets that went to in-use stock. Of the waste pallets, 0.15 Mt were incinerated, 0.12 Mt were recycled, and 0.01 Mt were landfilled. The pharmaceutical engineering industry generated 0.23 Mt of waste, in addition to 1.49 Mt of pallets that went to in-use stock. 28% (0.06 Mt) of the waste pallets were incinerated, 25% (0.06 Mt) were recycled, 46% (0.11 Mt) were landfilled, and 0.004 Mt were open dumped. Different industries have different patterns of pallet disposal and reuse, and that there is room for improvement in reducing waste and increasing recycling rates.

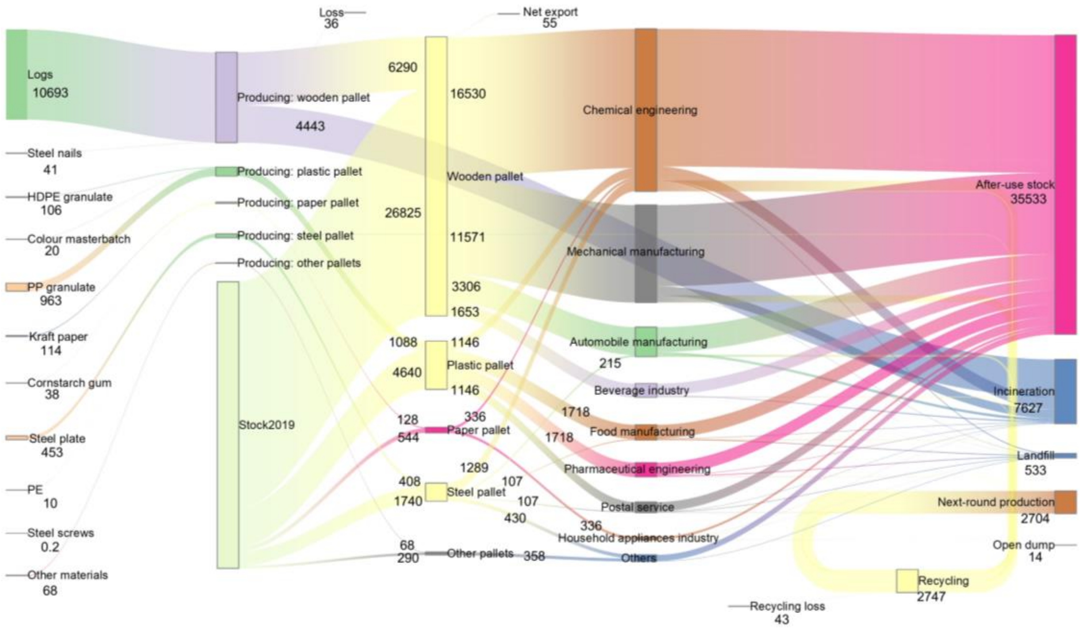
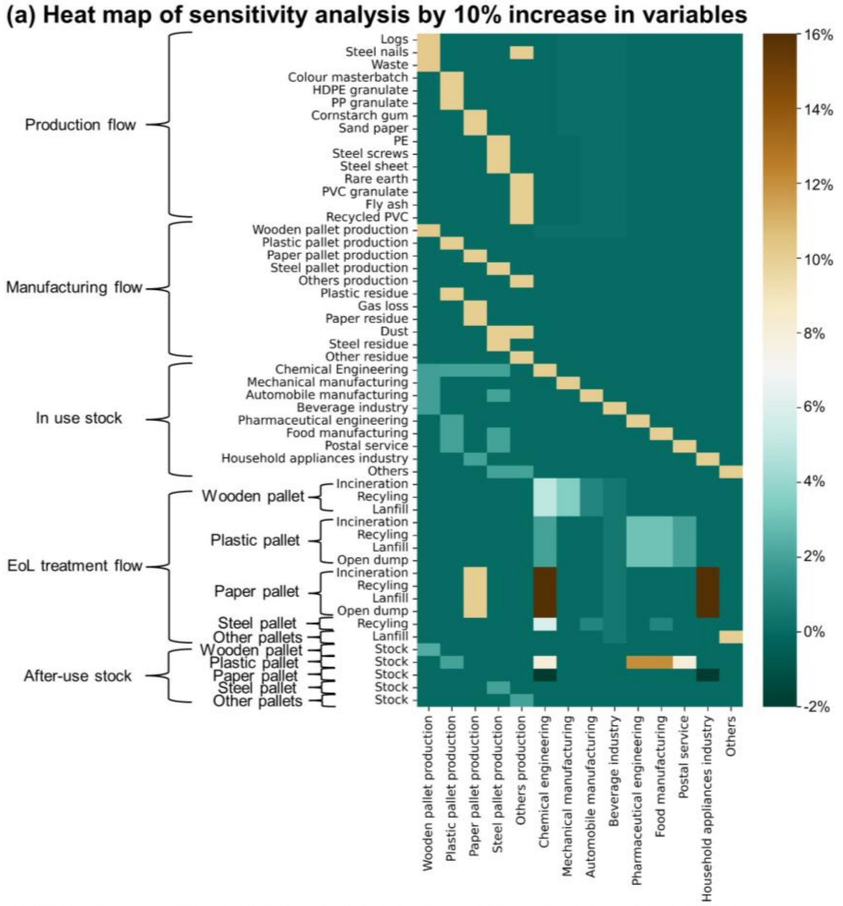


Fig. 2. Pallet flows and stocks in use in China in 2020

3.1.4 Sensitivity analysis

A ±10% change in manufacturing may lead to a ± 10% change in variables of material inputs, which means that if manufacturing increases by 10%, the material inputs required for manufacturing will also increase by approximately 10%, and vice versa. This relationship is based on the direct proportionality between manufacturing activity and material inputs. Paper pallet waste generation is notably sensitive to consumption sector fluctuations, with a ±10% change in consumption resulting in corresponding waste generation shifts. The change in the consumption of plastic pallets in pharmaceutical engineering, food manufacturing, chemical engineering and postal service affect the after-use plastic pallet stock by ±12%, ±12%, ±8% and ±8%, respectively (Fig. 3a). The 10% and -10% change in household appliances industry and chemical engineering industry affect paper pallet waste by 16% and -15%, respectively. The effect of the recycling volume of steel pallets is ±6%, in the case of a ±10% change in chemical engineering sector, showcasing moderate sensitivity to sector fluctuations (Fig. 3b).

(a) Heat map of sensitivity analysis by 10% increase in variables



(b) Heat map of sensitivity analysis by 10% reduction in variables

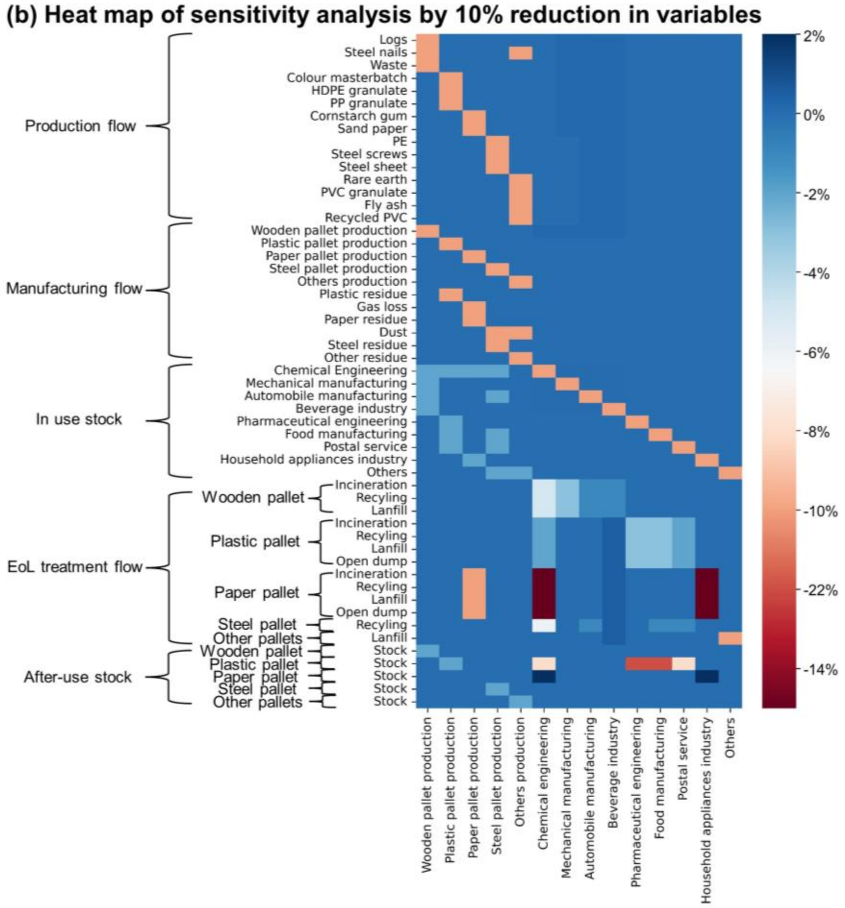


Fig. 3. Sensitivity analysis of the MFA model. The horizontal axis displays the key variables through the pallet life cycle. The vertical axis displays the results of flows and stocks under each change. The colour presents the magnitude of the implications under changes of +10% (a) and -10% (b).

3.2 Environmental impact assessment

The comparative analysis highlights the substantial environmental implications associated with various pallet types. Fly ash pallets exhibit the highest impacts across five categories, while plastic pallets lead in two. This is primarily due to the production processes of fly ash and plastic pallets, where significant proportions of impacts such as GWP, FD, FC and HT are attributed (Fig. S2). For instance, fly ash pallet production contributes 50% to GWP, 61% to FD, almost 100% to FC, and 71% to HT. Similarly, plastic pallet production accounts for 69% of GWP, 81% of FD, 98% of FC, and 66% of HT. The use of plastic pallets in transportation, particularly with diesel-operated trucks, significantly contributes to POF, with emissions such as polycyclic aromatic hydrocarbons and heavy metals being key factors (Ali et al., 2021; Dobbins et al., 2006). These substances can adversely affect the aquatic and terrestrial ecosystems and human health (Abbas et al., 2018; Yilmaz and Donaldson, 2022). Additionally, the EoL stage of plastic pallets presents both environmental benefits and challenges. While energy recovery processes and recycling alleviate FD, FC, HT, and POF, improper disposal risks pollution, including leaching of pollutants into water, soil, and air, posing significant hazards to ecosystems and human health (Geyer et al., 2017; Harris et al., 2021).

Carbon emissions are the highest for plastic pallets, reaching 61.68 kg CO_2 eq., while wooden pallets exhibit the lowest carbon footprint at 12.67 kg CO_2 eq. (Fig. 4). This disparity can be attributed to the lower resource and energy input in the production of wooden pallets, and the EoL processes such as reusing dismantled board and incinerating waste wood for energy recovery (Alanya-Rosenbaum et al., 2021). Conversely, steel pallets' production stage entails significant energy and material usage, emitting GHG and releasing radionuclides (Burchart-Korol, 2013; Norgate et al., 2007). The use stage of steel pallets has the highest impact on POF and HT, accounting for 68% and 63% respectively. However, the EoL benefits through steel recycling mitigate environmental impacts associated with primary steel production (Norgate and Haque, 2010).

In the case of paper pallets, both production and use stages significantly contribute to environmental impacts. For instance, the use stage accounts for 68% of GWP, 74% of FD, 70% of HT, and 86% of POF. The diesel fuel combustion during transportation generates a large number of toxic substances and particulate matter, such as polycyclic aromatic hydrocarbons, heavy metals and black carbon (Wu et al., 2017). The burning of diesel and petrol fuels in engines results in the formation of FPMs from combustion (Araujo and Nel, 2009; Morawska et al., 2008). The FPMs from vehicle exhaust are linked to higher rates of asthma and cardiovascular, respiratory, and other diseases (Laskin et al., 2012; Loomis et al., 2013; Watson and Chow, 2001). However, the EoL stage offers benefits through recycling and energy recovery processes. Furthermore, uncertainty analysis using the Monte Carlo method enhances the credibility of the findings are provided in supplementary materials, offering insights into the reliability of the results.

In line with the principles of LCA, our study identifies significant environmental benefits associated with the EoL phases of different pallet types. Specifically, the negative environmental impacts observed during these phases primarily result from the recycling of materials, which are reintroduced into a second life cycle as "avoided products." This approach aligns with recent studies examining the LCA of innovative materials derived from waste materials

(El-Seidy et al., 2022; Sambucci et al., 2023). These findings underscore the relevance of our research findings not only at the industrial and logistical decision-making levels but also in informing political and administrative strategies aimed at promoting sustainable development practices. By highlighting the positive environmental impacts of recycling in the pallet industry, our study contributes to advancing CE initiatives.

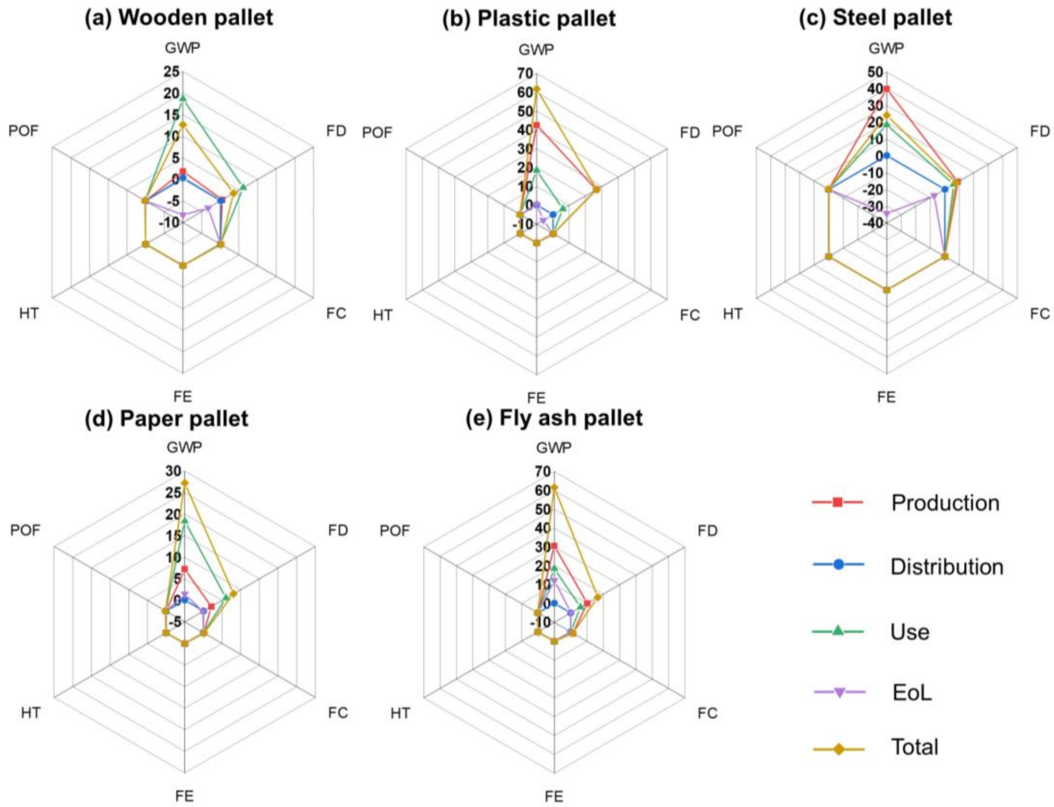


Fig. 4. Environmental impacts comparison of the five types of pallets. (a) Wooden pallet; (b) Plastic pallet; (c) Steel pallet; (d) Paper pallet; (e) Fly ash pallet. (GWP (kg CO_2 eq.); POF (kg NO_x eq.); FE (kg P eq.); FC (m^3); FD (kg oil eq.); HT (kg 1,4-DB eq.)).

3.3 Evaluation framework of circular economy performance for pallets

3.3.1 Development of the circular economy performance index framework for pallets

The development of the CEPI framework is a systematic and iterative process, meticulously crafted to provide a comprehensive assessment tool for the pallet industry. The process commenced with the review of the existing literature on CEPI, aiming to identify the relevant indicators and evaluate their applicability to the pallet industry (such as Elia et al., 2017; Pauliuk, 2018). These reviews revealed a significant gap in tailored evaluation indices for the pallet industry in China. Based on the literature review, a preliminary set of indicators was identified. They are selected for their alignment with CE principles and their theoretical applicability to the industry's unique characteristics, such as the RRI (Elia et al., 2017). To refine the understanding and ensure the practical relevance of these indicators, field studies are conducted with industry experts to gain insights into the specific challenges and characteristics of the pallet industry. This process has led to the development of new indicators, such as RI and LSI, which are critical for evaluating the reparability and durability of pallets. MFA and LCA methodologies were then integrated to evaluate material flows and environmental impacts throughout the pallet lifecycle, providing a robust data-driven foundation for selecting pertinent indicators.

The integration of MFA study, such as the consumption of raw materials and waste generation, allowed for a comprehensive understanding of the material efficiency and waste management within the pallet industry in China. For example, the substantial proportion of pre-consumer waste, which amounts to 4.53 Mt and represents 36% of the total material inputs in the pallet manufacturing process, indicates a significant inefficiency in resource utilisation during the production phase. This has led to the selection of WWRI and MERI within the CEPI framework, aiming to provide a measure of production efficiency and the effectiveness of waste minimisation strategies. Recognising the potential for reducing the environmental impacts of pallet manufacturers, REUI has been introduced to reflect the adoption of renewable energy sources in the production process. Field studies have revealed that some pallet companies in China have initiated energy transitions, employing solar energy for pallet production, underscoring the relevance of the REUI. The use of recycled materials is identified as a key strategy for enhancing circularity and reducing environmental impact (El-Seidy et al., 2022). However, the current recycling rate is 25%, with only 2.70 Mt of pallet waste being recycled to replace raw material input in subsequent production cycles out of the total 10.92 Mt of pallet waste generated in 2020. This has prompted the development of RMI to assess the extent of recycled materials used in production. Furthermore, the EoL management of pallets presents an area for improvement, with 70% of post-consumer waste being incinerated and a concerning 5% being either landfilled or openly dumped. To evaluate the CEP of the EoL stage, the RRI, ERRI, and WRI have been developed to reflect the effectiveness of recycling efforts, energy recovery from waste materials, and waste reduction strategies. To optimise resource utilisation throughout the pallet lifecycle, the FUI has been introduced, encouraging stakeholders to maximise the number of times pallets are used before EoL disposal.

In addition, the comparative analysis has highlighted the varying environmental implications associated with different types of pallets, necessitating a comprehensive environmental impact assessment. This has led to the inclusion of impact categories, GWP, POF, FE, FC, FD and HT, within the CEPI framework. While MFA is instrumental in identifying inefficiencies and waste generation points, LCA can be adopted to assess the environmental benefits derived from improving the indicators identified through MFA (Elia et al., 2017). This approach fosters a direct link between circularity practices and their environmental advantages. Based on field studies and a joint analysis of MFA and LCA, the set of indicators are further refined. The selection of these indicators was based on their ability to quantify essential aspects of the CE within the pallet lifecycle, their measurability, and data availability. Finally, these indicators are integrated into a comprehensive CEPI framework that covers the entire lifecycle of pallets, from design, production, and consumption to EoL management. The development of these indices within the CEPI framework is a direct response to the empirical evidence and quantitative data presented in our study, ensuring a comprehensive approach to evaluating the CEP of pallets.

3.3.2 Circular economy performance index framework for pallets

The CEPI framework proposed in this study serves as a comprehensive tool for assessing the circularity and environmental implications of pallet products within a CE framework (Fig. 5). This index covers the entire lifecycle of pallets and the design of indices for evaluating the CEP of pallets is carefully tailored to address the specific characteristics and challenges of the pallet industry based on the insights from comprehensive field studies. In order to ensure comparability of index results across different types of pallets, it is essential to establish a consistent FU. The FU serves as a reference point for quantifying the performance of pallets throughout their lifecycle. The FU is defined as “One tonne of cargo delivered using pallets”, which is consistent with the approach utilised in the LCA study conducted as part of this research.

Design metrics encompass factors such as LSI which assesses the durability of pallets by considering their maximum weight capacity and reference service life (Table S10). Durability is crucial for prolonging the lifespan of pallets and reducing the need for the additional pallets input, thus minimising resource consumption. The inclusion of the RI reflects the ability of pallets being repaired when broken in enhancing the longevity of pallets. Pallets that can be repaired contribute to a CE by extending their useful life and reducing the demand for new pallets.

Production metrics, which focus on the utilisation of recycled materials

(Haupt et al., 2017), waste generation, renewable energy usage, and production costs, are primarily derived from globally recognised indicators from the existing literature (Elia, et al., 2017; Pauliuk, 2018). WWRI is selected to evaluate production efficiency and waste minimisation efforts. By quantifying the ratio of waste generated during pallet production to the total weight of pallets manufactured, this index provides insights into the effectiveness of resource utilisation and waste reduction strategies. RMI is designed to assess the extent to which recycled materials are incorporated into pallet production, reflecting resource conservation and circularity principles. By promoting the use of recycled materials, pallet manufacturers can reduce reliance on virgin resources and minimise environmental impact. MERI is included to gauge the efficiency of material utilisation during production, emphasising the importance of optimising resource use and minimising waste generation. Higher MERI values indicate more efficient use of materials, contributing to sustainable production practices. REUI reflects the proportion of renewable energy sources used during pallet production, highlighting efforts to reduce GHG emissions and promote environmental sustainability. PCI considers material and energy expenses to evaluate the economic viability of production practices. This index provides valuable insights into the cost-effectiveness of production methods and supports informed decision-making regarding resource allocation.

Understanding pallet usage patterns is crucial for optimising resource efficiency and minimising environmental impacts. FUI measures the number of times pallets are utilised before reaching the end of their lifespan, reflecting utilisation efficiency. Stakeholders can optimise resource utilisation throughout the pallet lifecycle by maximising the frequency of use.

EoL metrics assess recycling rate, energy recovery rate, and waste reduction index, reflecting the effectiveness of waste management practices (Graedel et al., 2011). RRI assesses the proportion of pallet materials that are successfully recycled at the end of their lifespan, reflecting effective waste management practices (Elia et al., 2017). By promoting recycling, stakeholders can divert materials from landfills and contribute to CE. ERRI evaluates the proportion of energy recovered from waste materials at the end of their lifespan, supporting resource optimisation and waste-to-energy initiatives (Elia et al., 2017). WRI measures the proportion of pallets diverted from open dumps and landfills, indicating responsible EoL management practices (Fei et al., 2022). By reducing WRI, stakeholders can minimise environmental pollution and promote circularity within the pallet industry.

In addition to the specific indices within each lifecycle stage, various impact categories including GWP, POF, FE, FC, FD and HT are assessed through LCA. This holistic approach provides a comprehensive understanding of the environmental footprint of pallets across their entire lifecycle, supporting informed decision-making and guiding efforts to enhance CE within the pallet industry.

Overall, the framework for the CEPI is designed to be comprehensive, capturing key aspects of CE across the pallet lifecycle, such as economic efficiency, material consumption, waste management, and environmental impact. The framework enables stakeholders to evaluate and improve the CEP of pallets in a systematic and evidence-based manner by incorporating a diverse range of indices and methodologies.

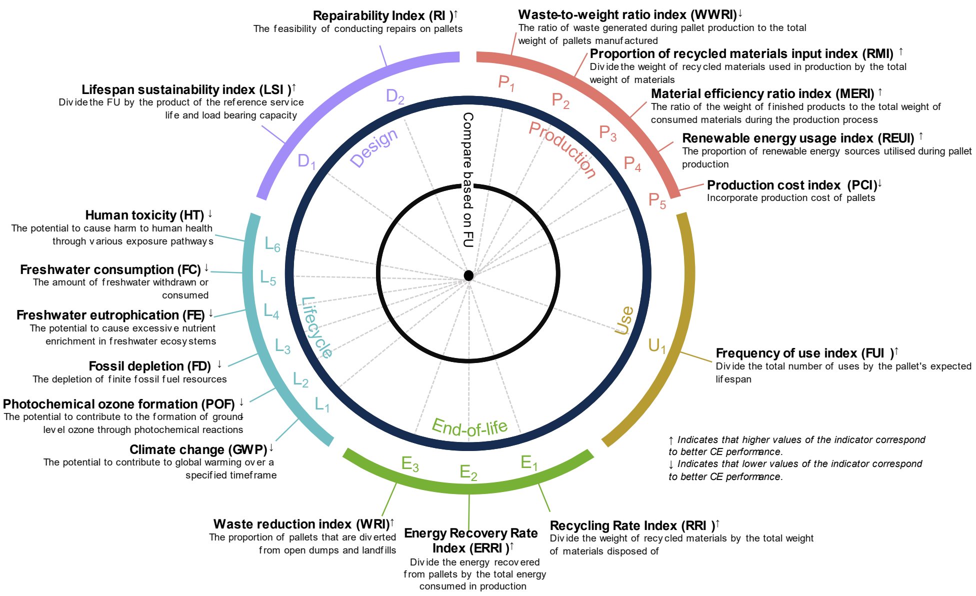


Fig. 5. CEPI framework for pallets. Explanation of the framework for evaluating CEP of each pallet type. The lifecycle stages addressed within the framework are distinguished by colours: design (purple), production (red), use (yellow), EoL (green), and overall lifecycle (blue). Each indicator corresponding to a specific lifecycle stage is represented by the respective colour. Environmental impacts are comprehensively considered across the entire lifecycle, encompassed within the blue category. The upwards arrow (↑) Indicates that higher values of the indicator correspond to better CE performance; The downwards arrow (↓) Indicates that lower values of the indicator correspond to better CE performance.

3.3.3 Circular economy performance index results for each pallet type

The CEPI provides a comprehensive understanding of the CEP of different pallet types, with numerical values shedding light on their respective strengths and weaknesses. Wooden pallets stand out for their exemplary performance in two critical indices: the ERRI and RRI (Fig. 6). These metrics underscore the remarkable capacity of wooden pallets to recover energy at the end of their life cycle and their effectiveness in recycling waste pallets. Besides, they can be repaired which is primarily attributed to the robust structure, which allows for easy repair when damaged, prolonging their useful lifespan and minimising the need for disposal. Despite these strengths, wooden pallets face challenges in the realm of waste generation, as indicated by their high WWRI. This metric points to inefficiencies in wood processing and manufacturing processes, resulting in significant waste generation throughout the production lifecycle.

Plastic pallets, although falling short in RI due to their inability to be repaired, exhibit notable strengths in other key indices. Particularly, their exceptional performance in MERI, scoring 99.88%, underscores their efficiency in utilising materials during production. This efficiency is primarily attributed to the moulding process employed in plastic pallet manufacturing, which effectively minimises material waste, resulting in a low WWRI of 0.12%. However, despite these efficiency gains, plastic pallets face significant challenges in terms of environmental impact. Their high scores in GWP and FD indices suggest unfavourable environmental performance. These results highlight the substantial carbon emissions and resource depletion associated with plastic pallet production processes, primarily due to the reliance on non-renewable resources and energy-intensive manufacturing techniques inherent to plastic production (Lu et al., 2023).

The LSI (0.25) of paper pallets and PCSI (15.00) are notable, because of their significant expenses linked to carrying one tonne of cargo. This expense can be attributed to their shortest reference service life of 4 and the lowest carrying capacity of one tonne among these five types of pallets. Besides, paper pallets face significant challenges in environmental impact, particularly in FE. The high FE score implies a potential risk of water bodies becoming enriched with nutrients, which can adversely affect aquatic ecosystems. This environmental concern may stem from the materials and processes involved in paper pallet production, potentially leading to nutrient runoff and pollution of freshwater systems.

Steel pallets exhibit poor performance in the FUI (1.00), indicating a significant underutilisation relative to their extensive lifespan. This disparity underscores the necessity for implementing a pallet sharing system to increase their usage. Despite the underutilisation issue, steel pallets demonstrate commendable waste management practices, as evidenced by their WRI and RRI both scoring 100%. This indicates that steel pallets are effectively recycled at the end of their life cycle, preventing them from being landfilled or openly dumped. The high recycling rate reflects the intrinsic value of steel pallets in the recycling industry, where they can be repurposed into new products, thus contributing to resource conservation and waste reduction efforts.

Fly ash pallets are notable for their utilisation of recycled materials, as reflected in their RMI of 59.68%. Additionally, these pallets demonstrate repairability, because of their designed structure. Remarkably, they achieve the highest MERI among the five types of pallets, reaching 99.96%, indicative of the exceptional efficiency in material utilisation during the production process. However, fly ash pallets exhibit elevated environmental impacts, particularly in terms of POF, FE, FC and HT due to the inputs of adjuvant in the production stage.

Label	Unit	Wooden pallet	Plastic pallet	Paper pallet	Steel pallet	Fly ash pallet
D_1	pieces	0.07	0.01	0.25	0.01	0.04
D_2	N/A	1	0	0	0	1
P_1	%	58.60	0.12	16.20	11.94	0.04
P_2	%	0.00	0.00	0.00	0.00	59.68
P_3	%	41.40	99.88	83.80	88.06	99.96
P_4	%	0.00	0.00	0.00	0.00	0.00
P_5	CNY	6.67	2.86	15.00	1.50	3.56
U_1	%	6.67	1.43	25.00	1.00	6.67
E_1	%	44.60	25.00	51.30	100.00	0.00
E_2	%	8453.21	80.06	270.53	0.00	0.00
E_3	%	98.00	52.50	80.60	100.00	0.00
L_1	kg CO_2 eq.	12.67	61.68	27.21	24.25	61.54
L_2	kg NO_x eq.	0.16	0.19	0.16	0.15	0.21
L_3	kg oil eq.	3.58	26.77	8.08	7.88	16.61
L_4	10^{-4} kg P eq.	0.09	1.45	2.25	0.08	2.52
L_5	m^3	0.16	0.17	0.16	0.02	1.35
L_6	kg 1,4-DB eq.	0.01	0.02	0.01	0.01	0.03

Minimum Second minimum Median Second maximum Maximum

Fig. 6 CEPI results for each type of pallet. The yellow-green gradient scale is applied to depict the magnitude of each quantitative metric. Intensity ranges from vibrant green denoting higher metric values to subdued yellow indicating lower metric values.

4. Discussion

Pallets are essential components of supply chain management, playing a pivotal role in logistics. However, their CEPI vary significantly depending on the material used, necessitating tailored strategies to enhance their CEP. At the pallet manufacturing stage, the total pre-consumer waste generated is 4.53 Mt, accounting for 36% of the total material inputs, indicating the low efficiency of resource use. This is mainly because of the high WWRI (58.60%) of wooden pallets. Eco-design and design for circularity are two complementary approaches that can enhance the environmental sustainability and circularity of pallets. Eco-design focuses on reducing pre-consumer waste and increasing material efficiency by using renewable energy, recycled materials, and minimising resource consumption (Duan et al., 2019; Donnelly et al., 2006; Kang et al., 2021). It aims to improve the environmental performance of pallets by facilitating reuse and recycling (Maxwell and Van der Vorst, 2003). On the other hand, design for circularity emphasises extending the product's life cycle and recovering resources at the end of its use. It promotes the incorporation of discarded products and unwanted waste, thereby increasing the utilisation of unused materials and reintegrating them into economic activities (Suppipat and Hu, 2022). Although wooden pallets demonstrate commendable strengths in energy recovery, there remains room for more sustainable waste management. Focusing on the WRI indicator, the landfill rate of wooden pallets in the US decreased from 1% in 1995 to only 0.3% in 2016 (Gerber, 2018). In contrast, the landfill rate of wooden pallets in China was 2% in 2020, which is more than five times higher than that of the US. Landfilling can cause leachate contamination of groundwater, methane emissions that contribute to GWP, loss of natural habitats for wildlife, and degradation of land value for nearby communities (Yadav et al., 2020).

China's pallet management system reveals significant opportunities for enhancing circularity. The establishment of closed-loop recycling systems, coupled with effective waste collection and segregation processes, is imperative to minimise mismanagement and promote resource efficiency, with reference to the situation that post-consumer waste accounts for 59% of the total waste generated with the 0.53 Mt has been landfilled and 0.01 Mt of waste has been open dumped. Plastic pallets exhibit relatively high efficiency rate in material utilisation (with MERI of 99.88%) but face substantial challenges in recycling (with RRI of 25%), and environmental impact (with GWP of 61.68 kg CO_2 eq.). These findings align with previous research by Anil et al. (2020), corroborating the notion that plastic pallets perform worse in environmental impact compared to wooden pallets. Focusing on the EoL stage, 45.9% of plastic pallets are landfilled, causing serious environmental impacts. 1.6% of pallets are open dumped, which can cause visual pollution, fire hazards, soil erosion, and harm to animals that ingest or get entangled in them (Zhang et al., 2021). For example, untreated plastic pallet waste may breakdown into micro debris, accumulate in the environment and transfer toxic chemicals to the organisms by entering the food chain (Chen et al., 2018; Lehner et al., 2019; Yonkos et al., 2014), posing serious threat to the health of ecosystems and humans (Alimi et al., 2018).

Steel pallets showcase exemplary waste management practices, yet underutilisation remains a challenge. Pallet sharing systems present a viable solution to increase their usage and promote a more sustainable approach to pallet management. Similarly, paper pallets require improvements in durability to enhance their circularity, necessitating investments in research and development for more durable alternatives shown from its highest PCI of 15.00.

Fly ash pallets demonstrate ability in reparability and the use of recycled materials, including the inputs of recycled PVC and fly ash accounting for 59.68%, albeit with environmental concerns related to adjuvants. Mitigating these impacts requires the exploration of alternative materials and refining production processes.

In addition, the chemical industry is the largest consumer, accounting for 46% of the total pallet stock (19.30 Mt), and the largest waste producer sector of pallets in China (2.96 Mt) in 2020. The chemical industry can become a potential target sector for advancing CE. Currently, Sinopec which is the largest chemical products producer, has designed and established a pallet sharing system. Sinopec chose synthetic resin products as the starting point for building the pallet sharing system. Synthetic resin products have high scale and standardisation of packaging, making them more feasible to apply the pallet sharing system and upgrade the supply chain to employ CE strategies. Therefore, chemical industry can be served as a trial for promoting more CE strategies for the entire pallet supply chain.

The CEPI framework serves as a quantitative tool for policymakers and industry decision-makers, enabling them to assess the CEP of different pallet types and identify opportunities to improve resource efficiency and reduce environmental impacts. By analysing the CEP of various pallet materials, this study offers customised improvement strategies for each type of pallet, such as enhancing the resource utilisation efficiency of wooden pallets and reducing the environmental impact of plastic pallets. The application of the framework can promote broader CE practices within supply chains by optimising pallet design, production, use, and disposal management. Companies can use the CEPI framework to evaluate and improve the CEP of their products, meeting consumer and investor demands for environmental responsibility and transparency. This study also enriches CE theory through empirical analysis, demonstrating how theoretical concepts can be applied to specific industries, such as the pallet industry. By integrating MFA and LCA methods, the research provides a new perspective and methodological framework for assessing the CEP of pallets. This framework contributes to bridging the gap between circularity and environmental sustainability assessments through considering both circularity and environmental sustainability aspects.

Limitations arise regarding the CEPI due to its narrow focus on environmental and economic metrics, which neglects social dimensions within the pallet industry. CE is an umbrella concept which involves environment, social and economic perspectives (CIGAIG, 2015; Murray et al., 2017). The CEPI's oversight of social impact indicators, such as the worker welfare index, undermines the assessment of ethical practices and social responsibility (Naustdalslid, 2014). The oversight of social impact indicators is largely attributed to data unavailability. This limited scope hampers comprehensive CEP assessments, impeding efforts to promote fair labour practices and ethical production within the pallet industry and beyond. Addressing these limitations is crucial for fostering a more inclusive and holistic understanding of CEP. Future research endeavours could focus on incorporating additional CE metrics to provide a more comprehensive evaluation of CEP, thereby enriching sustainability assessments and facilitating informed decision-making in pallet management and related industries.

5. Conclusion

Our study proposes a framework for assessing the CEP of different pallet types within the context of China's pallet industry. This framework integrates MFA and LCA to comprehensively evaluate material flows and environmental impacts across the entire pallet life cycle, providing a valuable tool for guiding efforts to promote CE within the pallet industry, and facilitating progress towards a more sustainable future.

The CEPI varies significantly depending on the material used, requiring tailored strategies for improvement. Wooden pallets, with their high waste generation attributed to a lack of resource efficiency, can benefit from a joint approach of design for circularity and eco-design. China's pallet management system presents opportunities for enhancing circularity through closed-loop recycling systems and effective waste collection processes. Plastic pallets exhibit high material utilisation efficiency but face challenges in recycling and environmental impact. Steel pallets demonstrate exemplary waste management practices, yet underutilisation remains a challenge that can be addressed through pallet sharing systems. Paper pallets require durability improvements, while fly ash pallets show promise in reparability but require mitigation of environmental concerns related to adjuvants. Efforts to explore alternative materials and refine production processes are essential for mitigating environmental impacts across all pallet types.

The existing waste pallet disposal practices present opportunities for improving circularity, as a substantial portion of waste pallets end up in landfills or are openly dumped, leading to severe environmental and social repercussions. It is essential to implement closed-loop recycling systems and improve waste collection and segregation processes to reduce mismanagement and enhance sustainability. Additionally, the chemical industry, being the largest consumer and waste producer sector of pallets in China, presents a significant opportunity for advancing CE practices. The initiative for establishing a pallet sharing system in Sinopec serves as a potential trial for promoting CE strategies across the entire pallet supply chain, leveraging the chemical industry's influence and resources to drive sustainability efforts.

CRediT authorship contribution statement

Tingting Zhang: Conceptualisation, Methodology, Data collection, Software, Writing–original draft. **Zongguo Wen**: Project administration, Supervision, Writing–original draft, review & editing, Funding acquisition. **Yiqi Tan**: Visualisation. **Xiang Shi**: Data collection. **Yemin Sun**: Data collection. **Paul Ekins**: Project administration, Supervision, Writing – review & editing.

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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Supplementary materials

Supplementary materials associated with this article can be found in the online version.

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