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Green transformation strategy of pallet logistics in China based on the life cycle analysis

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Abstract

The Anthropocene is a new geologic epoch defined by the significant impact of human activity on the planet. Industrialisation and population growth have altered the natural environment. The logistics industry, which facilitates economic development and enhances human well-being, relies on logistic carriers as essential equipment. Pallets, the most representative tools of logistic carriers, transport more than 80% of the world’s trade. The conventional pallet market structure is largely determined by economic and convenience factors, but in light of the global environmental changes, the leading users of pallet products have raised their environmental standards, making

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environmental performance a key factor in the pallet industry. While China is the second largest pallet holder and accounts for 25% of the global pallet holdings, it lacks an in-depth understanding on the pallet market structure, the environmental effects, and the barriers for developing pallet sharing system in China. This study conducts comprehensive field studies to reveal the pallet market structure in China, applies life cycle assessment to present a cradle to grave environmental evaluation of the five widely-used pallet material types that account for 99% of market share, and compare various end-of-life treatment methods using scenario analysis. Results show that the current market structure does not align with the optimal environmental outcomes, but would be improved by establishing the circulation-sharing system. Therefore, there is an urgent need for the pallet industry to undergo a green transition. The focus for developing a sharing system should be on engaging the leading user enterprises in the supply chain, rather than merely relying on the pallet manufacturers who have limited bargaining power. Additionally, the environmental impacts can be reduced by 20% to 300% via choosing the appropriate end-of-life treatment method for each pallet material type.

Keywords: Pallet; Material selection; End-of-life treatment; Life cycle assessment; Green transformation; Environmental impact

1 Introduction

The Anthropocene is a new geologic epoch defined by the significant impact of human activity on the planet. Industrialisation and population growth have altered the natural environment. The logistics industry, which facilitates economic development and enhances human well-being, relies on logistic carriers as essential equipment. Pallets, the most common type of logistic carriers, account for over 80% of the world's trade. The size of the global pallet market was estimated at 78 billion USD in 2020, and it is anticipated to exceed 110 billion USD by 2027 (Statista, 2023). China is the second largest pallet holder and accounts for 25% of the global pallet holdings (GLPA, 2018), and the pallet holdings in China has exceeded 1.55 billion in 2020 with an annual increasing rate of 6.9% (Fig. S1). The absence of pallets in logistics would have detrimental consequences for the efficiency, safety, and sustainability of the supply chain (Buehlmann et al., 2009; Kim et al., 2009; Tornese et al., 2016). Pallets facilitate the loading, unloading, and storage of goods in bulk, reducing the time and labour required for logistics operations. Pallets also protect the goods from damage and contamination during transportation and handling. There is evidence to suggest that resource use and emissions related to pallets have increased significantly in recent years, resulting to enormous environmental impacts (Alanya-Rosenbaum et al., 2021).

The prevailing structure of the pallet market in China is detrimental from an environmental standpoint. The conventional structure of the pallet market is largely determined by economic and convenience factors, but in light of the global environmental changes, the leading users of pallet products have raised their environmental standards, making environmental performance a key factor in the pallet industry. Therefore, there is an urgent need for the pallet industry in China to undergo a green transition. There used to be four widely used pallet material types in China. Wooden pallets, plastic pallets, steel pallets and paper pallets together occupy 99% of the pallet market in 2020 (Fig. S2). A new pallet material type made of fly ash appeared in the market in 2018 and was increasingly favoured by users, since it can relieve the pressure on the disposal of solid wastes. It is found that different material composition of pallets have different environmental impacts (Anil et al., 2020; Deviatkin et al., 2019; Kang et al., 2021; Khan et al., 2021; Kočí, 2019; Weththasinghe et al., 2022), and various EoL treatment methods result in different environmental burden or benefits (Alanya-Rosenbaum et al., 2021; Carrano et al., 2014).

Although independent life cycle assessment (LCA) of wooden pallets (Alanya-Rosenbaum et al., 2021; Alanya-Rosenbaum and Bergman, 2020; Carrano et al., 2014; García-Durañona et al., 2016) and paper pallets (Bengtsson and Logie, 2015) have been carried out, which help identify the hotpots of environmental effects from the life cycle perspective, and very limited studies have compared environmental impacts of plastic pallets and wooden pallet (Anil et al., 2020; Deviatkin et al., 2019; Kočí, 2019), a comprehensive understanding on the five widely-used pallet material types is still lacking, resulting in an unoptimised pallet market structure that significantly increases the environmental burdens, especially in China. In addition, the LCA results of pallets in the United States (Alanya-Rosenbaum et al., 2021), Australia (Weththasinghe et al., 2022), and Singapore (Ng et al., 2014), etc., have been figured out based on the life cycle inventory (LCI) data. However, the current LCA research have adopted distinguished goals and scopes, making the environmental impact results difficult to compare. The direct comparison of these studies is hindered by the variations in system boundaries and levels of transparency (Schenker et al., 2022). Moreover, the pallet market structure, the environmental effects of five pallet material types, and the barriers for developing pallet sharing system in China, remain unstudied because the fundamental data, including annual pallet holdings, technical parameters of production, EoL flows of pallets are currently unknown.

To fill this research gap, this study provides an efficient approach for comprehensively understanding the pallet market structure, the environmental effects, and the barriers for developing pallet sharing system in China with a well-defined system boundary by conducting field studies and LCA to evaluate the environmental impacts on pallets. Herein, comprehensive field studies have been conducted to collect primary data. The cradle to grave environmental evaluation of five pallet material types including wooden, plastic, paper, steel and fly ash pallets, covering the production stage, distribution stage, use stage and EoL stage are investigated. LCA, uncertainty analysis, sensitivity analysis, and scenario analysis are employed to investigate various EoL treatment methods, and identify the barriers in the green transformation of pallet industry. This paper could provide guidance for the government, the logistics carriers industry, and companies along the entire supply chain, to optimise the pallet market structure for reducing the environmental burdens.

2. Materials and methods

2.1 Goal and scope

The aim of this paper is to evaluate the environmental impacts of five different pallet material types, including wooden pallet, plastic pallet, paper pallet, steel pallet, and fly ash pallet from cradle to grave using LCA method. In addition, recycling and energy recovery scenarios are designed to explore the environmental impact mitigation strategies. The assessment is conducted on the basis of the international LCA standards (ISO, 2006a, b).

The system boundary is defined as a “cradle-to-grave” scope in order to evaluate the contribution of environmental impacts during the entire life cycle of pallets, including the production, distribution, use and EoL disposal stages (as shown in Fig. 1). The production stage can be traced back to the extraction of primary materials, such as oil extraction in the manufacture of plastic granulates. The stage of infrastructure construction and the transportation of raw materials are excluded. The distribution stage occurs in order to distribute pallets from the pallet manufacturing plants to the users. The use stage involves using electric forklift to palletise cargo and use pallets to transfer cargo between different users. The EoL stage includes different treatment methods based on the current waste treatment flows.

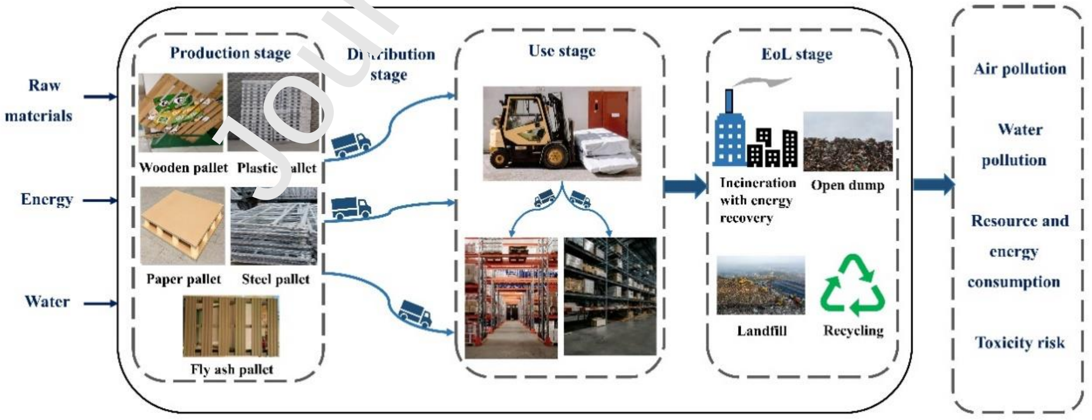

Fig. 1. System boundary of environmental impact assessment for pallets

This study selects “one tonne of cargo delivered using pallets” as the functional unit. This functional unit is used to more accurately describe the function of pallets in comparison to other studies, through taking reference service life (RSL) and load bearing capacity of pallets into consideration (Table 1). The FU is based on the "racked across the length" (RAL) support condition, which means that the pallet is only supported at its ends, instead of the racked across width condition, which means that the pallet is only supported at its edges. The RSL and load bearing capacity are used to determine the number of pallets needed to meet the functional unit (Alanya-Rosenbaum et al., 2021):

$$Number\ of\ pallets\ needed = \frac{One\ tonne\ of\ cargo\ delivered}{RSL\ (number\ of\ trips\ per\ pallet) \times Load\ bearing\ capacity}$$

Table 1

Specifications, RSL, and functional units of pallet designs

Pallet material type	Load capacity (tonnes)[a]	RSL (trips)	Number of pallets required
Wooden pallet	1	15	0.07
Plastic pallet	1.5	70	0.01
Paper pallet	1	4	0.25
Steel pallet	2	100	0.01
Fly ash pallet	1.5	15	0.04

[a] Load capacity as specified by manufacturer

It is worth noting that the system in China with no reuse loop for pallets is unique and differs from other countries or regions of the world where reuse is prominent. For example, the pallet sharing system has been established in which pallets are leased to the customers and collected after use for reuse in Europe and the US. The system aims to solve the problems of repeated pallet exchange in the traditional pallet management strategies, which can cause low operation efficiency and extensive materials input in the logistics process. Despite the advantages and success of pallet sharing systems in other countries, the adoption of this strategy in China is still very low. Based on field studies, expendable pallets still accounted for about 98.2% in China in 2020, indicating that the majority of pallets were still managed under the single use system, mainly due to the low awareness and willingness of users to return pallets, and the insufficient infrastructure and regulation for pallet repairing and recycling. These barriers hinder the development of sharing system for pallets in China and pose significant challenges for the green transition of the pallet industry.

2.2 Data sources

In order to collect reliable data on the pallet industry in China, we first conducted field study at the Pallet Professional Committee of China Federation of Logistics and Purchasing (CFLP). The CFLP is the largest and most authoritative organisation in the pallet industry in China, with 269 member companies that account for over 50% of the market share across 24 provinces (Fig. 2 (a)). Data on the annual holdings of pallets (Fig 2 (b), the main pallet material type and the market share of different pallet material types are collected (Fig 2 (c). We then used a purposive sampling method to select 20 companies from data sources. We chose representative companies based on their size, location and technology representativeness, etc. to ensure a diverse and representative sample. We conducted field trip and collected primary data covering the entire pallet supply chain for 2020 from these companies. The data was then analysed using descriptive and inferential statistics. Data collection was checked against requirements for data quality relating to limitations in terms of time, data representativeness and system boundaries, etc. Production values can be considered as universally representative, because production is standardised worldwide (Kočí, 2019). The background processes such as electricity and water are used in Gabi and ecoinvent database. The data inventory has been presented in table S1. The EU-28 average was used as a replacement for any specific item that had insufficient data for China. A cut-off criterion was used because of the limited data availability. In particular, an input that weighed less than 1% of the total weight of the outputs in a process would be excluded from the study (Wei et al., 2022).

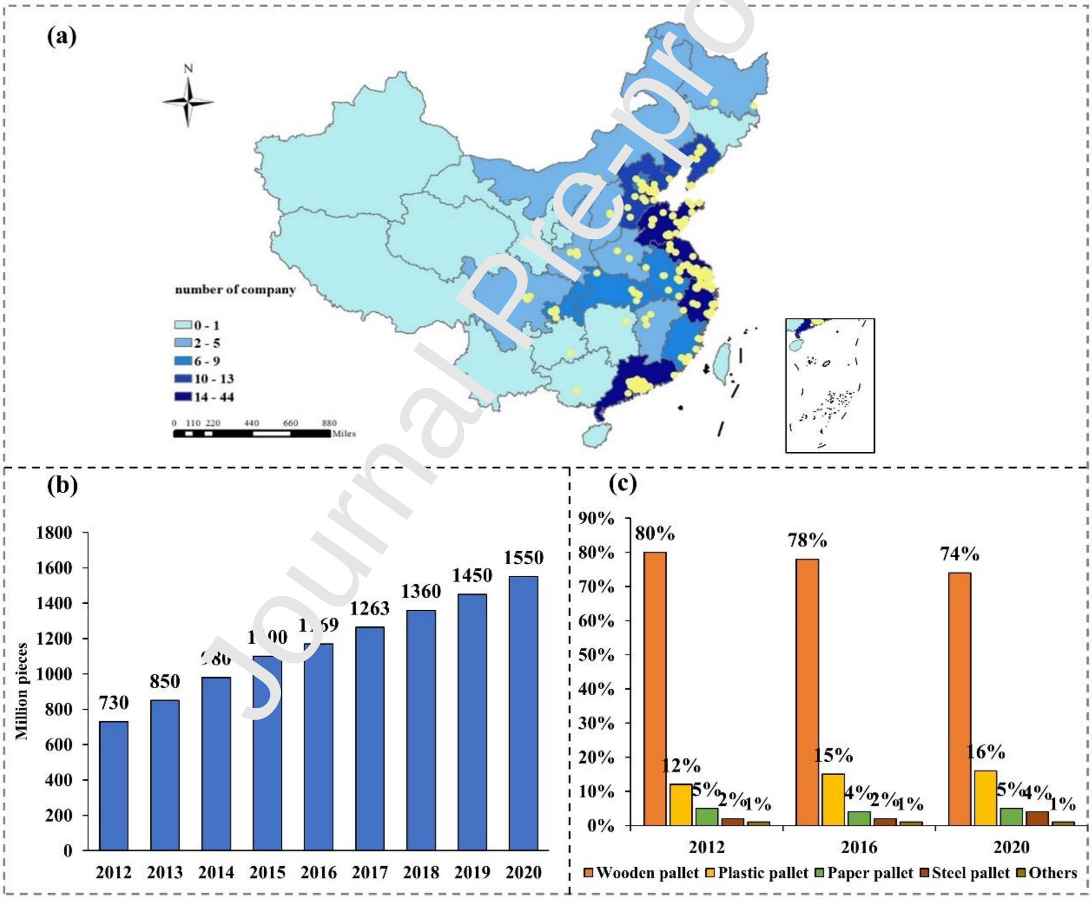

Fig. 2. Pallet market situation in China. (a) member companies in China of CFLP; (b) total pallet holdings in China from 2012 to 2020; (c) market structure of each pallet material type in China in 2012, 2015 and 2020 respectively.

2.2.1 Production stage

Wooden pallet. The bark on the logs is stripped, and the logs are cut into planks of the required pallet size. Heat treatment is carried out in order to meet the required dryness standard. After that, the required pallets can be obtained by cutting, sanding and assembling the planks, and connecting the upper panel and the wooden pier with nails. The production process generates wood residues which constitute 35% of the log input (García-Durañona et al., 2016). The wood residues become the by-product to be used as fuel (Alanya-Rosenbaum et al., 2021; Alanya-Rosenbaum and Bergman, 2020; García-Durañona et al., 2016).

Plastic pallet. Plastic particles and the colour concentrate are mixed uniformly in the mixer according to the customer's needs in a certain proportion as raw materials, and then the mixed raw materials are stirred by the screw of the injection molding machine. After the mixture is turned into a melt at a high temperature, the melt is injected into the mold of the plastic tray by an injection device, and it is formed after four stages of filling, pressure holding, cooling and demolding. The demolded pallet is processed and trimmed manually to obtain the required plastic pallets.

Paper pallet. Paper pallets are made by gluing corrugated cardboard and sand paper together in a certain way, and then dried under high temperature. Paper pallets are usually made by using the moisture-proof cardboard as the surface layer, or a layer of PE coating as the outer layer to increase water resistance.

Steel pallet. The production process of the steel pallet is to assemble and weld the plate or profile after sawing, punching and pressing, so that the steel panel and the steel leg are connected together under high temperature and high pressure. The powder coating is sprayed on the surface of the workpiece, and then the powder is heated to the specified temperature and kept for a corresponding time to melt and level before solidification, so as to obtain the desired surface effect.

Fly ash pallet. Fly ash pallet is made from fly ash, polyvinyl chloride (PVC), stabiliser, and lubricants. Adjuvant, with the main components of cerium and lanthanum make up 10% of the total materials in the fly ash pallet. The boards are made from injection molding, and steel nails are used to assemble the boards to make fly ash pallets.

2.2.2 Distribution stage

Based on field studies, the average transportation distance from the pallet warehouse to the customer's plant is 250 km, and the transportation method is road transportation by truck (Euro 4, 34–40 t gross weight with 27 t payload capacity).

2.2.3 Use stage

The process of the pallet usage stage is identified through field studies of pallet use companies: pallets are loaded with certain tonnes of goods based on their loading capacity by a forklift, transported with goods to the end user, and then unloaded by a forklift. The RSL numbers are collected from comprehensive field studies, by interviewing pallet manufacturers who have performed rigorous tests and the users who possess rich pallet use experience. Then the RSL numbers are validated and cross-checked with academic papers (Alanya-Rosenbaum et al., 2021; Anil et al., 2020). The data are also verified with experts from CFLP, who have extensive knowledge and experience in the pallet industry.

The average power consumption of electric forklifts is 0.05 kWh each time for loading and unloading respectively. This calculation assumes that the unitised logistics process is loaded and unloaded once each time. The average transportation distance of the logistics process is 300 km by truck (Euro 4, 34–40 t gross weight with 27 t payload capacity). Different pallet material types have different carrying capacity and RSL. Wooden, plastic, paper, steel and fly ash pallet has the carrying capacity of 1, 1.5, 1, 2 and 1.5 tonnes, and RSL of 15, 70, 4, 100, 15 trips. These RSL numbers are reasonable with reference to Anil et al. (2020), Deviatkin et al., (2019) and Khan et al. (2021). The main difference between wooden pallets and other pallets is that wooden pallets need to be repaired twice in its use stage (Weththasinghe et al., 2022), which is also considered.

2.2.4 EoL stage

The base scenarios for the EoL management of different pallet material types are established by using data collected from field studies. About 33.3% of waste wooden pallets are dismantled to be reused as boards, 53.4% are used as biomass fuel, 11.3% are recycled to make wood shavings, and 2.0% are landfilled. Due to the lack of available data on EoL path situation of plastic pallets and paper pallets, the data applied are based on general waste plastics and waste paper EoL flows in China. The EoL path for plastic pallets is as follows: 25% pallets are recycled, 27.5% are incinerated for energy recovery, 45.9% are landfilled and 1.6% are open dumped (Jiang et al., 2020). The base case for waste paper pallets is: 51.3% of waste paper pallets are recycled, 29.3% are incinerated as fuel, 17.8% are landfilled, and 1.6% are leaked in the environment (Liu et al., 2020). The EoL for steel pallets and fly ash pallets are 100% recycled and 100% landfilled respectively. One tonne of waste paper can produce 0.8 tonnes of pulp (Liu et al., 2020). Collection rates of 90%, 85% and 85% are used for waste steel, waste plastic and waste fly ash pallets, respectively (Thinkstep, 2021).

2.3 Life cycle impact assessment

The whole life cycle of pallets involves the consumption of resources and energy. In addition, the production process of pallet can cause air pollution, such as greenhouse gases (GHGs) emission, dust and sulfur dioxide (SO_2), etc. and waste water pollution. The pollutants discharged during the entire life cycle can cause toxicity both to human beings and the natural environment. Therefore, this research chooses four categories of environmental impact indicators: air pollution (GWP, FPMF, IR, POF and TA); water pollution (FEu), the consumption of resources and energy (FC, FD and MD); and toxicity risk (HT, TE and FE) (Table 2). In order to make the overall environmental impacts more comparable, the ReCiPe methodology which is based on Eco-indicator 99 (Goedkoop et al., 1998) and CML methodology (Cabeza et al., 2014) is adopted to get comparable normalised indexes. The mass allocation and unit process modelling approach are used to model the LCA. Default normalisation and weighting methods in the ReCiPe model are selected in order to get a weighted index (Huijbregts et al., 2017).

Table 2

Interpretation of environmental impact indicators

Category	Name	Abbreviation	Unit
Air pollution	Climate Change	GWP	kg CO_2 eq.
	Fine Particulate Matter Formation	FPMF	kg $PM_{2.5}$ eq.
	Ionizing Radiation	IR	Bq C-60 eq. to air
	Photochemical Ozone Formation	POF	kg NOx eq.

	Terrestrial Acidification	TA	kg SO_2 eq.
Water pollution	Freshwater Eutrophication	FEu	kg P eq.
Resource and energy consumption	Freshwater Consumption	FC	m^3
	Fossil Depletion	FD	kg oil eq.
	Metal Depletion	MD	kg Cu eq.
Toxicity risk	Human Toxicity, cancer	HT	kg 1,4-DB eq.
	Terrestrial Ecotoxicity	TE	kg 1,4-DB eq.
	Freshwater Ecotoxicity	FE	kg 1,4-DB eq.

Note: eq. is the abbreviation of equivalent.

2.4 Uncertainty and sensitivity analysis

Uncertainty refers to the variations in outcomes brought on by the uncertainty of input parameters. The Monte Carlo method is used to capture the uncertainty based on 10,000 sampling values (Zhao et al., 2019). The data collected from production process is subject to more uncertainty because of the operation data of multiple pallet producing plants (Li et al., 2022). Therefore, variations in resource and energy consumption, direct atmospheric and wastewater emissions in the production stage are all taken into consideration in uncertainty analysis and assuming that the parameters are normally distributed. Probability distribution histograms and 95% confidence intervals are constructed based on simulations (Li et al., 2022).

Besides, a comprehensive sensitivity analysis is performed to evaluate to what extent a single parameter change can influence the results (Alanya-Rosenbaum et al., 2021). The lifespan of pallets depends on a variety of elements, e.g., the type and grade of materials used, and quantity of handlings, etc (Anil et al., 2020; Weththasinghe et al., 2022). Therefore, RSL is tested to evaluate the effects on LCIA results.

2.5 Scenario analysis

In addition to parameter-based sensitivity analysis, alternative EoL scenarios are considered to assess the potential environmental benefits and burdens of different EoL treatments, in order to encourage pallet industry to adopt more sustainable waste management practices that enable a circular economy for waste pallets, and provide guidance on reducing environmental impacts of pallet industry (Korhonen et al., 2018). Scenario analysis will be performed by system expansion approach to account for the avoided burden from material recycling and energy recovery (Eriksson et al., 2010; Frischknecht, 2010). If recycled materials are used, the environmental impacts of virgin materials will be avoided. If pallet waste is incinerated during EoL treatment, significant amounts of energy can be recovered in the form of electricity or district heat, and the environmental effects from combustion of other fuels will be avoided (Ng et al., 2014). Therefore, scenarios for increasing the portion of recycling or energy recovery are established to explore the EoL treatment method with more potential environmental benefits.

Two scenarios are set for wooden pallets to compare the environmental implications of dismantling against incineration for energy recovery. 86.7% of waste wooden pallets are used for fuel, and 86.7% of waste pallets are used for dismantling respectively, with the portion of wood shavings and landfill constant. The environmental credits from using by-products, e.g., wood dust, derived from pallet manufacturing for energy recovery are also considered (Table S2). In order to explore the environmentally friendly EoL method for plastic pallets, environmental impacts of recycling and energy recovery are compared, keeping the portion of landfill and open dump unchanged. For paper pallets, 80.6% of waste paper pallets are recycled to make pulp or incinerated for energy recovery, keeping the remaining 19.4% are unchanged. The scenario is also set to explore the environmental implications of recycling waste fly ash pallets (Fig. 3).

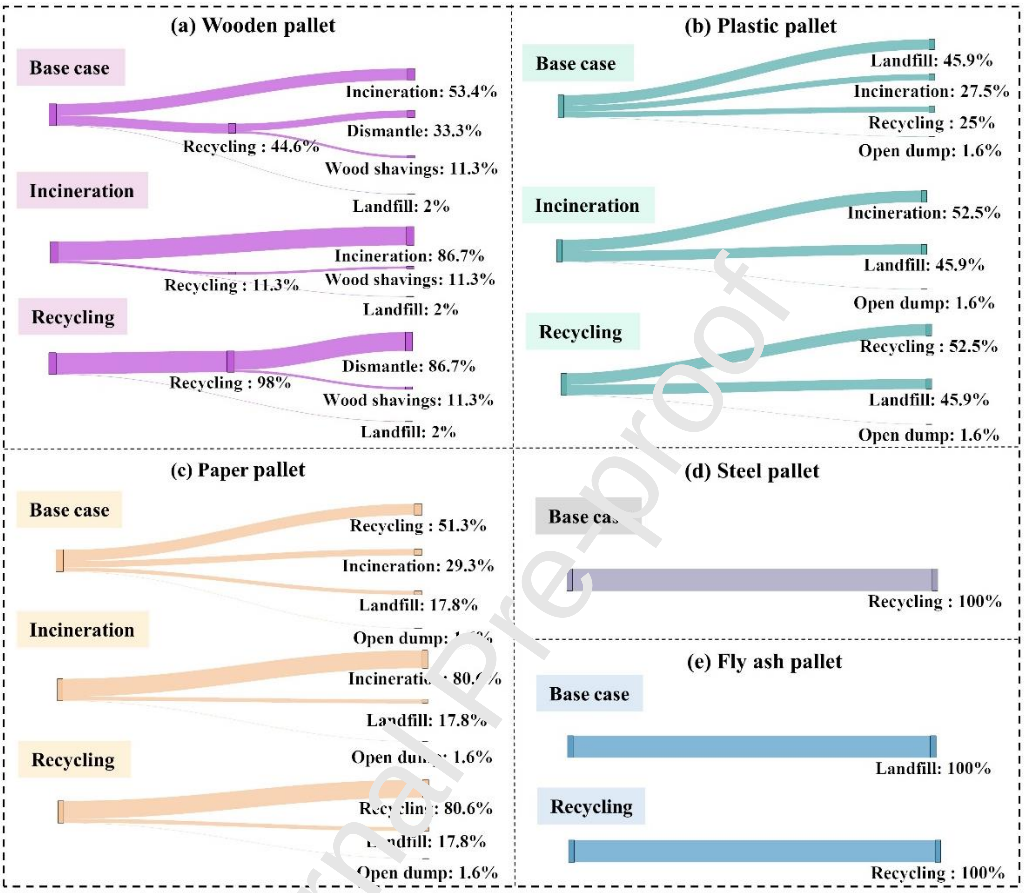

Fig. 3. Scenario settings for EoL flows of five pallet material types

3. Results

The annual production of pallets in China is about 340 million pieces, and the pallet market has reached 1.55 billion pieces in 2020 (Fig. 2 (b)). There are currently four widely used pallet material types in China. Wooden pallets have the highest market share, accounting for 74% in 2020 (Fig. 2 (c)). However, they are limited in industries that require high hygiene conditions (such as food and pharmaceutical industries) since wooden pallets have burrs and easily go mouldy. Plastic pallets are gradually occupying the market due to their advantages of easy cleaning and smoothness, and their market share has increased from 12% in 2012 to 16% in 2020. Paper pallets account for 5% of the market. The main advantage of paper pallets is that the pallet specifications and structures can be designed and customised according to product characteristics and shapes, avoiding the high costs of opening molds. Due to the high carrying capacity, the share of steel pallets has increased from 2% in 2012 to 4% in 2020.

3.1 The environmental impact analysis of different pallet material types

Wooden pallet. The production stage of wooden pallets contributes the most to MD and IR, accounting for 70% and 65% respectively (Fig. 4 (a)). Use stage is the most important contributor to most of the environmental impact indicators, from 59% in FE to 91% in FD, because of the use of the electricity consumed during service life. EoL stage accounts for 100% negatively to GWP indicator (Table S3), because of the avoided impacts from using dismantled board and incinerating waste wood (Alanya-Rosenbaum et al., 2021; Gasol et al., 2008). In the production stage of wooden pallet, logs contribute 73% in FEu, because of the application of chemical fertilisers and pesticides during tree planting. Nails are one of the major contributors to IR and MD. Electricity is consumed in sawing process (García-Durañona et al., 2016), contributing 70% in FC and 95% in TE in logs treatment stage.

Plastic pallet. The results show that the production stage of plastic pallets is the most important contributor to most of the environmental impacts (from 46% positive contributions in TA to 94% positive contributions in IR (Fig. 4 (b)), while EoL stage decreases the results of nine environmental impacts (Table S4), because of the energy recovery process and using waste plastics to replace virgin materials. Focusing on the production stage, the main impact is caused by the manufacturing of polypropylene granulates (from 52% in TA to 84% in FD), which make up 88% of all materials consumed in pallets. Polypropylene granulates are the largest contributor (accounting for 73%) to GWP through the extraction and transportation of fossil fuels and the refining and manufacturing processes. Moreover, plastic waste that enters the ocean, waterways and natural landscapes poses a long-term toxic threat. The emission of aromatics brings about higher environmental risks during the whole production process of polyester fibres, especially in the upstream processes: the thermal cracking and refining of petroleum (Zhang et al., 2021). Electricity accounts for the most environmental impact in FPMF (accounting for 49%), because of the emission of primary and secondary aerosols in the generation of electricity from coal. Electricity also accounts for 17% of GWP (Weththasinghe et al., 2022). Direct emissions from the pallet manufacturing plants are relatively low (2%) in POF, but they still release non-methane hydrocarbon (NMHC) during the production process.

Paper pallet. The production stage of paper pallets is the most important contributor to most of the environmental impacts (from 68% positive contributions in FC to 98% positive contributions in IR), while the production stage contributes almost 100% to FEu because of the pesticides or fertilisers used during tree planting in the upstream process of paper, and the nutrient load of the water body increases (Zhang et al., 2021). The use stage contributes 68% in GWP, 74% in FD and 71% in HT (Fig. 4 (c)), because of the electricity consumed in carrying cargo. EoL stage contributes negatively to most of the environmental impacts (Table S5), because of the avoided impacts from using recycled pulp and incinerating waste paper for energy recovery. Focusing on the production stage, sand paper has high environmental impacts on four air pollution indicators, GWP (44%), FPMF (40%), IR (89%) and POF (67%), which is mainly because of the chemical pulp process. GHG is emitted when mixed wood chips and the pulping chemicals are heated in order to dissolve lignin, hemicellulose and cellulose, and separate the remaining cellulose fibres from the liquid (Thinkstep, 2021). The kraft pulping process requires high temperatures (usually from 165 to 175℃) which adversely affects the climate change. Besides, the heating process contributes to TA because of the inputs of sodium sulfide and sodium sulfate. In addition, gum with corn starch contributes 35% to GWP and 32% to FD owing to the consumption of electricity during the manufacturing process.

Steel pallet. The production process of steel pallets has the most significant impact on GWP (64%) and MD (almost 100%), because of the radionuclide emission during smelting process (Fig. 4 (d)). EoL stage brings out environmental benefits (Table S6), because waste steel pallets and by-products from steel pallets manufacturing process are recycled to make steel pipes, which avoids the production of primary steel. For the production stage, steel pipe contributes 96% in GWP, since the production processes, such as crushing and palletisation stage, emit large amounts of greenhouse gases (GHGs) (Jing et al., 2014). Besides, high temperatures are required in the process of melting steel plates in order to produce steel pallets (Burchart-Korol, 2013; Norgate et al., 2007; Tian et al., 2013). Steel pipe accounts for 95% in POF result, because of the emission of volatile organic compounds during its production process. Steel pipe contributes the most to the remaining environmental impact indicators (from 77% in FC to almost 100% in MD).

Fly ash pallet. The results indicate that the production stage of fly ash pallets has the highest impact on resource and energy consumption indicators, accounting for 99% in FC and almost 100% in MD (Fig. 4 (e)). In addition, the use stage contributes the most to FE and POF, accounting for 54% and 67% respectively, and landfill contributes 87% in water pollution indicator (Table S7). Regarding to the production stage, adjuvant accounts for 52% of the total GWP emissions of the pallet, because processes for treating real earths, such as the extraction, separation, concentration, etc. emit a large amount of GHGs. Besides, adjuvant causes 74% of TA, mainly because of the roasting process in which the acid residue (mainly consisting of rare earth fluoride) is converted into an alkali hydrate under high temperatures and dissolved with hydrochloric acid (Thinkstep, 2021). PVC contributes 48% of FD, since it accounts for 30% of the total weight of the pallet, and the production process of the polymers emits a large amount of GHGs. Adjuvant also contributes the most to toxicity risk, ranging from 58% in FE to 74% in TE.

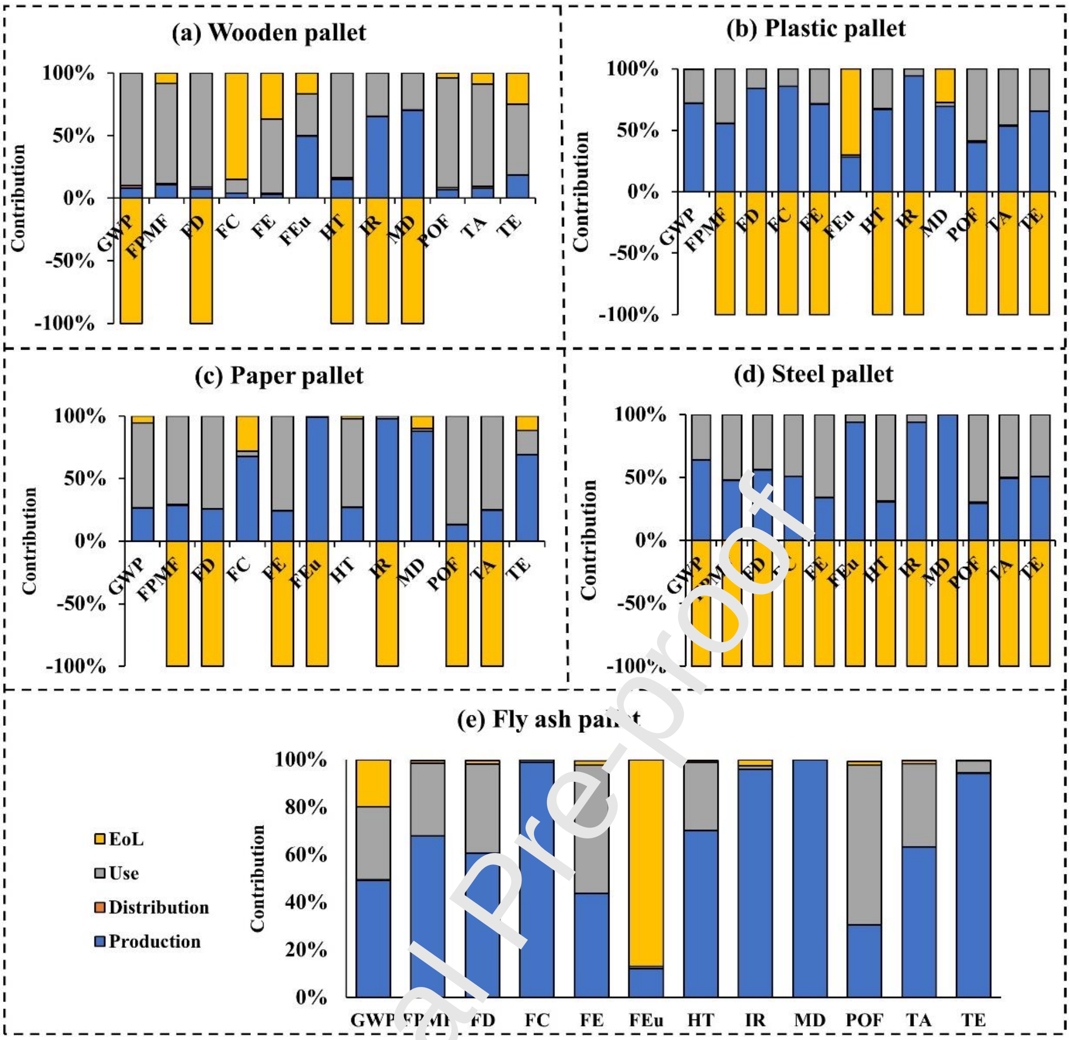

Fig.4. Source of environmental impacts for five pallet material types from cradle to grave. (a) wooden pallet; (b) plastic pallet; (c) paper pallet; (d) steel pallet; (e) fly ash pallet.

3.2 Uncertainty and sensitivity analysis

The distributions based on Monte Carlo simulations are more convincing based on 10,000 sampling values that better represent the actual situation of the pallet industry (Li et al., 2022). Wooden pallet displays the smallest GWP result (0.12 ± 0.01 kg CO_2 eq.), while fly ash pallet achieves the value of 2.05 ± 0.08 kg CO_2 eq. (mean ± SD). Steel pallet, plastic pallet and paper pallet has the GWP result of 0.40

± 0.03, 0.61 ± 0.05 and 1.81 ± 0.20 kg CO_2 eq. respectively (Fig. 5 (a)). Regarding FD indicator, wooden pallet has the smallest result of 0.04 ± 0.002 kg oil eq., followed by steel pallet (0.09 ± 0.01 kg oil eq.), and paper pallet has the highest result (0.53 ± 0.06 kg oil eq.). Steel pallet has 0.18 ± 0.01, wooden pallet has 0.18 ± 0.01, and fly ash pallet has 6.20 ± 0.29 kg 1,4-DB eq. for TE (Table S8).

Through changing RSL of wooden pallets from 5 trips to 25 trips, air pollution indicators can be reduced from 78% in GWP (Fig. 5 (b)), FPMF, FD to 80% in FE and POF. FEu result has a variance of 79% (Table S9). The increase in service life (from 40 to 120 trips) has the greatest effect on GWP results, about 64% variance for plastic pallets. The overall environmental impacts have been reduced through increasing RSL for plastic pallets (Fig. 5 (c)). Paper pallets are not waterproof, and they are more easily broken without standard operations, leading to the smallest life span range (1 to 9 trips). GWP has been significantly reduced by 89% through expanding the service life to 9 trips (Fig. 5 (d)). Steel pallets are more durable, thus having the longest life span compared with other pallets. From changing the service life from 50 to 250 trips, GWP result can be reduced by 74% (Fig.5 (e)). MD is the most sensitive to service life, having 79% output variance. FC and TE are not sensitive to the life times (Table S10). The increasing service life of fly ash pallets leads to the decreased environmental impacts (80% output variance). GWP has been decreased by 80% through prolonging its service life (Fig. 5 (f)). The findings indicate a negative correlation between the number of RSL and the overall environmental effects, which is consistent with Weththasinghe et al. (2022).

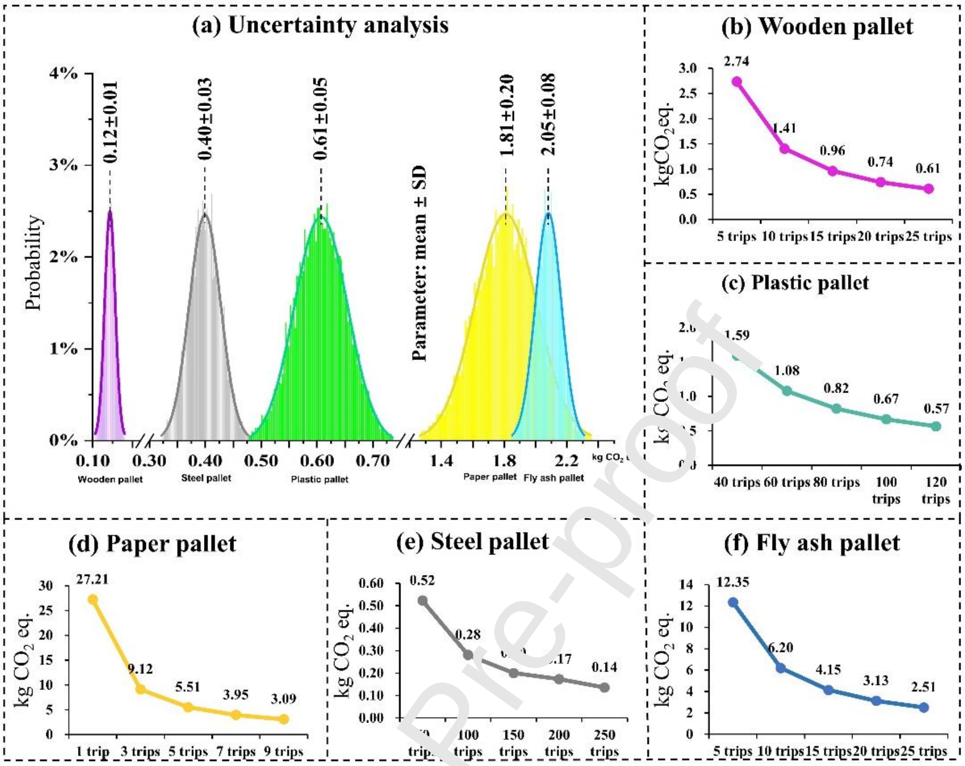

Fig.5. Uncertainty and sensitivity analysis for each pallet. (a) uncertainty analysis for five pallet material types; (b) sensitivity analysis for wooden pallet; (c) sensitivity analysis for plastic pallet; (d) sensitivity analysis for paper pallet; (e) sensitivity analysis for steel pallet; (f) sensitivity analysis for fly ash pallet.

3.3 Scenario analysis for waste management methods

Wooden pallet. Under incineration scenario, the process of making waste wood into biomass fuel and the combustion of wood fuel increase the overall environmental impacts, while steam recovery reduces environmental impacts (García-Durañona et al., 2016). The environmental performance of incineration scenario (-0.06) is better than base case (-0.05) scenario, owing to the environmental benefits derived from using waste wood as fuel (Fig. 6 (a)). GWP result of incineration scenario (-0.73 kg CO_2 eq.)

is smaller than base case scenario (-0.58 kg CO_2 eq.). The recycling scenario (-0.03) performs worse than the base case scenario. The finding that the energy recovery treatment method is better than dismantling method is consistent with Alanya-Rosenbaum et al. (2022).

Plastic pallet. The recycling scenario has the lowest environmental implications (-0.03), because of the environmental benefits derived from using waste plastics as raw materials to replace virgin materials, which outweighs the environmental burdens caused by the process associated with the production of secondary plastic pellets from waste plastic pallets. The incineration scenario performs worse than the base case scenario (Fig. 6 (b)), owing to the high carbon emissions from incineration of waste plastics. The air pollution indicator of base case scenario is 119% lower than incineration scenario. The weighted environmental impacts of recycling scenario is lower than incineraion scenario, which reaches the same conclusion with research on waste plastics (Chen et al., 2019; Razzaq et al., 2021).

Paper pallet. The incineration scenario has the lowest environmental impacts (-0.02), which is significantly lower than the weighted environmental implications of base case scenario (0.01) (Fig. 6 (c)), because of the environmental benefits derived from recovered steam. The weighted index of recycling scenario is 100% higher than base case scenario, owing to the resource and energy consumption in recycling waste paper. Therefore, the development of recycling technologies at a high environmental performance level is vital (Merrild et al., 2008).

Steel pallet. The weighted environmental impacts index of base case scenario is -0.04 (Fig. 6 (d)), considering the avoided impacts of recycling waste steel. The resource and energy consumption weighted index reduces to -0.02 through recycling waste steel, because the manufacturing of primary steel is highly energy intensive. GWP result and FD result of base case scenario are -55.6 kg CO_2 eq. and -13.0 kg oil eq. respectively.

Fly ash pallet. The recycling scenario achieves -0.15 weighted index (Fig. 6 (e)), while the base case scenario has the weighted index of 0.03, showing that the recycling method brings out environmental benefits due to the avoidance of virgin raw materials.

Considering the whole life cycle of each pallet, under the current EoL paths for each pallet material type, steel pallets perform the best in accordance with the comprehensive weighted index of environmental impacts (Fig. 6 (f)). Steel pallets have the highest load carrying capacity and the longest life span (100 trips), which largely reduces environmental impacts based on the functional unit, demonstrating that the life span and carrying capacity are negatively with environmental effects (Weththasinghe et al., 2022). Through recycling waste steel pallets, the environmental benefits will be created. Paper pallets cause the most environmental impacts through the entire life cycle, because of the shortest RSL (4 trips). Under the base case scenario, wooden pallets are more environmentally friendly than plastic pallets (Anil et al., 2020; Kočí, 2019; Weththasinghe et al., 2022). Through incinerating waste wooden pallets for steam, the overall environmental impacts can be reduced by 11%. The overall weighted impacts can be reduced by 10% through recycling waste plastic pallet as the EoL treatment method.

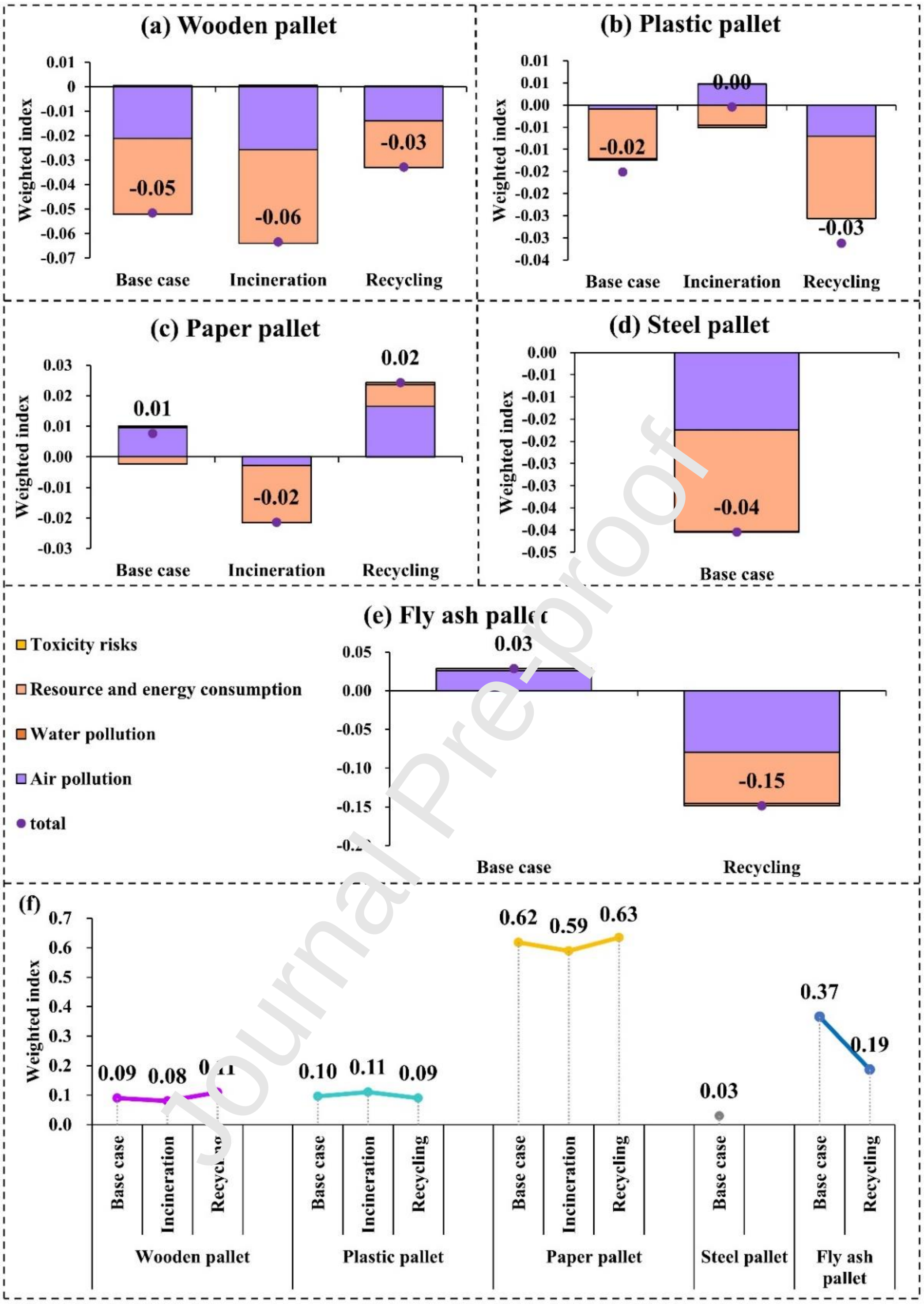

Fig.6. Weighted environmental impacts for each pallet material type. (a) weighted index for EoL stage of wooden pallet; (b) weighted index for EoL stage of plastic pallet; (c) weighted index for EoL stage of paper pallet; (d) weighted index for EoL stage of steel pallet; (e) weighted index for EoL stage of fly ash pallet. (f) Weighted environmental impacts for the whole life cycle of each pallet

4. Discussion

4.1 Hotspots of environmental impacts

Steel pallets will have the least environmental impacts when used more than 34 times. Due to their long lifespan, steel pallets exhibit the highest environmental performance among different pallet material types. Nevertheless, the diffusion of steel pallets is hindered by several barriers. The high price and weight of steel pallets entail higher transportation costs. It is suggested to implement eco-design strategies, such as reducing the weight of pallets without affecting the performance of the pallet (Duan et al., 2019; Kang et al., 2021). Through reducing the weight of pallets, the diesel used to transport pallets can be correspondingly reduced.

Plastic pallets are regarded as a competitor for wooden pallet, and are occupying the market share of wooden pallets. However, the quality of plastic pallets in China varies widely. Some vendors mix poor-quality plastic particles into the production process of pallets, which lowers the price of plastic pallets below that of wooden pallets and encroaches on the market of wooden pallets. A vicious cycle will be formed in the long run. Besides, in the current scenario, plastic pallets perform worse in environmental impacts than wooden pallets. Therefore, awareness needs to be raised on the traceability and supervision of plastic raw materials, and the increasing of recycling rates on plastic pallets.

Among all the factors that cause environmental impacts, the production stage is the hotspot for plastic, paper, steel and fly ash pallets. In the production of pallets, raw material production and electricity consumption are usually major issues. Using recycled materials to replace virgin materials and using renewable energy, such as solar energy are two strategies to reduce environmental impacts (Buonocore et al., 2016; Plachinski et al., 2014; Williams et al., 2012; Wu et al., 2019). The construction of industrial recycling plants, with in-depth cooperation between the upstream and downstream of the industrial chain, to realise the closed loop of waste materials is an effective way for these pallets (Hao et al., 2017; Tong et al., 2018; Villanueva and Wenzel, 2007). However, for wooden pallets, the use stage contributes to the most environmental impacts. Environmental performance could be improved through reducing the inefficient driving of transport vehicles, deploying clean energy trucks to transport pallets and developing lightweight pallets (Bauer et al., 2015; Wu et al., 2019).

In the EoL treatment stage, incinerating for energy recovery creates the most environmental benefits compared with other EoL methods for wooden pallets and paper pallets, reducing the overall environmental impacts by 20% and 300% respectively. Besides, adopting recycling as the EoL treatment method can significantly reduce environmental impacts for plastic, steel and fly ash pallets.

A negative correlation between the number of RSL and the overall environmental effects has been confirmed through sensitivity analysis. From increasing the reuse times, environmental impacts can be reduced from 38% to 80%, and the GW impact can be reduced from 65% to 89% for pallets. In order to reduce environmental burden, training employees on best pallet-handling practices to prolong the service life of pallets is an effective strategy (Carrano et al., 2014).

4.2 Implications for management

The 14th Five-Year Plan for Logistics proposes to advance the development of a pallet circulation and sharing system, which can effectively reduce environmental impacts compared with single-use system. However, the current rate of pallet circulation and sharing in China is only 1.8%. It fails to address the challenges that impede the diffusion of pallet circulation and sharing in China. One of the challenges of promoting pallet sharing system in China is the lack of pallet standardisation which can make reuse easier by reducing sorting costs and facilitating pallet exchange. The key factor influencing pallet standardisation in China is not the pallet manufacturers, but the pallet users who dominate the market. The pallet users require the pallet manufacturers to produce pallets of different sizes according to their product specifications, resulting in a large variety of pallet sizes in China, which severely restricts the inter-firm flow of pallets. Therefore, the focus should be on engaging the leading user enterprises in the supply chain to foster the standardisation of pallets, rather than merely relying on the pallet manufacturers who have limited voice or bargaining power.

However, pallet standardisation is not a prerequisite for pallet reuse, as evidenced by the US market, where pallet reuse is very prominent despite the diversity of pallet sizes and types. The key factors that enable pallet reuse are the availability of pallet repair and recycling services, the industry consolidation, and the environmental awareness of reducing pallet waste (Gerber, 2020). Therefore, besides focusing on pallet standardisation, China could explore other ways to encourage pallet reuse, such as developing a network of pallet service providers, creating a platform for pallet sharing and exchange, and raising public awareness of the benefits of pallet reuse for sustainability.

In addition, the existing policy lacks differentiation in the management strategies for various pallet material types. Different materials of pallets have different hotspots of environmental effects. For wooden pallets, the use stage has the greatest environmental impact, and the maintenance and transportation routes need to be optimised. For other pallet material types, the production stage is the hotspot, and the production process needs to be optimised. At the same time, for wooden and paper pallets, incineration to recover energy is better than other disposal methods; while for other three pallet material types, establishing a sound recycling system is an effective measure.

However, the data collection in this study may not capture the full diversity and complexity of the pallet industry in China, and that this may limit the generalisability of our findings. Future research could collect more comprehensive and representative data from a larger sample of pallet stakeholders in China, and compare the results with other countries or regions with different pallet market structures and environmental regulations.

5. Conclusion

The current pallet market structure has potential for improvement from the perspective of environmental impact. The traditional pallet market structure is mainly influenced by economic, convenience and other factors, but now with the global environmental change, the environmental requirements of the head-end users for pallet products are improved, resulting in environmental performance becoming a main influencing factor of the pallet industry. Therefore, there are opportunities to improve the environmental impacts related to pallets and to achieve a green transition of the pallet industry in China.

The use of different disposal methods plays a crucial role in causing different pallet material types' environmental impact. By choosing the appropriate treatment method for each pallet material type, the environmental impact can be significantly reduced. For example, burning wooden and paper pallets for energy recovery can create the greatest environmental benefits, reducing the overall environmental impacts by 20% and 300%, respectively. For plastic, steel and fly ash pallets, waste recycling is an effective treatment strategy. There is a negative correlation between RSL and the overall environmental effects. By increasing the number of uses, the environmental impacts can be reduced by 38% to 80%.

Furthermore, the existing structure of the pallet market is disadvantageous from an environmental standpoint. Steel pallets will have the lowest environmental impacts when they are used more than 34 times, but they only accounted for 4% of the market share in 2020. The high cost and weight of steel pallets impeded their dissemination, and China has not yet developed a circular sharing system. Moreover, plastic pallets are regarded as rivals of wooden pallets, as their market share increased from 12% to 16%, while that of wooden pallets decreased from 80% to 74%. However, plastic pallets have a worse environmental impact than wooden pallets. This is mainly because some producers use low-quality plastic pallets, which lower the price of plastic pallets below that of wooden pallets, thereby eroding the market share of wooden pallets and creating a vicious cycle. Therefore, the current market structure of pallet logistics does not align with the market structure that can achieve optimal environmental performance.

In addition to focusing on pallet standardisation which can make reuse easier, the availability of pallet repair and recycling services, the industry consolidation, and the environmental awareness of reducing pallet waste can also contribute to encouraging pallet reuse. For different pallet material types, it is recommended to formulate different management strategies according to the environmental hotspots in the whole life cycle. It is very important to assess the environmental impact for the logistics carrier industry to achieve green transformation, but the current research lacks sufficient analysis and data gap. This study takes pallets as an example, fills the data gap of pallet LCA research, proposes a comprehensive LCA framework to assess the environmental impact of pallets, and identifies the barriers that hinder the development of sharing system in China's logistics transportation carrier industry, providing some enlightenment for the whole logistics carrier industry.

CRediT authorship contribution statement

Tingting Zhang: Conceptualization, Methodology, Data collection, Software, Writing–original draft. **Zongguo Wen**: Project administration, Supervision, Writing–original draft, review & editing, Funding acquisition. **Fan Fei**: review & editing. **Vorada Kosajan**: Methodology. **Yiqi Tan**: review & editing. **Mao Xu**: 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 material associated with this article can be found in the online version.

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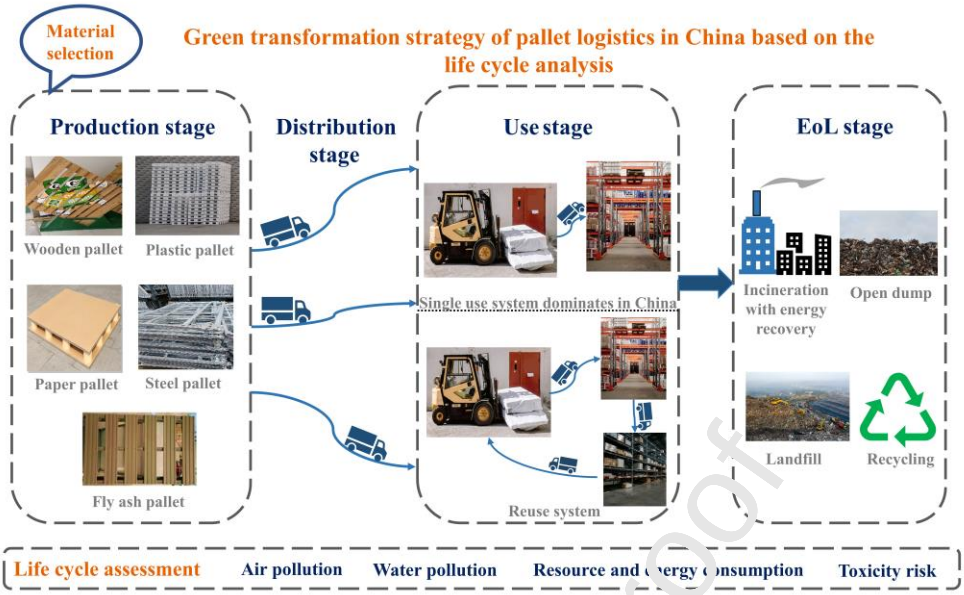
Graphical abstract



Highlights

- Trace the source of environmental impacts in the entire life cycle of pallets
- Compare the environmental performance of five representative pallet material types
- Provide the path for more sustainable waste management to make contributions to the green transformation of the pallet industry
- Identify the barriers that hinder the development of sharing system in China’s logistics transportation carrier industry