Pallets in China: an assessment of lifecycle environmental impacts and moves towards greater circularity

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Declaration

I, Tingting Zhang, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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I would like to dedicate this thesis to all the people who have supported me throughout my PhD journey. Without their help, guidance and encouragement, this work would not have been possible.

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Abstract

Global trade has significantly reshaped both economic systems and the environment. As essential tools in the logistics industry, pallets play an important role in protecting and transporting over 80% of global trade. However, the widespread use of pallets comes with notable environmental implications. 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 circularity, environmental impacts, and the green transformation pathway of the pallet industry.

This study evaluates the circularity of the pallet industry in China considering the complex interactions among materials, products, sectors, and waste management systems in the entire supply chain, based on field studies and material flow analysis. Additionally, it develops a comprehensive framework for the green transformation of the pallet industry, employing life cycle assessment to evaluate environmental impacts across five pallet types under three scenarios at product and national scales. The framework encompasses three scenarios: the pallet system as in China today, the establishment of a pallet sharing system and the adoption of circular economy (CE) strategies.

Results show that (1) pre-consumer waste constitutes 36% of total inputs, generating 4.53 Mt of waste, with current waste management practices being far from circular; (2) the Chinese pallet market can achieve significant environmental impact reductions by transitioning to a pallet sharing system and CE scenario, with reductions ranging from 90% to 96%, and 94% to 108% respectively; (3) key barriers to promoting the green transformation of the pallet industry in China, such as low standardisation, insufficient recycling infrastructure, and lack of awareness, have been identified, along with tailored strategies to address these challenges. The study can help policy-makers guide

joint efforts for green logistics along the supply chain and contribute to Sustainable Development Goal 12 targets.

Impact Statement

This thesis combines material flow analysis and life cycle assessment methods to reveal the material metabolism and resource efficiency of the pallet industry, and provides a scientific basis and reference guidance for improving the environmental performance of the pallet industry. Part of the results have been published in *Resources, Conservation & Recycling.* Besides, a comprehensive environmental impacts comparison for the main pallet types has been conducted, which identifies environmental hotspots and fills the data gap by collecting the primary data on the entire supply chain of pallets in China through field trips. This part of research has been published in *Science of The Total Environment*. In addition, a comprehensive framework, which can be generalised to other types of logistics carriers has been constructed, to identify the green transformation pathway of the pallet logistics in the second-largest pallet holder, China. This part of the research has been published in *Sustainable Production and Consumption.*

This study provides valuable insights for stakeholders in China to make rational and sustainable decisions based on the results of the current circularity status and the potential of environmental impact reduction in the pallet industry. Besides, this research uses pallets as an example to provide some enlightenment for the stakeholders in China and beyond which is facing challenges and opportunities of green transformation in the logistics carrier industry. By facilitating the green transformation of the booming Chinese pallet industry which accounts for 25% of the total global pallet market, the study can contribute to Sustainable Development Goal 12 (Sustainable Consumption and Production) targets and China's pledge to achieve carbon neutrality by 2060.

This PhD project has also supported the compilation of the 2021 Report on Sustainable Development of the Pallet Industry in China, for which the author is the associator editor. In addition, the research supported a project, Research on accounting for greenhouse gas emissions from shared pallets, in Tsinghua University, which has been used as a reference for evaluating the carbon footprint of pallets, to guide the pallet logistics how to become more environmentally friendly.

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List of acronyms and abbreviations

ALCA	Attributional LCA
AP	Acidification potential
BC	Black carbon
CE	Circular economy
CF	Cotton fibres
CFLP	Pallet Professional Committee of China Federation of Logistics and Purchasing
CLCA	Consequential LCA
CW	Consumption waste
DPC	Domestic physical consumption
EDDEC	Environnement, développement durable et économie circulaire
EIA	Environmental impact assessment
EoL	End-of-Life
EP	Eutrophication potential
EPS	Environmental priority strategy
EU	European Union
FC	Freshwater consumption
FD	Fossil depletion
FE	Freshwater ecotoxicity
FEu	Freshwater eutrophication
FPMF	Fine particulate matter formation
FPMs	Fine particulate matters
FU	Functional unit
GF	Glass fibres
GHG	Greenhouse gas
Gt	Gigatonnes
GWP	Climate change
HF	Hidden flows
HT	Human toxicity
ICCE	Implementation Centre for Circular Economy
IPAG	Institut de préparation à l'administration et à la gestion
IR	Ionizing radiation
ISO	International Organisation for Standardisation
ISPM 15	Standards for Phytosanitary Measures document No. 15
JF	Jute fibres
KF	Kenaf fibres
Kt	Kilotonnes
LCA	Life cycle assessment
LCI	Life cycle inventory

LCIA	Life cycle impact assessment
LU	Land use
MD	Metal depletion
ME	Marine ecotoxicity
MeBr	Methyl bromide
MEu	Marine eutrophication
MFA	Material flow analysis
mm	Millimetre
Mt	Million tonnes
NAS	Net addition to the stock
NMHC	Non-methane hydrocarbon
NMVOCs	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
OD	Ozone depletion
PAHs	Polycyclic aromatic hydrocarbons
PE	Primary extraction
POF	Photochemical ozone formation
PP	Polypropylene
PS	Photochemical smog
PVC	Polyvinyl chloride
RAL	Racked across the length
REPA	Resource and environmental profile analysis
RSL	Reference service life
SDG	Sustainable Development Goal
SFA	Substance flow analysis
Sinopec	China Petroleum & Chemical Corporation
SO_2	Sulphur dioxide
SOD	Stratospheric ozone depletion
TA	Terrestrial acidification
TDE	Total domestic extraction
TE	Terrestrial ecotoxicity
VOCs	Volatile organic compounds
WRI	World Resources Institute

Chapter 1 Introduction

1.1 Motivation

Human activities have brought about significant changes to the planet, particularly through industrialisation and population growth (Lewis and Maslin, 2015). These developments have led to alterations in the natural environment and a substantial increase in resource consumption. Humans need materials, such as plastics, construction minerals and steel, etc., to sustain our lives. The ability of the environment to support human activity determines the sustainability of our life. However, the current trend of material use, which may double or even triple by 2050 according to UNEP's estimates, is likely to surpass the Earth's capacity and jeopardise the ability (Ekins, 2002). Global resource consumption has experienced substantial acceleration since the 21st century, with the material extraction increasing by 53% from 2002 to 2015 despite the 2008 economic crises. A global convergence in resource consumption patterns could lead to a 2.5x growth in material demand and the material extraction could increase to 218 Gt/yr in 2050 (Krausmann et al., 2018).

Logistic carriers are crucial equipment in the logistics industry, which promotes economic growth and improves human welfare (Deng et al., 2020). Over 80% of global trade is transported using pallets, the most common type of logistic carrier and the most generic platform for unit load formation, enabling seamless and efficient transportation throughout entire supply chains (Duraccio et al., 2015; Tornese et al., 2018). By 2027, the worldwide pallet market is expected to have grown from its 2020 projection of 78 billion USD to over 110 billion USD (Statista, 2023). China is the world's second-largest holder of pallets, representing a substantial 25% share of global pallet holdings (GLPA, 2018). 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 have important connection functions in various logistics links, such as loading and unloading, storage, transportation and packaging. Without pallets, cargo has to be moved manually, resulting in inefficiency and higher operational costs (Buehlmann et al., 2009). The use of pallets can realise the mechanisation and automation of logistics activities, improving transportation efficiency of the entire logistics system. The use of pallets can also prevent goods from being directly transported and handed over, improving the quality of cargo transfer and reducing goods damage and shortage rates during logistics activities. Besides, pallets can be stacked and stored directly with goods, which can increase the storage capacity per unit area, save storage space and improve warehouse utilisation. In addition, pallets can enhance inventory counting efficiency and reduce the scattering and loss of goods. However, there is evidence to suggest that resource use and emissions associated with pallets have increased significantly in recent years, resulting to enormous waste and environmental impacts (Alanya-Rosenbaum et al., 2021). Economic considerations and convenience factors dominate the traditional pallet market structure. Historically, the pallet industry has been primarily driven by cost-efficiency and operational practicality. Businesses have focused on minimising expenses and maximising logistical efficiency when selecting pallet materials and designs. Factors such as low production costs, ease of handling, and compatibility with existing transportation and storage systems have been the key determinants in pallet selection (Olumide and Olumide, 2023; Roy et al., 2016). However, the growing recognition of the negative impacts of human actions on the environment has increased the necessity for incorporating environmental considerations into the decision-making frameworks. Therefore, notable consumers of pallet products have recently elevated their environmental requirements in response to global environmental development, thereby rendering environmental performance a critical component of the pallet sector. Consequently, China's pallet sector urgently has to go through a green transformation which is characterised by the mitigation of environmental effects.

The evaluation of material consumption and waste generation of Chinese pallet industry forms the basis for understanding the current state of the supply chain, and identifying the hotspots for improving the resource efficiency as well as reducing environmental impacts. MFA is a useful method to evaluate the current situation. MFA depicts the pathways of pallet streams, identifying the hotspots for waste prevention and reduction (Franklin-Johnson et al., 2016). However, research on pallet MFA is limited by the lack of foundational data on the flows and stocks of pallets in different sectors and regions. Only very little research has provided the waste disposal rates of pallets market in the US through questionnaires (Buehlmann et al., 2009; Gerber, 2020), without covering other aspects of pallet life cycle, such as raw materials input, production volume and consumption. Current knowledge of anthropogenic material cycles, such as material compositions, quantities, consumption patterns and waste treatment of pallets, is lacking, which hinders the research on the MFA of the Chinese pallet market. Consequently, it impedes the ability to understand the circularity of the pallet industry and promote CE for this sector.

In addition, there used to be four widely used types of pallets in China. Wooden pallets, plastic pallets, steel pallets and paper pallets together occupy 99% of the pallet market in 2020 (Zhang et al., 2023). A new type of pallets made of fly ash which is a by-product of coal combustion, appeared in the market in 2018 and was increasingly favoured by users, since they can relieve the pressure on the disposal of solid wastes. By using fly ash as a raw material for pallets, the amount of fly ash that would otherwise be disposed of in landfills can be reduced, which can also save landfill space and avoid toxic substances (Zhu et al., 2019). It is found that different material composition of pallets has different environmental impacts, and the environmental impacts exist during the entire life cycle (Anil et al., 2020; Deviatkin et al., 2019). 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 LCI for LCA (Brunner and Rechberger, 2016). Therefore, integrating MFA and LCA can provide a more holistic evaluation of 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). Although several independent LCAs of wooden pallets (Alanya-Rosenbaum et al., 2021; Carrano et al., 2014; García-Durañona et al., 2016) and paper pallets (Bengtsson and Logie, 2015) have been carried out, which help identify the hotspots of environmental effects, research comparing the environmental impacts of different pallet materials remains limited. Only a few studies have compared environmental impacts of plastic pallets and wooden pallets (Anil et al., 2020; Deviatkin et al., 2019; Kočí, 2019), a comprehensive environmental impacts evaluation on the five types of pallets—wooden, plastic, steel, paper, and fly ash—is still lacking, resulting in an unoptimised pallet market structure that potentially increases the environmental burdens in China. In addition, while the LCA results of pallets for other countries, such as the US (Alanya-Rosenbaum et al., 2021), Australia (Weththasinghe et al., 2022), and Singapore (Ng et al., 2014), etc., have been figured out with reference to the LCI data that reflect local practices, up-to-date data reflecting current practices in China are lacking. Additionally, variations in the goals, scopes, and system boundaries of existing studies, as well as inconsistencies in FUs and limited transparency of methodological choices (Schenker et al., 2022), make direct comparisons of environmental impacts challenging. Given these challenges and the significant presence of various pallet materials in the Chinese market, the LCA study on the five types of pallets in China is required to assess the environmental effects of the pallet industry.

Since the sharing economy can facilitate a transition in collective consumption pattern (Zhou et al., 2020), a pallet sharing system has the potential to promote the industry to achieve the green transformation. 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 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 transformation of the pallet industry.

Opportunities exist in further reducing the environmental impacts by adopting CE (Blomsma and Brennan, 2017). CE is regarded as one of the responses which can relieve the pressure on the natural environment through more circular use of pallets, whilst enabling the economic system to thrive in the long run (BSI, 2017). By applying CE strategies, such as reusing, recycling, and remanufacturing, the pallet industry can save resources, lower emissions, and foster innovation, thus contributing to a harmonious development of economy, society, and environment (Kirchherr et al., 2017; Pan et al., 2022). At present, the traditional “3R CE strategies”, reduce, reuse and recycle, has been further expanded to “10R CE strategies”. Several studies have explored the environmental implications of different environmental impact mitigation strategies, such as repairing (Alanya‐Rosenbaum et al., 2021; Araman and Bush, 2015; Clarke et al., 2005; Gasol et al., 2008; Park et al., 2018), remanufacturing (Alanya-Rosenbaum et al., 2022; Clarke et al., 2001, 2005; Tornese et al., 2016), reuse (Carrano et al., 2015; Gasol et al., 2008) and recycling strategy for wooden pallets (Kočí, 2019). However, different types of pallets require different CE measures to correspondingly reduce the environmental burdens they cause. The existing research only focus on the environmental impact reduction potential of a single CE strategy for a single type of pallet, particularly wooden pallets, without identifying corresponding strategies for other types, such as plastic, paper, steel, and fly ash pallets. This narrow focus leads to a notable gap in the literature regarding the comprehensive assessment of combined CE strategies across the full life cycle of various pallet types in the Chinese pallet industry. Furthermore, these studies tend to concentrate solely on the products themselves, neglecting broader aspects such as industry structure, which are critical for understanding the full impact of CE measures in the Chinese pallet market. This will hinder a holistic understanding of how various CE strategies can be integrated to enhance environmental performance of the entire pallet industry, limiting the identification of the green transformation pathway of the pallet industry in China.

This study aims to evaluate the circularity of pallet market and develop a comprehensive framework for the green transformation of pallet logistics in China. Herein, this research evaluates the circularity of the pallet industry in China considering the complex interactions among materials, products, sectors, and waste management systems in the entire supply chain. Comprehensive field studies have been conducted to collect primary data covering the entire life cycle. The sources, sinks and flows of different pallet materials in China which account for more than 99% of Chinese pallet market share, have been mapped by adopting MFA. Additionally, it develops a green transformation framework to improve the environmental performance of the pallet industry in China, employing LCA to evaluate environmental impacts across five pallet types under three scenarios at product and national scales. The framework is constructed through the data basis from MFA, and the formulation and comparison of three distinct scenarios: the base case scenario, reflecting the current state of the pallet system in China; the sharing system scenario, which introduces a pallet sharing system; and the CE scenario, which incorporates combined strategies aligned with CE principles. To validate this framework, the methodology of LCA is applied, integrating field surveys and robust modelling. Initially, a rigorous assessment and comparison of the environmental impacts associated with each pallet type, including wooden, plastic, paper, steel and fly ash pallets, are conducted across three scenarios. However, it fails to account for real-world market conditions, including factors such as the market share distribution among different types of pallets. Subsequently, utilising the insights derived from these assessments, a detailed LCA analysis of the Chinese pallet market is undertaken under three scenarios established in the framework, offering practical implications for the pallet industry in China. This research would provide valuable insights into the challenges related to increasing circularity and reducing the environmental impacts of pallet logistics, thereby contributing to the sustainable development of the industry in the Chinese context. The study can also be helpful for policy-makers to guide joint efforts for low-carbon logistics along the supply chain and contribute to SDG 12 targets.

1.2 Research aim

The aim of this thesis is to investigate the circularity and establish a framework for the green transformation pathway of the pallet industry. To achieve this aim, the following objectives are set:

- To develop and apply an MFA framework for pallets at the national scale in China, and to quantify the sources, sinks and pathways of pallet products in the Chinese socio-economic system in 2020.
- To provide a comprehensive framework to identify the green transformation pathway of the pallet industry in China and examine the potential for the environmental impacts reduction brought by the scenarios established in the framework.
- To provide guidance for the stakeholders along the entire supply chain

on the barriers and strategies that facilitate the green transformation of the logistics carrier industry in China.

1.3 Research design

1.3.1 Research significance

This research conducts a comprehensive and in-depth analysis and evaluation of the circularity and proposes the green transformation framework for the pallet industry in China, which has important theoretical and practical significance. The main contributions and innovations of this study include:

- This study brings together circularity and environmental sustainability aspects in the analysis of the pallet industry in China. It systematically tracks the input, output, and stock of pallet-related materials, offering a detailed overview of material flows by employing MFA. This analysis helps highlight areas where material use can be optimised and provides a comprehensive data inventory for the evaluation of environmental impacts and the reduction potential of the pallet industry. This integration of circularity and environmental sustainability provides valuable insights into resource efficiency and environmental challenges, which can be adapted for other types of logistics carriers.
- This thesis establishes a green transformation framework of the pallet industry in China which can be generalised to other contexts in the world. This study adopts the sharing economy model and identifies the suitable CE strategies for different types of pallets. Three scenarios - base case scenario, sharing system scenario and CE scenarios are constructed, simulating the situations of pallets sharing and managing pallets under CE strategies, respectively, and analysing their role on mitigating the environmental effects at pallet scale and national scale. This framework provides a practical reference for industries seeking sustainable practices, fostering a transition towards greener logistics

systems.

- This research collects the primary data on the entire supply chain of pallets in China through field trips. Key data collected include the market structure, the pallet material types, the consumption sectors, and detailed production information such as resource and energy inputs, outputs of products and emissions. This primary data collection fills data gap in the existing research on MFA and LCA of pallets.
- This study provides valuable insights for the stakeholders of the pallet market in China and other countries and regions, as well as for the logistics carrier equipment system to comprehend the current status and the potential of green transformation in the pallet industry, and to make rational and sustainable decisions. This study also offers guidance for implementing the sharing system and CE strategies in the pallet market in other contexts and regions, which are confronted with similar challenges and opportunities for green transformation.

1.3.2 Thesis overview

Block 1: Conceptual foundations

The first block identifies the significance of achieving green transformation of pallet market in China through evaluating the circularity and environmental impacts of pallet industry. Chapter 1 introduces the motivation of the research, states the research objectives, describes the research methodology and significance, and outlines the structure of the thesis. Chapter 2 reviews the relevant literature, including pallet classification, MFA, LCA and CE studies on pallets. It first provides an overview of the function and classification of pallets, and the current studies of pallet material flows. Then, it discusses the current studies of environmental impacts of pallets. Next, it introduces the CE strategies, including the development of CE strategies, and the identification of CE strategies for the pallet industry. Finally, it summarises the literature review and identifies research gaps.

Block 2: Methodology application

Chapter 3 describes the research methodology employed in this thesis and explains the steps and procedures for assessing circularity and the structure of the green transformation framework of the pallet logistics. It first presents the research design, including research questions. Then, it details the MFA method for pallets at the national scale in China, and defines the system boundary, data categories, calculation formulas. After that, it details the structure of the framework, procedure of LCA method at product and national scales.

Block 3: Results

Chapter 4, Section 4.1 presents the results and discussion of the circularity of pallets in China based on MFA. It analyses the sources, sinks and pathways of pallet products in the Chinese socio-economic system, as well as discusses the inefficiencies in resource consumption and hotspots for waste generation. Chapter 4, Section 4.2 presents the results of the green transformation of the pallet industry in China based on LCA and scenario analysis. It reports and compares environmental impacts of different types of pallets in China under three scenarios: base case, sharing system, and CE scenario at product and national scales. The LCA also identifies the hotspots and the environmental impact reduction potential for each pallet system. Besides, this section presents LCA study at national scale under three scenarios to illustrate the practical outcomes of the green transformation of the pallet industry in China.

Block 4: Overall discussion and Conclusions

Chapter 5, Section 5.1 discusses the results from the integration of MFA and LCA, and link back to research questions. Besides, it highlights the key insights and implications for policy makers and industry practitioners by identifying and analysing the barriers for achieving the green transformation of the pallet industry in China and suggests possible solutions and strategies to overcome them. Finally, it acknowledges the research limitations and reflects on how they could be addressed or mitigated. Section 5.2 concludes the thesis by summarising the main findings which are linked back to the objectives of this research, and discussing some directions for future research based on this study (Fig. 1).

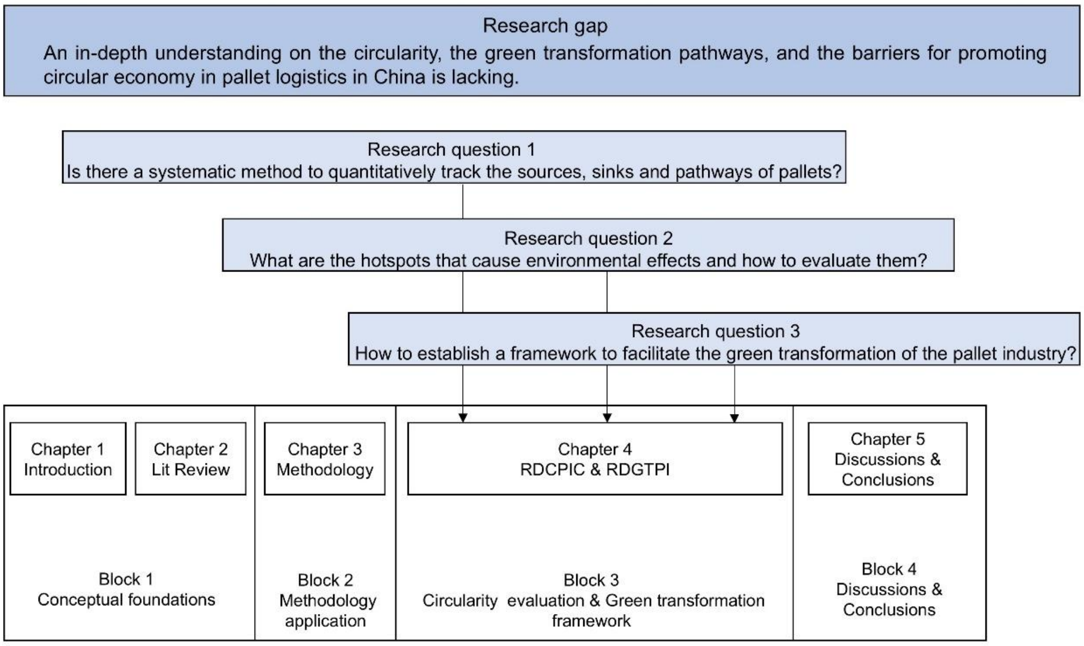


Fig. 1 Structure of the thesis. Full titles of the chapters: Chapter 1 Introduction: Introduction; Chapter 2 Lit Review: Literature review; Chapter 3 Methodology: Methodology; Chapter 4 RDCPIC: Results and discussion on the circularity of pallet industry in China; RDGTPI: Results and discussion on the green transformation of pallet industry; Chapter 5 Discussions and Conclusions: Overall discussion and Conclusions.

Chapter 2 Literature review

This chapter introduces an in-depth analysis of the role and significance of pallets within the Chinese industry, followed by the introduction of the relevant methodologies employed in this thesis. Section 2.1 and 2.2 provide an overview of the importance of pallets, covering the function and classification of the Chinese pallet industry. Section 2.3 provides introduction of MFA methodology, and summarises the current studies on MFA of pallets. Section 2.4 presents the procedure of conducting LCA research, and summarises the current studies on the environmental impact analysis of pallets. Section 2.5 introduces the concept of CE and the current studies on the environmental impacts of adopting CE strategies on pallets.

2.1 Function of pallets in logistics

Pallets, the most generic platform for unit load formation (Tornese et al., 2018), are indispensable equipment in logistic activities (Duraccio et al., 2015), enabling seamless and efficient transportation in whole supply chains (Kim et al., 2009). Pallets play a vital role in connecting various logistics activities, such as assembly, storage, and transportation, etc. (Kočí, 2019). 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).

Assembly. The palletised cargo can be treated as one unit, which can prevent the damage and loss of goods due to rough handling. Furthermore, with the advancement of mechanisation and automation equipment, especially the widespread application of loading and unloading handling tools, such as forklifts, pallets are the main supporting equipment for them, which can reduce the time and labour required for logistics operations. For instance, the integrated operation of pallet and forklift can significantly enhance the loading and unloading speed, improve operational efficiency and shorten operational time.

Storage. Pallets are essential tools for storage and turnover in warehouses, where they can be used for both ground and shelf storage. By stacking goods on pallets, the storage capacity utilisation can be enhanced through space saving in the factory, and the goods circulation can be accelerated through automation of warehouse operations. Moreover, the palletised cargo which is treated as one unit, can facilitate inventory counting and management, and improve the efficiency of inbound and outbound operations.

Transportation. Pallets are also known as “moving cargo platforms” or “moving grounds”. Pallets can enhance the convenience of operations at both ends of the transportation by reducing the operation time of cargo loading and unloading. Moreover, pallets can effectively protect goods from damage during the transportation process. Once the goods are stacked on the pallets, they can be carried by mechanical equipment, such as forklifts, and moved as a unit to the designated destinations. In addition, the goods remain on the pallet throughout the transportation, regardless of how many times they are moved or how many modes of transportation are changed, thus enabling the seamless operation of logistics. Without pallets, goods have to be loaded, unloaded and transported manually one by one, which lowers the efficiency of logistics.

2.2 Pallet classification

Pallets can be categorised according to their class, size, raw materials and management approach.

2.2.1 Class

Pallet class can be either stringer class or block class, depending on the type of support beams used. Stringer pallets use stringers, which are support beams that run perpendicular to the top and bottom deck boards and separate them (Anil, 2010). Stringers can be either solid or notched to allow forklift tines to enter. These pallets are called two-way entry or partial four-way entry, depending on the stringer type. On the other hand, block pallets consist of rectangular blocks and have full four-way entry, which means that both pallet jacks and forklifts can access them from any side. This feature is highly valued in industries that use pallet jacks or that operate in crowded material handling environments. Four-way functionality allows material handlers to place pallets more easily in tight spaces, saving time and space. For example, block pallets can provide significant value by enabling pallets to be rotated to fit more on a trailer or to be accessed on congested loading docks.

2.2.2 Size

Pallet dimensions vary widely across the world, and there is no global consensus on a standard size (Anil, 2010; Clarke, 2004). Pallet production is not governed by a single dimensional standard, but rather by the diverse needs and preferences of the users. However, a few common sizes are frequently used by different organisations. ISO stipulates six standardised pallet sizes, namely, 1200 mm × 800 mm, 1200 mm × 1000 mm, 1219 mm × 1016 mm, 1140 mm × 1140 mm, 1100 mm × 1100 mm and 1067 mm × 1067 mm. These sizes reflect the diverse needs and preferences of different regions and users. The original ISO 6780 standard only included the 1200 mm series (i.e., 1200 mm × 1000 mm and 1200 mm × 800 mm), which was based on the unified packaging reference size of 600 mm × 400 mm in Europe. In 1988, ISO added the standard specification of 48 inch × 40 inch (1219 mm × 1016 mm) specification to accommodate the market in the US, but this size was incompatible with the shipping container (2330 mm size), leading to inefficient use of container space. Therefore, ISO 6780 introduced the 1140 mm × 1140 mm pallet to match the container size. To meet the needs of Japan and South Korea, ISO also added the 1100 mm × 1100 mm type pallet as an international standard specification. Moreover, the size of 1067 mm × 1067 mm (42 inch × 42 inch) pallet, which had a wide application in Australia, was incorporated into the ISO standard specifications (ISO, 2003). In China, the standard specifications of pallets are 1200 mm × 1000 mm and 1100 mm × 1100 mm, with the former being the preferred specification and one of the Asian standards recognised by the Asian Pallet System Federation. The latter accounts for 12% of the market share, while the 1200 mm × 800 mm size pallet accounts for 9%.

2.2.3 Raw materials

Pallets are most frequently categorised according to the types of raw materials, i.e., wood, metal, plastic, paper, and composite. Wooden pallets, the first type of pallets that have been invented (Clarke, 2004), still dominate the global market, accounting for 86.5% in 2018, followed by plastic pallets in the global pallet market (Fortune Business Insights, 2023). A similar trend can be observed in other nations. For example, in Australia, where wooden pallets accounted for more than 85% of the annual market share in 2017, while plastic pallets contributed to less than 10% (Weththasinghe et al., 2022). In the US, a survey of pallet users in 2020 revealed that 94% of the respondents used wooden pallets in their operations, while 37% used plastic pallets, which was a 2% increase from 2018, 12% used wood composite pallets which underwent a decline from 14% usage in 2018, 6% used metal pallets, 4% used cardboard or corrugated pallets, and 1% used other materials (McCrea, 2020). Based on field studies, there are currently four widely used types of pallets in China. Wooden pallets have the highest market share, accounting for 74% in 2020. 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. Due to the high carrying capacity, the share of steel pallet has increased from 2% in 2012 to 4% in 2020. Wooden pallets, plastic pallets, steel pallets and paper pallets together occupy 99% of the pallet market in 2020. A new type of pallets 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. Therefore, this thesis focuses on these five types of pallets in China (Fig. 2).

Wooden pallet. Wooden pallets are generally made from raw woods that are dried and shaped to reduce moisture and eliminate internal stress. Wooden pallets can be easily repaired by changing broken planks or replacing nails to assemble boards. However, wooden pallets require heat treatment to meet the dryness standard and to comply with the ISPM 15 guidelines for international shipment in order to eliminate any pests inside the wood (Anil, 2010; Anil et al., 2020). Compared to non-wooden pallets, wooden pallets are at a disadvantage because of this feature. Moreover, wooden pallets are susceptible to damage from moisture, insects, fungi and bacteria. They can also splinter, warp or break over time and produce burrs or chips that can injure workers or contaminate products, limiting its application in industries that require high hygiene conditions, such as food and pharmaceutical industries.

Plastic pallet. Plastic pallets are mainly made of polyethylene, either from new or recycled plastic granulates. The production and processing technologies of plastic pallets mainly include two main technologies: injection moulding and blow moulding. Injection moulding involves injecting molten plastics into a mould under pressure, and cooling them to form pallets with various shapes and structures. Blow moulding involves placing the extruded tubular plastic parison into the mould, using air to blow them to adhere to the mould wall, and cooling them to form a hollow pallet. Currently, injection moulding technology is more prevalent than blow moulding technology because Injection-moulded pallets have higher quality, precision and durability than blow-moulded pallets, which are prone to deformation or cracking due to temperature changes. Moreover, blow-moulded technology can only produce double-sided flat pallets with two-way fork direction, while injection-moulded technology can produce both single-or double-sided pallets. Third, injection-moulded pallets can be reinforced with steel pipes or bars to increase their load-bearing capacity and rigidity, making them suitable for high-rise warehouses or automated systems. Fourth, injection-moulded pallets generally have lower costs as they can use recycled or mixed materials to save raw materials and resources, while blow-moulded pallets have higher requirements for raw materials and can only use new materials for production.

Plastic pallets are gradually occupying the market due to advantages of easy cleaning and smoothness, as well as resistance to moisture and insects, which compensate for the drawbacks of wooden pallets. However, plastic pallets also have some disadvantages, such as being more expensive than wooden pallets, difficulty in changing shape due to high mould cost, and inability to be repaired.

Paper pallet. Paper pallets are made from paper or cardboard materials using processes such as lamination or gluing. They have the advantage of being lightweight and not requiring heat treatment or MeBr fumigation, which are both energy-intensive and environmentally harmful methods. Heat treatment involves using large and costly kilns that burn fossil fuels and produce pollutants (e.g., oxides of nitrogen). Fumigation releases MeBr, which is a substance that depletes the ozone layer and causes environmental problems (Anil et al., 2020). Another benefit of paper pallets is that they can be designed and customised according to the specifications and structures of the products, avoiding the high expenses of creating moulds. However, paper pallets also have the drawback of being the weakest and least durable kind of pallets. They cannot bear heavy loads or resist moisture, humidity or rough handling. Paper pallets may get torn, collapsed or crumbled over time and may create a fire risk. They are more prone to breakage without standard operations.

Steel pallet. Steel pallets are manufactured from carbon steel or stainless steel and have the highest strength and durability. They can carry heavy loads without cracking or bending. Steel pallets are resistant to fire, weather and corrosion. They are also easy to clean and sanitise and do not attract pests or pathogens. Steel pallets are suitable for high-rack storage and long-term use. However, steel pallets are also the most costly and heaviest type of pallets among these five types of pallets. They can harm products or equipment if handled roughly and may rust if not properly coated. Steel pallets are also loud, bulky, hard to customise and lack reparability.

Fly ash pallet. Fly ash pallets are a novel type of pallets that emerged in the Chinese market in 2018 and gained increasing popularity among users, as they can alleviate the environmental burden of solid waste disposal, saving landfill space and avoiding toxic substances (Zhu et al., 2019). The raw materials of fly ash pallets consist of PVC resin, fly ash (a by-product of coal combustion), recycled materials and additives. The production process involves mixing and melting the raw materials, and then forming them by injection moulding. Fly ash pallets are assembled with steel nails, which allow the replacement of broken boards with new ones, thus solving the repair problem of plastic pallets.

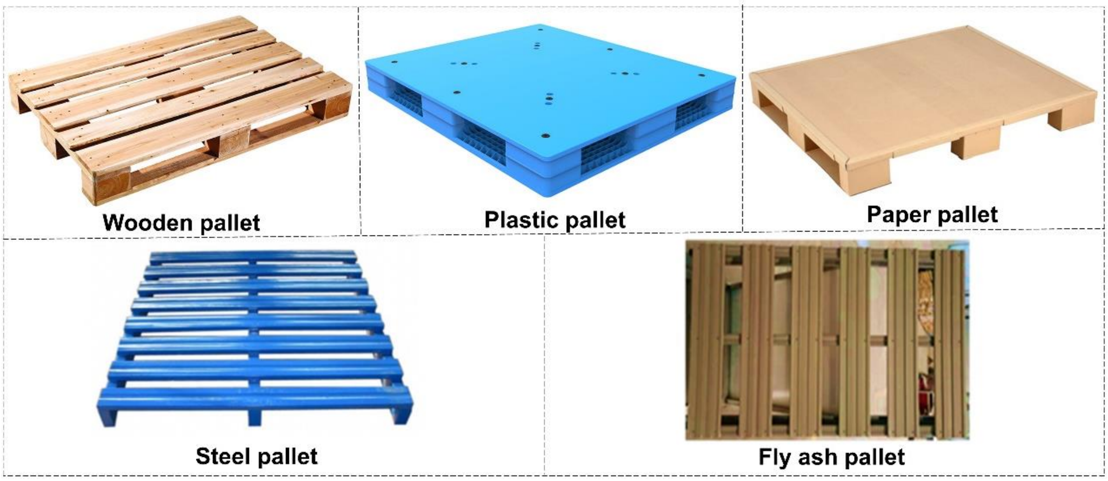


Fig. 2 Representative pallet types in China

2.2.4 Management strategy

The management strategy implemented throughout the lifecycle of pallets can have a notable impact on the environment (Bhattacharjya and Kleine-Moellhoff, 2013; Bilbao et al., 2011). There are currently two dominant pallet management strategies in the world: “traditional” (wherein pallets are disposed after one trip) which is also called one-way, single use, expendable, or non-pooled pallets (Deviatkin et al., 2019), and “pallet sharing system” (wherein pallets are leased to customers for use in multiple times) which is also known as leased pallet pooling, closed loop, leased, or take-back pallet system (Deviatkin et al., 2019).

Developed countries such as the US, South Korea, Japan and Australia have operated sharing systems effectively. The State Council of China issued the “Guiding Opinions on Accelerating the Establishment and Improvement of a Green, Low-Carbon, and Circular Development Economic System” which states that the first aspect of the logistics system is to support logistics companies to promote the establishment of pallet sharing system in February 2021. The General Office of the State Council of China issued the “14th Five-Year Modern Logistics Development Plan”, pointing out the importance of the establishment of pallet sharing system in December 2022. However, there are many obstacles to really construct such a system as many Chinese pallet companies are still unaware how much environmental benefit can be brought about by changing the current pallet management strategy. So far, expendable pallets still account for about 98.2% in China.

This thesis adopts the classification based on raw materials, because different material composition of pallets has significant differences in the environmental impacts (Anil et al., 2020; Deviatkin et al., 2019; Kang et al., 2021; Khan et al., 2021; Kočí, 2019; Weththasinghe et al., 2022). 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 reduce the environmental impacts of each pallet type, thereby effectively advancing the progress of the green transformation of the pallet industry in China.

2.3 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. This applies to any sub-system, ranging from national economies, industrial sectors and households (Hinterberger et al., 2003).

Human beings have long been concerned about the process, effect and mechanism of material flow (Fischer-Kowalski, 1997; Fischer-Kowalski, 1998), but the establishment of systematic methods and frameworks is only a recent matter of decades. Since the 1960s, due to the concern about the material cycle metabolism problems between the socio-economic system and the natural ecological system caused by urbanisation and industrialisation, analytical methods such as urban metabolism (Wolman, 1965), social metabolism and industrial metabolism have been developed (Ayres and Simonis, 1994). These methods try to establish the connection between material flow, economic development and environmental impact by depicting the scale, structure and process of material flow, and seek ways to improve resource utilisation efficiency and benefit, slow down natural resource consumption and reduce negative environmental impacts. In biology, the physiological processes involved in the conversion of energy are referred to as metabolism. In analogy to this, social metabolism refers to the physical interaction between human activities and the nature (Lettenmeier, 2018; Schandl et al., 2015). Therefore, social metabolism becomes a metaphor to describe the separation between ecosphere (Ayres and Kneese, 1969; Baccini and Brunner, 1991; Bringezu, 1993; Lehmann and Schmidt-Bleek, 1993; Lettenmeier, 2018; Schröter et al., 2005; Steffen et al., 2007), and anthroposphere, and a tool to analyse this interaction (Lettenmeier, 2018). Human energy and material consumption have increased significantly (Haberl et al., 2011; Krausmann et al., 2009; Lettenmeier, 2018), which leads to serious environmental consequences, e.g., climate change, acid rain, soil erosion (Haberl et al., 2011; Lettenmeier, 2018). Social metabolism aids in comprehending the flow of natural resources through human activities (Haberl et al., 2011), and the path to sustainability (Lettenmeier, 2018). Schmidt-Bleek (1993a, 1993b) stated that the total amount of material flow from the biological earth layer into the field of human technology should be taken as the basic measurement method of human influence on the environment, because sooner or later every input into the human economy will eventually become the output of returning to the biogeosphere. This idea leads to the establishment of material flow accounting (Ayres and Kneese, 1969; Baccini and Brunner, 1991; Bringezu and Moriguchi, 2002; Bringezu et al., 2003; Lettenmeier, 2018). MFA is 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). MFA tracks the product lifecycle from extraction to manufacturing, consumption and waste disposal (Haberl and Weisz, 2007).

The environment and the economy exchange physical flows of materials that are extracted (PE) and waste produced (Fig. 3). Waste can be generated by both production and consumption, known as CW. Waste refers to the materials that are returned to the environment, possibly after some EoL treatment. There are also HF of materials that are mobilised by the economic process but not incorporated in economic products. In addition, countries also trade physical flows with other countries, which are direct physical imports and direct physical exports. DPC can be split into a perishable fraction that will be discarded to nature during the analysis period (usually one year which is CW) and the NAS of physical capital. The sum of PE and HF is TDE which accounts for the material inputs that occur within the country. Therefore, the sum of TDE of all countries accounts for all inputs in the world (Rodrigues and Giljum, 2005).

The three primary components of the economic subsystem are stocks, flows, and processes. Certain economic goods are represented by the flows and stocks. Goods that move from one process to another are called flows. Goods kept inside the economic subsystem are called stocks. Through the processes, goods are transferred between states. When the movement takes place within the time frame taken into account in the model, which in this case is one year, the goods will show up as flows in the MFA system. If there is a delay in this transfer, the goods will show up as stocks (Elshkaki, 2007).

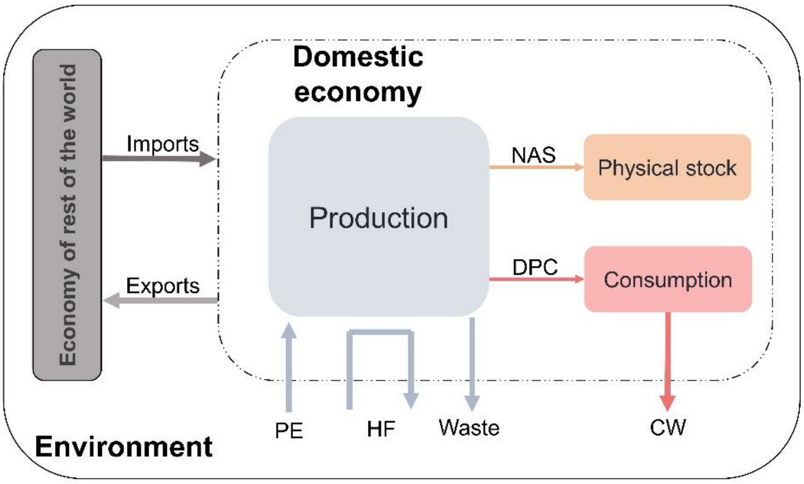


Fig. 3 Basic concept of material flow analysis

The early work of Ayres and Kneese (1969), who put out the concepts of material and energy balancing, served as the foundation for MFA. However, a few nations, such as Austria (Steurer, 1992), Germany (Fischer-Kowalski et al., 1994), and Japan (Haberl and Weisz, 2007), undertook the first MFAs at the national level in the early 1990s. At the same time, various research groups tried to harmonise different MFA methods. International MFA standards were first established by the European Commission-funded Concerted Action Group (Fischer-Kowalski, 1997). Despite this effort, the WRI facilitated two publications comparing MFA studies at national level. The first one defined resource input indicators by analysing resource inputs, while the second one defined emission indicators by analysing material outflows (Haberl and Weisz, 2007; Matthews et al., 2000). Nevertheless, the number of publications or breakthroughs in the MFA field did not significantly rise. It was only in 2001 that

MFA reached a turning point. The European Statistical Office published a manual including the first standardised technique for economy-wide material flows (Eurostat et al., 2002). The movement of materials between economic sectors (internal flows) and within natural systems was not included in these MFAs; instead, they paid attention to the movement of materials between the economy and the environment.

Following the release of the methodological MFA guide, the number of OECD and EU member states that have embraced MFA has increased. Consequently, MFAs have been used in several developing countries such as Thailand (Weisz et al., 2004), Laos (Schandl et al., 2004), Chile (Giljum, 2004), and Philippines (Rapera, 2004). Additionally, Eurostat has released MFAs for the EU economy (Amann et al., 2004). The OECD countries are having MFA databases developed by the OECD (Haberl and Weisz, 2007).

The original Eurostat MFA guidance is presently being revised in collaboration with the OECD and Eurostat. According to Haberl and Weisz (2007), these improvements address data sources, the application of MFAs, and their relevance to OECD nations. While there is now a standard for economy-wide material flows, the ISO standard for MFAs is lacking, which could lead to increased output variance and weaker conclusions, particularly during comparative analysis of different studies. Therefore, a standard of MFAs is required to provide consistency and reliability of future studies.

The system in MFA is generally determined by temporal and spatial boundaries. The temporal boundary varies depending on the objective, and generally, due to the influence of data availability and result applicability, the boundary is in units of years, such as one year or several years. The spatial boundary varies depending on the research purpose, such as a city, a watershed or a country. Currently, many studies have been carried out across national boundaries.

2.3.1 Stages of MFA

The various phases of the material flow cycle describe how materials are extracted, produced, transported, consumed, stored and treated in the economic system. The first stage is mining and extraction, where raw materials are obtained from the biosphere or geosphere. The second stage is production and manufacturing, where raw materials are converted into finished products. The third stage is transportation, where goods are moved from one place to another. The fourth stage is consumption and use, where products are used and eventually discarded. The fifth stage is hibernation, where products that are no longer in use, but have not been discarded, are stored. The final stage is waste treatment, where discarded products are either reused, recovered, recycled, landfilled or emitted.

The economic subsystem interacts with the environmental subsystem through various kinds of material flows. These flows can be classified as follows: mined raw materials, which are the extracted or mined resources that enter the economic subsystem from the environment. Products, which are the finished goods that enter the consumption stage, either produced within the system or traded from other systems. Discarded products, which are the waste products from the consumption and/or hibernation stages that go into the waste-processing stage. The recovered items from the waste stream that are returned to the manufacturing or consumption phases are known as recycled materials or reused goods. Final waste, which are the currently worthless materials that are disposed of, either by landfilling or incinerating. Emissions, which are the substances or materials that are released from the economy into the environmental subsystem. Emissions can occur at any stages of the life cycle and are unintended losses from processes in the economy brought on by corrosion, leakage, or volatilisation. Certain processes can be changed to purposefully reduce or eliminate emissions. Materials, semi-finished products, and finished products that are brought into the system from outside through commerce with other nations or areas are known as imported goods. Exported commodities are resources, semi-finished products, and final goods that are traded out of the system.

Types of stocks: resource stocks refer to the amount of the substance that exists in the natural environment, such as the biosphere. Product and material stocks represent goods and materials that are stored in industrial or commercial facilities before being used. Product stocks in use denote the inventory of items that are currently providing the intended service to consumers or users. Hibernating products are those goods that have ceased to provide the intended service but have not been disposed of yet. Pallets are part of the product stock category, as they offer service to users. They produce both pre-consumer and post-consumer waste in their life cycle stages, and their EoL stage comprises landfill, open dump, incineration and recycling. Fig. 4 illustrates the conceptual framework of pallets MFA in China.

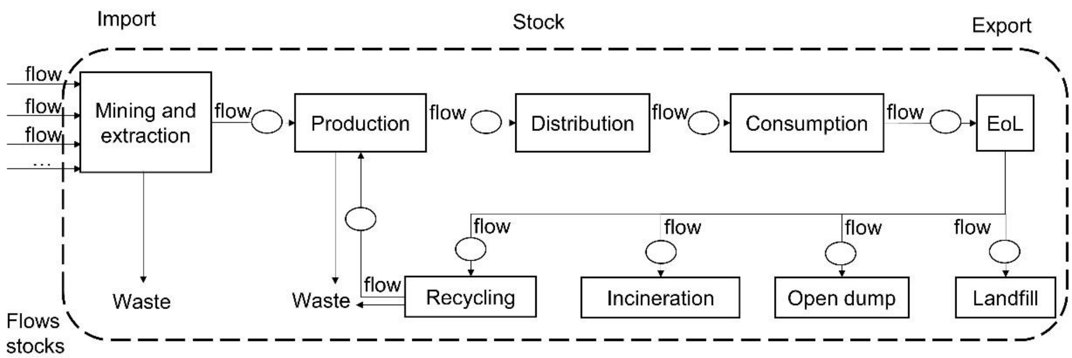


Fig. 4 Conceptual framework of pallets material flow analysis in China.

2.3.2 Types of MFA

The effects per unit flow of substances, resources, and products inside specific industrial enterprises, regions, and sectors are measured by Type 1 MFA studies. They also develop environmental policies and evaluate the environmental implications of a product. On the other hand, the adoption of the Type 2 MFAs is to gather information on environmental performance, create MFA accounts and statistics, and improve sustainability indicators (Fig. 5).

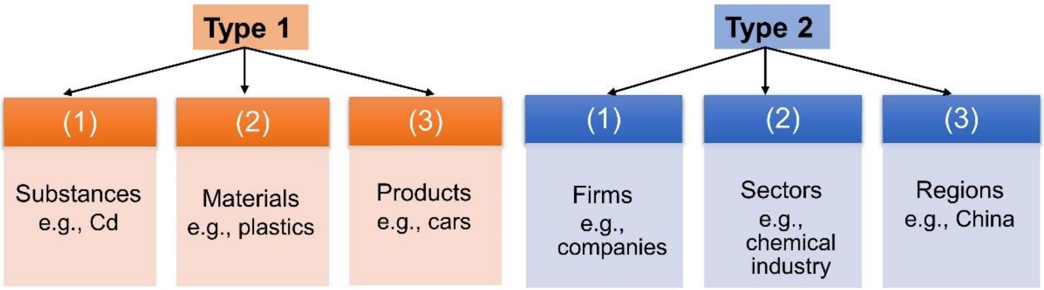


Fig. 5 Types of material flow analysis. Type 1: Effects per unit flow of substance, materials and products within specific firms, sectors and regions; Type 2: Throughput of firms, sectors and regions related to substances, materials and products.

The principle behind the design and use of MFAs is consistent regardless of the type. In addition to giving accurate and elucidating information on the material flows and stocks in the system, a visual depiction of MFAs can be beneficial in the following ways:

- Monitor the movement of materials within a process, organisation or nation;
- Identify areas of concern of a procedure;
- Trace the loss of materials and its source;
- Make decisions on the basis of results;
- Take measures to recover essential resources and decrease emissions and waste.

The use of MFAs can identify potential opportunities and threats. However, MFA studies are often mistaken for SFA. In contrast to SFAs, which focus on a particular kind of matter, such as the element Cu, MFA studies address a collection of substances and products, like pallets.

Static and dynamic models are the two broad categories into which MFA models can be separated. Static models refer to MFA for a specific time period (usually one year). The main features that distinguish dynamic models from static models are two aspects: (1) dynamic models usually analyse the changes of material stock and flow for a time series (such as multiple years); (2) dynamic models consider the dynamic change mechanism of use stock, that is, according to the characteristics of various final products that have a certain time lag and accumulation effect in the use process, a dynamic model between input and output is established to simulate the output.

In addition, the connection and difference between dynamic models and static models also include: (1) dynamic models need to be based on the stock and flow inventory provided by static models; (2) static models can analyse flow and stock separately or simultaneously, while dynamic models need to calculate various flows related to use stock while accounting for use stock; (3) dynamic models need to collect long-term data, leading to higher data cost and uncertainty; (4) dynamic models have better mathematical logic, and can provide scenario and forecast analysis for future long-term trends based on the simulation and summary of historical data.

Static MFA will continue to be relevant and useful, despite the growing interest in dynamic MFA studies. In order to investigate the patterns of material use and losses in a system, it can be done at different levels of complexity and provides a snapshot of the system at a given time. Static MFA has several advantages for analysing a material system. First, it can provide adequate information without the need for temporal data. Second, it requires significantly less resources than a dynamic MFA, which involves more complex modelling and computation. Third, it can enhance the effectiveness of a dynamic MFA if done beforehand, as it can help identify the relevant material stocks and flows (Brunner and Rechberger, 2016).

Dynamic MFA allows the description of future states of a material system based on the current state and deterministic or stochastic functions. Since the 1990s, when the first dynamic MFA studies were published (Kleijn et al., 2000; Müller et al., 2004), the number of studies that use dynamic models to investigate material flow systems over time have increased significantly. Dynamic MFA is especially relevant for metals because they are widely used and accumulated in society and they have potential value as secondary raw materials (Muller et al., 2014). Dynamic MFA has also been applied to the management of hazardous organic materials (Morf et al., 2008). By understanding how material stocks have changed over time, MFA can be adopted to predict future material flows and plan for efficient recovery or elimination of materials based on the existing and historical stocks (Chen and Graedel, 2012).

2.3.3 Calculations of MFA

One way to estimate the output of obsolete products from different use sectors is to use lifetime functions, which are specific to each product and sector. These functions calculate the output by adding up the portion of previous inputs that become obsolete in a given year (Muller et al., 2014). The Dirac delta distribution and the Weibull distribution are two lifetime distribution functions that are frequently utilised in MFA and system reliability. Other functions are also employed to estimate output flows considering the residence time of each product in the stock, including the normal, beta, lognormal, and gamma distributions. However, for some stocks, using leaching coefficients may be more appropriate than lifetime functions (Van der Voet, 2002).

2.3.4 Data uncertainties in MFA

Data quality is crucial for any MFA, but direct measurements are often unavailable and alternative sources may have varying reliability (Laner et al., 2014). All data values have some degree of uncertainty, which can cause conflicts with model constraints, such as mass conservation. To resolve these conflicts, the uncertainty of the data must be considered. Therefore, data information should include not only the values but also their uncertainty.

There are two types of data uncertainties: aleatory variability and epistemic uncertainty (Abrahamson, 2007). Aleatory variability is caused by the inherent randomness, natural variation, environmental or structural changes, manufacturing or genetic differences, and other sources of unpredictability.

Aleatory variability is irreducible but can be better understood. In contrast, epistemic uncertainty refers to the lack of knowledge that affects the data, such as small sample sizes, detection limits, etc. Epistemic uncertainty can be reduced by the probabilistic approach. Many computations are simplified by using the normality assumption whereas epistemic uncertainties are often assumed to follow a normal distribution. However, this is not always true for scientific models. They can be modelled by a uniform, triangular, or trapezoidal distribution (Cencic and Frühwirth, 2015).

The useful way to propagate uncertainties when the shape of the resulting probability density function matters or when linear approximations are not feasible due to large uncertainties of input parameters in nonlinear functions is to perform Monte Carlo simulations. Monte Carlo simulations use computer algorithms to generate n random numbers for each of the m input parameters of a function based on their distribution. These n sets of m input parameters produce n possible outcomes of the function, which are then statistically analysed (e.g., mean value, standard deviation, shape of density function). The resulting distribution function and its parameters become more precise as the number of repetitions n increases.

2.3.5 Presentation of results

MFA can produce a figure that summarises the system's processes, stocks, and flows, such as a Sankey diagram. Such figures can be useful for policy evaluation and decision making, because they help to understand, communicate, and clarify the main issues, which is important for decision makers who have limited time. Therefore, it is essential to present the MFA results in a suitable way.

2.3.6 Limitations of the MFA methodology

MFA is not sufficient as a tool for making decisions and policies. It requires integration with other methods that take into account criteria, such as economic values (Millward-Hopkins et al., 2023), product qualities (Rotter et al., 2004), and environmental impacts to enable informed judgments (Corona et al., 2019; Elia et al., 2017; Huang et al., 2013). Moreover, MFA requires numerous data to be applied, which may not be accessible or transparent for some regions or sectors. Data can originate from different sources (Song et al., 2019), which introduce uncertainty (Laner et al., 2014). The issue of characterising data uncertainty is a major challenge for MFA because data constraints and limited information make the selection of probability distributions a subjective task (Muller et al., 2014). Moreover, balancing substances in complex processing such as a blast furnace can be very challenging without adequate methods for sampling and analysis.

This thesis integrates MFA and LCA to evaluate the environmental performance of pallet industry in China. The outcomes of MFA research can be utilised to construct a LCI for LCA (Brunner and Rechberger, 2016). MFA research focuses on transparency and manageability for certain systems. LCA studies, on the other hand, aim for comprehensiveness and a holistic view of the life cycle of a product or service (Silva et al., 2015). Some examples of combining MFA with LCA-based evaluation approaches are the comparison of sewage sludge treatment technologies (Lederer and Rechberger, 2010), the analysis of optimal treatment technologies for EoL cooling appliances (Laner and Rechberger, 2007), or the evaluation of waste management systems (Wäger et al., 2011). MFA and LCA have been further integrated within formal optimisation frameworks, which enables the development of optimal resource use strategies from a life cycle thinking aspect (Islam and Huda, 2019). The resource flows are mapped and the transfer coefficients for various processes are established on the basis of MFA. LCA can then be used to determine the environmentally favourable solution that meets the required functionality and adheres to the given constraints (Hatayama et al., 2010).

2.3.7 Current MFA studies on pallets

MFA is a method that offers a comprehensive evaluation on the flows and stocks of a certain material over time within a defined spatial system. MFA can help in evaluating the impacts of resource use, waste generation, environmental protection, and policy making (Chen et al., 2022; Huang et al., 2012). In addition, MFA detects the material stock depletion or accumulation early enough, to enable interventions or to encourage further growth and future use. Furthermore, MFA can capture minor changes that may not be noticeable in short time scales but that may cause long-term damage over time. Moreover, MFA can assist policy makers, serving various groups such as governments, regions, and organisations (Allesch and Brunner, 2015; Brunner and Rechberger, 2016). It is especially useful for developing and evaluating national and regional policies in the areas of environmental protection, waste management, economic trade, and technology development (Brunner and Rechberger, 2016).

Common basis. MFA is a suitable tool for policy decisions and evaluations, as it follows the mass-balance principle (Nakamura et al., 2007; Stanisavljevic and Brunner, 2014), which ensures transparency. Policy decisions are often complex, involving several fields of interest. MFA offers a common basis to integrate different fields, such as economy, environment, and resources. Decision-makers can therefore obtain a holistic and reliable picture of the material system, as goods and substances are also mathematically linked in an MFA. System boundaries of MFA are consistent and evident, and each flux and accumulation of goods and substances has a quantitative measure, enhancing the comprehension of the dynamics of the material system, which is also of significance for the dissemination of existing expertise and knowledge.

Transparent comparison. Policy decisions entail an inherent risk due to uncertainties of the underlying knowledge base (Morgan et al., 1992). Decision-makers have to choose among several alternatives that have different costs and benefits of, for example, product quality, environmental impacts, and resource conservation. MFA offers a numerical basis for decision making that is verified by mass balance, by accounting for uncertainty in an explicit way. Moreover, MFA offers a consistent and clear metric that draws on common knowledge and scientific traditions. It provides a framework for measuring and comparing material flows and stocks across different regions (Klinglmair et al., 2016), countries, organisations, etc. It allows for a uniform approach to data collection and analysis among policy analysts and researchers.

Monitoring instrument. MFA is a useful method for tracking material flows from source to sink, which is essential for various policy fields. For example, MFA can help to link environmental loadings with emissions, to estimate resource accumulations, or to identify opportunities for improving resource efficiency (Saidani et al., 2019). MFA can also support policy evaluations by using both an input-oriented approach such as materials accounting and an output-oriented approach focusing on emissions and accumulations.

Early detection. MFA systems can monitor changes in human and environmental stocks by considering multiple time periods (Baars et al., 2022), facilitating early detection of beneficial or harmful accumulations and depletions, which can have significant benefits for stakeholders, as they can assess future constraints and plan for necessary prevention or system capacities.

Priorities identification. MFA provides a comprehensive view of the system considered, which reveals the significance of the flows and stocks of individual processes. Therefore, if material reductions or increases are desired for economic, environmental, or resource reasons, MFA can help to identify the most relevant flows and stocks (Brunner and Rechberger, 2016).

Interdisciplinarity. MFA can be adopted to examine concerns that span across multiple fields, such as socioeconomic, environmental, and engineering topics, etc. MFA can serve as a common denominator for all disciplines involved, by proving a shared backbone for all stakeholders involved in a specific decision.

Research on MFA of pallets is significant in understanding and improving the circularity of the pallet industry by tracking the pallet product lifecycle from extraction to production, consumption and waste disposal in different regions and temporal boundaries. MFA can provide comprehensive, reliable and transparent information on the flows and stocks of pallets across different stages and sectors, and offer a holistic view of the pallet pattern. The production and consumption patterns of various types of pallets can reveal the market structure of the pallet industry, recognising the most relevant flows and stocks to improve resource efficiency for policy makers. Moreover, MFA can quantify the waste generation and management of pallets (Allesch and Brunner, 2015; Stanisavljevic and Brunner, 2014), and indicate the main sources and destinations of waste flows, which can provide guidance for enhancing the waste prevention and recovery of pallets (Makarichi et al., 2018). Furthermore, MFA can measure the recovery rate and circularity of pallets, and examine the extent to which CE strategies are implemented in the pallet industry (Gao et al., 2020; Jacobi et al., 2018), which can help to foster the green development and transition of the pallet industry, both nationally and globally. Besides, MFA can track the progress of CE strategies (Graedel, 2019; Li et al., 2013; Wang, H. et al., 2020), which can foster the sustainable use of resources and benefit both the environment and the society. Furthermore, MFA of pallets can be served as a basis for further environmental effect studies (Corona et al., 2019; Elia et al., 2017), enabling the evaluation of the environmental performance of each type of pallet, and thus explore the potential scenarios for the green transformation of pallets industry in the future. MFA can also facilitate interdisciplinary collaboration among the logistics, socioeconomic and environmental fields, and act as a common framework for cross-country comparisons and academic research, providing policy support for decision-makers from different fields.

The author conducted a literature review to find published studies on pallet MFA. The following combinations of search strings were used to conduct keyword searches in Web of Science and Google Scholar:

- “pallet” AND “material flow analysis” AND “China”
- “pallet” AND “material flow analysis”

Initially, no article concerning the MFA of pallets in China was identified. To broaden the scope and uncover more relevant research, the author removed “China” from the keywords and conducted additional searches. The search results were then cross-checked to eliminate duplicates and studies not addressing the topic. These searches yielded a total of 23 studies as of May 2024. Only conference papers, peer-reviewed articles, and doctoral and master's theses published in English were taken into consideration. Consequently, book chapters and handbooks were left out. The contents of these studies were screened for relevance, resulting in the exclusion of 20 studies that did not explicitly assess the material flows of pallets.

Results show that the research on pallet MFA is still limited by the lack of foundational data on the flows and stocks of pallets in different sectors and regions. Only very few researchers have provided the waste disposal rates of the pallet market in the US through questionnaires (Buehlmann et al., 2009; Gerber, 2020), and did not cover other aspects of pallet life cycle, such as raw materials input, production volume, consumption and inventory. Schweinle et al. (2020) conducted MFA of EPAL 1 pallet production in Germany in 2010 and 2015, but they only focus on the EPAL 1 pallet type, overlooking other types of pallets. Besides, EoL rates of wooden pallets are based on assumptions. Data on raw material consumption, pallet use patterns, and waste disposal rates of different pallet types, etc. in China are lacking. This data gap hinders the identification of potential opportunities for improving the efficiency and circularity of pallets in China, such as reducing losses during production, increasing recycling rates. Therefore, this thesis aims to fill the research gap of MFA on pallets in China by collecting primary data from field studies and applying MFA method to analyse the material flows and stocks of pallets in China. This thesis can contribute to the development of a methodological framework for conducting further research on pallets MFA in different contexts, such as other countries or sectors in the world. This work can help to standardise the data collection and evaluation methods for pallets MFA and facilitate the comparison and evaluation of the results across different regions and industries.

2.4 Life cycle assessment

Over the past years, there has been a growing recognition of the importance of incorporating environmental considerations into decision-making frameworks. This shift is largely attributed to the heightened consciousness among people regarding the detrimental impacts of human activities on the Earth's ecosystems. LCA is an effective tool for assessing the environmental implications of a product system throughout its entire life cycle (Chau et al., 2022). The EU legislation increasingly requires the adoption of life cycle approaches and LCA (Azapagic et al., 2006). LCA has been employed in various systems, such as eco-product design; green procurement, and green supply chain (Nilsson and Eckerberg, 2009), environmental product claims and product carbon footprint, etc. (Löfgren et al., 2011).

2.4.1 The history of LCA

The embryonic stage. In the 1960s, LCI analysis has begun to take shape. Countries around the world have considered the limitation of resources and energy, which has led to a series of actions to recycle energy and plan the direction of future resource supply and use (Guinee et al., 2011). The Coca-Cola Company commissioned the US Midwest Research Institute to conduct an environmental impact assessment study on its beverage packaging bottles in 1969, which became the originator of the current life cycle analysis method. The study quantified the raw materials and petroleum used in different beverage cans and the environmental carrying capacity of each can to produce pollution during the production process, involving the assessment of about 40 materials, including glass, steel, aluminium, paper and plastic, etc. This study is supported by these industrial sectors as well as other corresponding industrial sectors. The evaluation study of the beverage packaging bottle of Coca-Cola Company can be said to be the sign of the beginning of the life cycle evaluation study. Subsequently, similar research work carried out during this period was mainly in universities and private consulting firms in Europe and the US. Most of the research objects were packaging materials and use more mature energy analysis methods at that time (Li, 2017).

The stage of slow exploration. In the 1970s, energy issues became the core of environmental issues, so the commonly used analysis method during this period was energy analysis. From the late 1970s to the mid-1980s, this research method was mainly used in the calculation of solid waste generated and raw material consumption. In the late 1980s, although the industry's interest in life cycle was gradually declining, the methodological research on the REPA in academia was still carried on. The British BOUSTEAD consulting company established a set of relatively standardised analysis methods, and laid a solid theoretical foundation for the later famous BOUSTEAD model. In addition, the health assessment analysis standard was first used by the Swiss Federal “Material Testing and Research Laboratory”. The University of Zurich conducted a thorough and systematic exploration from the standpoint of ecological balance and environmental evaluation, significantly contributing to the establishment of a new field within LCA (Guinee et al., 2011).

The rapid development stage. In the late 1980s, people's awareness of environmental protection gradually increased, sustainable ideas gained unprecedented popularity, and green product action plans continued to rise (Guinee et al., 2011). In particular, the emergence of the “garbage ship” incident has brought the issue of solid waste to the forefront of public opinion. As an important tool for analysing environmental problems, LCA regained the favour of research institutions and government departments. Product-oriented LCA was widely accepted.

The maturity and standardisation stage. The concept of "LCA" was first introduced in August 1990, and several discussions were held by the Society of Environmental Toxicology and Chemistry in the following years. Until 1993, it published the "Outline of Life Cycle Assessment" based on the findings of a scientific meeting held in Portugal. This was a turning point in the beginning of LCA technique study as it offered a fundamental technical framework for LCA approaches (Romero-Hernandez, 2005). At the same time, after more than 20 years of practice, with the joint efforts of the ISO and the International Society of Environmental Toxicology and Chemistry, the IS014000 series of standards on LCA have been formulated and released. In 1999, ISO launched the IS014040 standard "Environmental Management - Life Cycle Assessment - Principles and Frameworks" (China National Institute of Standardisation, 1999), and in 2000 launched ISO14041 “Environmental Management - Life Cycle Assessment - Goal and scope definition and inventory analysis”, and other standards, such as ISO14042 standard “Environmental Management - Life Cycle Assessment - Life Cycle Impact Assessment”, and the ISO14043 Standard “Environmental Management - Life Cycle Assessment - Life Cycle Interpretation” was published in 2002 (China National Institute of Standardisation, 2002). In 2006, ISO revised ISO14040 and issued the new version of ISO14044 international standard.

The promotion and application stage. After the mid-1990s, since the release of the ISO series of life cycle standards, LCA has been adopted by a wide range of industry enterprises to evaluate the relevant environmental performance of their suppliers. In 2002, the United Nations Environment Programme and the International Society of Environmental Toxicology and Chemistry launched a further international LCA initiative. In 2005, the European Union established the LCA research platform (Guinée, 2016; Weidema et al., 2009).

An LCA study is composed of four phases, the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase. The topic and goal of the study determine the scope of an LCA, which includes the system boundary and the degree of detail. The goal of a specific LCA determines how extensive and comprehensive the study will be. The second phase is LCI phase, which involves gathering input/output data pertaining to the system under study. The third phase is the LCIA, which involves assessing the environmental implications of a product system's LCI results. The last phase is the life cycle interpretation, wherein the outcomes of an LCI, LCIA, or both, are synthesised to draw conclusions, offer recommendations, and provide decision-making guidance aligned with the defined goal and scope (Fig. 6).

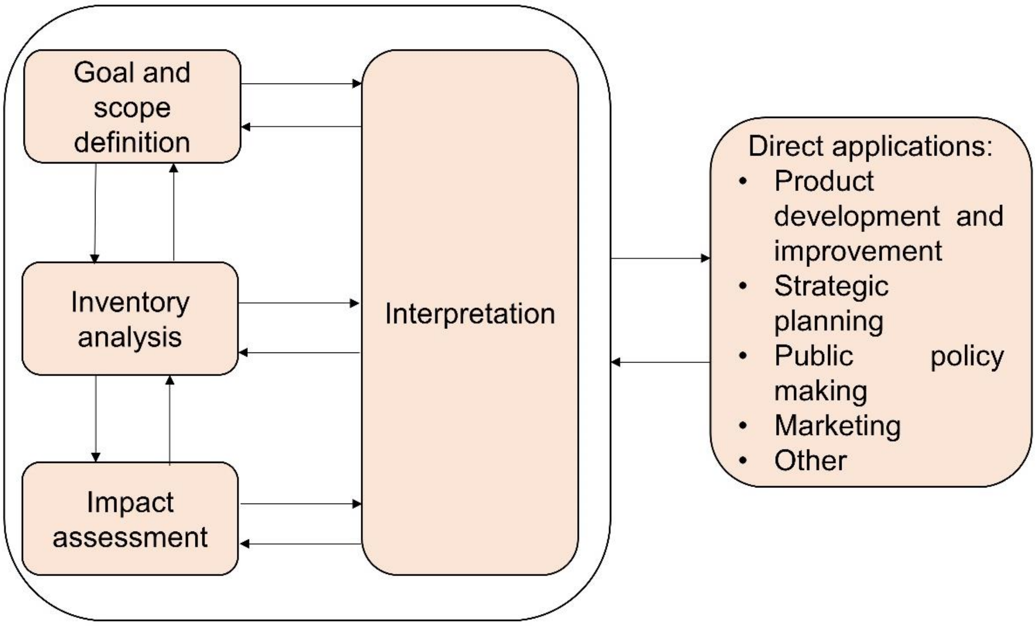


Fig. 6 Life cycle assessment framework

2.4.2 Goal and scope definition phase

Defining objectives includes identifying the research field of the study, determining the significance and limitations of the study, and specifying the target audience. Defining the research scope includes the determination of clear FUs, the system boundaries, and the data requirements, to lay the foundation for subsequent environmental impact analysis (ISO 2006a, b).

2.4.2.1 Functional unit

The FU delineates the specific aspects under investigation, pinpointing the function for which environmental impacts are assessed. The function delivered by the product under research is quantified by the FU, which serves as a reference for normalising input and output data. It lays the groundwork for quantifying the product's functions, serving as a benchmark that all input and output data are correlated with, consequently influencing the outcomes. The FU plays a crucial role in maintaining the comparability of LCA results, particularly when the objective is to evaluate and contrast multiple systems that fulfil the same function. Since LCA studies are frequently conducted to compare different approaches when provide a function, the comparison is also based on the FU. It is important to remember that an LCA study's findings are closely tied to the selection of the FU, and thus, outcomes and FUs must never be split apart. Besides, before conducting LCA studies, FU must be clearly defined.

2.4.2.2 System boundary

The system boundary separates the technical system from the surrounding environment and encompasses activities that are influenced by the life cycle of the product under consideration. Technical flows are the material or energy flows between processes, while elementary flows are the material or energy flows that cross the system boundaries. Elementary flows are either directly extracted from the environment without human alteration or returned to the environment without additional human intervention. Ideally, all input and output data in an LCA study should be elementary flows. However, this is not feasible because of time and data limitations. Therefore, the processes that should be included have to be decided regarding to the definition of goal and scope.

2.4.3 LCI phase

The energy and resource consumption of a product or production process in its whole life cycle within the system boundary, and the various pollutants (exhaust gas, wastewater, solid waste and other pollutants) released into the environment, are analysed and calculated in LCI phase. Inventory analysis should cover the whole life cycle of a product or process. LCI is an important basis for impact assessment in subsequent stages, and the most complete part in the current LCA development process. LCI analysis is an iterative process. After getting a set of data, new data needs or original limitations may be found. Therefore, the data collection procedure should be adjusted to meet the original research purpose. Revisions to the purpose and scope of the research may be required. In the process of data collection, the data of each unit in the system boundary is divided according to input and output. The input mainly consists of energy, raw material, auxiliary, and other physical input. The output mainly consists of products, waste gas, wastewater, emissions to the soil and other environmental emissions. For LCA modelling to accurately reflect the system being analysed, the data utilised should be as reflective of the system and its potential fluctuations as feasible. Typically, this data is gathered over a one-year production period and subsequently adjusted to align with the reference flow quantity selected for the study. It is very rare for an industrial production process to produce only one product or have a linear relationship between its raw material input and output. Most industrial production produces multiple products and recycles intermediate products and waste products as raw materials. Therefore, when assessing multiple products, a predetermined procedure should be arranged for each product or process.

Optimal primary data, which could be either direct observations from a particular location or inferred from on-site measurements, should be prioritised for LCA studies, despite the fact that their acquisition can be laborious and resource intensive. In scenarios where companies possess limited insight into the operational dynamics of certain production facilities, it is possible to approximate the material and energy flows by leveraging data from similar processes occurring at different sites, or by drawing on information from technical assessments, scholarly articles, and LCI databases—collectively known as secondary data sources. Secondary data, including industry averages or figures from studies and academic publications, are often utilised to characterise the background processes in an ALCA. Numerous commercial LCA databases, such as GaBi and Ecoinvent, compile average figures that encapsulate the typical manufacturing and distribution of commodities, making them suitable for use in ALCA studies. These databases are integrated into commercial LCA software platforms, which have significantly streamlined and expedited the process of gathering background data compared to methods employed in the past.

2.4.4 LCIA phase

LCIA is the core content of LCA. It is the most technically challenging and least developed stage among the four stages. Its methodology and theoretical framework, as well as the evaluation models of various impact categories, are at different stages of development, and there is no unified standard yet. LCIA aims to evaluate and describe the impact of environmental burden collected in the inventory stage, analyse the correlation between these data and the environment, and evaluate the severity of potential environmental implications caused by various environmental problems (Burgess and Brennan, 2001). Inventory analysis results typically consist of extensive tables of elementary flows, which can be challenging to interpret. LCIA simplifies this complexity by categorising elementary flows according to their contribution to specific environmental impacts (e.g., acidification, ozone layer depletion), and compares different flows based on the significance of their environmental effects. Results are classified based on the possible environmental impact categories, and the degree of impact in each category is evaluated. The impact assessment phase "translates" these elementary flows into environmental impacts that reflect the consequences of human activities (such as emissions or resource consumption) at specific points along the cause-effect chain. It is crucial to understand that LCIA results should be viewed as potential impacts, rather than actual impacts or indicators of threshold exceedances, safety margins, or risks. This is because: i) the impacts are linked to the FU and do not necessarily reflect the actual scale of emissions or resource use; ii) the inventory data is aggregated across different locations and timeframes, meaning LCIA results indicate impacts across various places and periods; and iii) the assessment is conducted using general models rather than site-specific ones. Impact assessment includes different stages (ISO, 2000):

- **Classification.** The process of classification involves categorising and allocating the LCI data to the respective environmental impact categories they are associated with. This task necessitates an understanding of how emissions or the use of resources can affect the environment. Certain species can contribute to various categories. For instance, NO_x has dual roles: it is acidic substance that can lead to acidification and be involved in chemical reactions that result in the formation of secondary pollutants, thereby impacting the photochemical oxidant formation category. This example highlights that substances released into the environment can have multiple environmental implications. They may affect various impact categories either through concurrent mechanisms, such as NO_x's simultaneous influence on acidification, or through a sequence of effects that culminate in other impact categories. In the latter case, NO_x participates in reactions that can lead to the creation of photo-oxidants, demonstrating how a substance can be linked to different environmental issues through a chain of environmental processes. In essence, classification in LCA is a critical step that requires detailed knowledge of the environmental implications of various substances, enabling a comprehensive assessment of their impact across multiple dimensions of environmental concern.

- **Characterisation.** Environmental impacts are measured as impact categories through the utilisation of publicly accessible equivalent factors derived from modelling causal chains (Baumann and Tillman, 2004). These equivalence factors indicate the extent of the substance contributes to a category (e.g., POF) compared to the reference material. Moreover, the value can vary depending on the characterisation methods used. Characterisation methods rely on physicochemical mechanisms that establish connections between compounds and their environmental harm. During the characterisation phase, the environmental scale and potency of polluting compounds are taken into account. (Taylor et al., 1994). A quantitative method for calculating the impact associated with the general category x is summarised in Equation (1):

$$x = \sum_{i=1}^{n} e_i * m_i \tag{1}$$

Where *x* represents the environmental burden based on the impact category, *n* denotes the total number of mass species within that category, *i* refers to the species, *e* stands for the equivalence factor for species *i*, and *m* represents the mass for species *i*.

- **Normalisation.** The normalisation process is optional. The reference value serves as a point of normalisation for the characterisation phase outcomes. All effect categories become dimensionless during this procedure, allowing the most influential process to be determined. It is important to be cautious when interpreting normalised scores in an analysis, as this process can alter the original results and potentially lead to different conclusions. The act of normalising data may introduce considerable bias, which is contingent upon the selection of the reference system and the comprehensiveness of its inventory data.
- **Weighting.** The process of weighting is optional in LCA, and it involves assigning either uniform or varying weights to the normalised category indicator results. This technique is primarily used to rank the

importance of different impact categories based on a predefined weighting scheme. The weighting phase aims to transform and aggregate the results for impact categories, obtaining a single score derived from existing assessment methods, such as Ecoindicator 99 (Clift et al., 2000), enabling comparisons across various impact categories. It is crucial to recognise that this step is subject to the personal preferences of an individual or a collective decision-making body and is not scientifically based. Consequently, the weighting step is inherently subjective, reflecting the values and priorities of those involved in the decision-making process.

- **Grouping.** The final suggested optional procedure is grouping, which entails consolidating various impact categories into a single or multiple groups. The primary objective of this step is to enhance the clarity and efficiency of communication. This process can be structured according to geographical criteria, ranging from global to regional and local scales, or it can follow a pre-established hierarchical system. An example of such a system might involve classifying impacts according to their priority levels, such as high, medium, or low.

The impact assessment method can be selected based on the research purposes. The selection of impact categories, equivalence factors, and factors for normalisation and weighting is contingent upon the specific impact assessment methodology employed. The representative methods in Europe are CML (Leiden University Institute of Environmental Sciences), ReCiPe and ILCD (International Reference Life Cycle Data System), etc., while Traci, Bees, etc (PRé Sustainability, 2020) are commonly used in North America. The ReCiPe methodology is advanced among the current impact assessment methods, since ReCiPe methodology is based on Eco-indicator 99 (Goedkoop et al., 1998) and CML methodology (Cabeza et al., 2014). The Recipe 2016 method involves 18 impact categories:

- **Climate change.** GWP addresses the release of GHGs, such as CO_2,

CH_4, N_2O, and others, quantifying their collective warming potential in terms of kg CO_2 eq.

- **Resources.** MD addresses the use of non-renewable abiotic resources, such as metals, and its implications for resource scarcity, measured in kg Cu eq.. FD reflects the impacts the future availability and extraction costs of fossil fuels, with potential expressed in kg oil eq.. FC analyses the consumption and scarcity of water resources due to human activities, with potential measured in m^3.
- **Ozone, fine particles and radiation.** SOD captures the impact of substances known to erode the ozone layer, with potential expressed in kg CFC-11 eq. IR addresses the effects of radioactive emissions on human health. Radioactive substances, known as radionuclides, are commonly released into the environment by human activities such as nuclear power generation, coal burning, and construction. These substances can be dispersed through air and water. When people are exposed to these radioactive materials, they may experience a range of health issues, including both random and predictable effects, such as various types of cancer, whether they are life-threatening or not, and potential genetic impacts. POF, human health arises due to the release of NMVOCs and NO_x as a result of various human activities, including transportation, industrial operations, and the utilisation of organic solvents. Emissions of NO_x also originate from incineration plants, which are typically a consequence of incomplete fuel combustion. The generation of ozone through these photochemical transformations can lead to adverse respiratory effects in humans and is quantified in terms of kg NO_x eq.. Similar to POF, human health, but POF, ecosystems extends the focus to the effects on plant life and terrestrial ecosystems. FPMF deals with the formation of fine particles that contribute to human health issues, with potential measured in kg $PM_{2.5}$ eq..

- **Acidification and eutrophication.** TA denotes the reduction in soils' ability to neutralise acidic substances, leading to increased soil acidity. The unit is kg SO_2 eq.. FEu evaluates the nutrient enrichment in freshwater systems, leading to issues, such as algal blooms, with potential in kg P eq.. Similar to FEu, but MEu measures the impacts on marine environments, often focusing on nitrogen as the limiting nutrient, also in kg N eq..
- **Eco and human toxicity.** TE encompasses the impact of chemical exposure on various ecosystems, including terrestrial, freshwater, and marine environments. It considers the propensity of these chemicals to move within the environment, their tendency to persist over time, and the subsequent harm they inflict on ecological systems. The origins of chemical emissions are vast, stemming from a multitude of processes throughout the inventory. FE mirrors TE but is specific to freshwater ecosystems. Its unit is kg 1,4 DB eq.. ME focuses on chemical exposure and damage specific to marine ecosystems, also measured in kg 1,4-DB eq.. HT, cancer quantifies the potential increase in cancer risks due to exposure to carcinogenic substances, using kg 1,4-DB eq. as a reference. Similar to HT, cancer, but HT, non-cancer relates to non-cancer health risks from toxic substances.
- **Land use.** Land transformation involves the alteration of land from its existing condition to another, and land occupation refers to the utilisation of land for specific purposes. Such shifts in land use can have profound effects on ecosystems, including the degradation of their quality and functionality. They can also interfere with the natural services provided by these systems, alter the water cycle, contribute to a decline in biodiversity, exacerbate soil erosion, and even influence local and regional climate patterns (Huijbregts et al., 2017).

2.4.5 Life cycle Interpretation phase

Life cycle interpretation is the phase that synthesises the outcomes of LCI and LCIA, and ultimately draws conclusions and recommendations. It systematically identifies hotspots to reduce material input and pollutant emissions throughout the life cycle of a product or process. Additionally, it provides relevant information and guidance for decision-making in accordance with its objectives. This phase comprises the following elements:

- **Identification of significant issues.** This element's mission is to organise the LCI or LCIA phase results in a way that aligns with the goal and scope specification, facilitating the identification of key concerns, and in collaboration with the evaluative aspects. This interaction aims to incorporate the consequences of the procedures followed, presumptions made, etc. in the earlier stages.
- **Evaluation.** Establishing and enhancing trust in the dependability of the LCA or LCI study's conclusions, as well as addressing the key problems mentioned in the first interpretation part, are the goals of the evaluation element. The evaluation's findings should be communicated in a way that provides the commissioner and any other interested parties with an intelligible and clear picture of the study's conclusion.
- **Conclusions, limitations and recommendations.** The goal of this phase in the life cycle interpretation process is to synthesise findings, identify constraints, and offer guidance tailored for the LCA's target audience. Conclusions must be derived from the study's data and insights, integrating them with other elements within the interpretation phase in a cyclical manner. Recommendations should stem from the conclusive results of the research, representing a coherent and rational deduction from the findings. When aligned with the study's objectives and scope, the interpretation should provide specific suggestions for decision-makers, ensuring they are well-founded and directly relevant to the study's aims.

2.4.6 Allocation procedures

To ascertain the exact contribution of resources and raw materials to the primary product, the environmental consequences of each co-product are divided among them through the process of allocation. According to ISO standards, the following allocation techniques should be utilised (ISO 2006a, b):

- According to the ISO guidelines, the initial approach to addressing issues related to multi-functionality should be the breakdown of a process into its constituent sub-processes. The process can be divided into multiple sub-processes, each producing a distinct co-product. This will help avoid allocation by only taking into account the sub-processes that result in the main product being studied. Typically, the presence of multiple functions is contingent upon the degree of detail with which the system is analysed. It could be feasible to dissect a single process into multiple sub-processes, thereby enabling the separation of previously combined outputs that were thought to originate from a single process unit. Implementing subdivision entails cutting off all processes that serve secondary functions. However, in the majority of biological processes and numerous chemical processes, multi-functionality issues cannot be resolved through subdivision. In such cases, it may be essential to employ alternative methods such as crediting or system expansion, or a partitioning approach.
- When the subdivision method is ineffective, alternative strategies such as system expansion and crediting are utilised to address the multi-functionality issue. These two approaches, though mathematically identical, differ conceptually. System expansion is a technique used in comparative assessments where one system (system 1) offers multiple services that another system (system 2) does not. If system 2 is limited to a single function, an additional process is integrated into the single-

function system to enable a fair comparison with the multifunctional system. On the other hand, the crediting approach is typically used in non-comparative, ALCA. It involves deducting the environmental impacts associated with the secondary function from the multifunctional system. This method effectively isolates the impacts of the primary function for a more accurate assessment. For instance, consider a scenario where two distinct power plants are being evaluated. Plant 1 generates both electricity and heat, whereas plant 2 is solely focused on electricity production. To account for the multifunctional nature of plant 1, one could either: 1) expand plant 2's system by incorporating an alternative heat generation process, thus rendering both systems comparable; or 2) detract the environmental burdens associated with heat production from plant 1, effectively crediting it for the reduced need to produce heat elsewhere.

- Ultimately, when the initial approaches mentioned are deemed inapplicable, the ISO 14044 standard recommends employing the partitioning, or allocation, method. Allocation entails the process of distributing all system inputs and outputs proportionally among the various functions or products. The ISO guidelines recommends assigning the environmental burden according to the physical factors that contribute to the outputs, including mass or energy content. In cases where an allocation based on physical relationships is not feasible, alternative criteria should be explored, such as the economic value of the co-products. The socio-economic allocation method, as recommended by ISO, is based on economic value. A co-product that made up 30% of the final product's value, for example, would be responsible for 30% of the environmental burden.

The first and second principles listed above are followed in this LCA analysis. For example, sawdust and other wood waste produced during the production of wooden pallets are often used as fuel in the production plant, eliminating the need to buy other off-site goods to meet fuel requirements. 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 either as electricity or as heat, and the environmental effects from combustion of other fuels will be avoided (Ng et al., 2014).

2.4.7 Product sustainability software

Significant amounts of data require processing in LCA and the selection of data processing software is critical. SimaPro software from PRé Consultants in the Netherlands and GaBi software from Thinkstep in Germany are two popular and widely used LCA software. In terms of operational convenience, the two are relatively similar, but in terms of databases, SimaPro and GaBi have their own advantages. The SimaPro database mainly consists of the following joint databases: Ecoinvent, BUWAL250, Data Archive, ETH-ESU 96 Unit process, IDEMAT2001and Dutch Input Output Database95, etc. These databases cover material input and output data, energy basic production data, global warming, acid rain effect and other data, which are mainly from various academic research. The GaBi software covers the production processes of different energy sources and materials. GaBi data mainly comes from PE-International' s nearly 20 years of global industrial LCA project cooperation and databases, such as ELCD, BUWAL and Plastics Europe. The GaBi software supports more than 100 impact classifications, including: CML 2001, Ecoindicator 99, EDIP 97, EPFL2002+ and EDIP 2003, etc. Since the research product in this thesis is an industrial product, this thesis chooses GaBi software which focuses more on actual production and industrial enterprise applications.

As one of the most advanced LCA software in the world, GaBi software was first released by the LBP Institute of the University of Stuttgart, Germany. In order to better promote GaBi software, an LCA consulting company PE-

International was established, and it was renamed Thinkstep in 2015. GaBi software is well-known in life cycle research and the related environmental consulting. The first version of GaBi software was developed in 1992.

2.4.8 Two modes of LCA

With the development of LCI and LCIA, different types of LCA methods have emerged. LCA can be classified into two types, ALCA and CLCA according to the principles of inventory data collection based on different research objectives (Brander et al., 2008; Guinee et al., 2011).

ALCA is a method for evaluating the material and energy flows related to the environment. The inventory analysis lists the consumption and emission data that have a direct causal relationship with the product under study. CLCA is the analysis of the indirect effects of the fluctuations in demand that will cause a marginal change in the market share of upstream raw material supply during the LCA. The inventory analysis collects data based on marginal data, and uses economic data to measure the environmental impact considering indirect effects.

Comparing the two evaluation methods, the classification of the two methods takes the research objective as the principle of inventory data collection, and its essence lies in the determination of the system boundary. ALCA includes direct substances or emissions that influence the environment, covering the entire life cycle. The calculation process of the ALCA method is more realistic and detailed, and its model is linear, which is suitable for environmental impacts of different scales. When the goal of the research is to identify the key activities, the contribution of key substances to environmental performance, and to assess the potential for technological optimisation, ALCA is more applicable (Rehl et al., 2012). In this study, ALCA is adopted, because of the goal to assess environmental impacts of pallets. However, this method relies more on secondary data when primary data are not available. The CLCA considers the system boundaries more holistically, but it uses marginal data and is mostly related to economic models, and models are mostly nonlinear. CLCA is suitable for macro-assessment of the regional and national environmental impacts of a policy (Rehl et al., 2012).

2.4.9 Uncertainty and sensitivity analysis in LCA

The ISO standards suggest conducting several types of analysis to enhance the quality of LCIA. These include uncertainty analysis and sensitivity analysis, which are crucial for pinpointing the data elements that most significantly influence the outcome of the LCIA. These analyses also shed light on the inherent uncertainties in the data and their potential impact on the LCIA results. The uncertainty analysis aims to quantify and communicate the uncertainty of the LCA results due to the variability and imprecision of the input data (Scrucca et al., 2020), indicating the level of confidence and reliability of the LCA results and identifying the sources and types of uncertainty that affect them (Benetto et al., 2006). The uncertainty analysis can also guide further research and data collection to reduce uncertainty and improve robustness of the LCA results (Lo et al., 2005; Perkins and Suh, 2019). However, it is not a common practice to see these additional layers of LCIA data quality presented in LCA studies, possibly due to the complexity and time-consuming nature of these analyses. Uncertainty analysis, in particular, aims to measure the degree to which each input variable contributes to the variability of the results. This process requires detailed information on the probability distribution of the input parameters, which might follow various patterns such as normal or log-normal distributions. To conduct an uncertainty analysis effectively, one must have access to data that describe the probability density functions of the input flows and parameters. This includes understanding the type of distribution, standard deviation, arithmetic mean, mode, and median. The complexity of the system under study, the level of technological development, and the availability of such data can make performing an uncertainty analysis a challenging task, adding to the already demanding LCI phase. Typically, the uncertainty range is set to cover a 95% confidence interval, which corresponds to the range between the 2.5th and 97.5th percentiles of the distribution. This means that the uncertainty range encompasses the values that would be expected to fall within 95% of the random measurements. Despite the challenges, incorporating these analyses can significantly enhance the robustness and reliability of the LCIA results (Hyde et al., 2005).

The Monte Carlo method is a prevalent technique used to capture the uncertainty by generating random values for the input data according to their probability distributions and computing the LCA results for each set of values (Zhao et al., 2019). The Monte Carlo method is widely adopted in LCA studies because it can account for different types and sources of uncertainty and provide information on the confidence of the LCA results (Helton et al., 2006). To enhance the precision of the results, it is essential to perform a large number of model calculations, or iterations. The more iterations conducted, the more precise the outcome is likely to be. Upon completion of the simulation, statistical analyses are conducted, and the findings are typically presented as a range of possible values, along with a central estimate and a confidence interval. This approach provides a comprehensive view of the potential variability in the outcomes, reflecting the inherent uncertainties in the input data and model parameters.

A model's sensitivity refers to the degree to which its outcomes are influenced by fluctuations in its parameters or the inputs of materials and energy. If a system exhibits high sensitivity to a particular parameter, minor adjustments to that parameter can lead to substantial alterations in the model's output. Conversely, a system is considered to have low sensitivity to a parameter if modifications to it yield only minor or insignificant effects on the model's results. This characteristic is crucial for understanding which factors are critical in driving the model's behaviour and which can be altered with minimal impact.

The 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). Also, the recycling rate of steel pallets in China is based on assumptions. The EoL scenario assumes a 100% recycling rate due to the high economic value of scrap steel and the significant role of waste pickers in China, who collect and sell discarded materials to recycling centres. Given the variability in these factors, sensitivity analysis of the RSL and recycling rate of steel pallets is essential to assess their impact on LCIA results.

2.4.10 Limitations of LCA methodology

LCA has some inherent limitations because of the artificial simplification of the real world, including the omission of certain human activity fluxes and imperfect modelling (Millet et al., 2007). LCA fails to account for the temporal dynamics of change and assumes a steady-state condition. Besides, it adjusts all reference flows linearly according to the FU, disregarding other external factors, such as economic or market influences. LCA also confines the inputs and outputs data to the product system, which excludes some environmental impacts, such as noise, that are incompatible with the indicator scheme. LCA focuses on environmental interventions that occur regularly, but frequently omits irregular emissions (e.g., emissions that are not annualised).

2.4.11 Current LCA studies on pallets

2.4.11.1 Methodology

The author conducted a literature review to find published studies on pallet LCA. The following combinations of search strings were used to conduct keyword searches in Web of Science and Google Scholar:

- “life cycle assessment” AND “pallet” AND “China”
- “environmental impact” AND “pallet” AND “China”
- “life cycle assessment” AND “pallet”
- “environmental impact” AND “pallet”

Initially, only one article concerning the LCA of wooden and plastic pallets in China was identified. To broaden the scope and uncover more relevant research, the author removed “China” from the keywords and conducted additional searches. The search results were then cross-checked to eliminate duplicates and studies not directly addressing the topic.

As detailed in Table A. 1 of the Appendices, these searches yielded a total of 120 studies as of May 2024. The contents of these studies were screened for relevance, resulting in the exclusion of 91 studies that did not explicitly assess the environmental impacts of pallets. Only conference papers, peer-reviewed articles, doctoral and master's theses published in English were taken into consideration. Consequently, book chapters and handbooks were left out. As a final sample, 29 studies were included in this review (Table A. 2 in Appendices) because they met one of the following criteria:

- Conducting an LCA of pallets in accordance with the ISO 14040: 2006 and ISO 14044: 2006 frameworks (ISO 2006a, b);
- Including an LCA of pallets as part of broader objectives, provided the LCA was thoroughly discussed, and the environmental impacts were explicitly attributed to the LCA process;
- Performing an LCI, accounting for energy, emissions, and material flows;
- Investigating one or more environmental impact categories of pallets, such as the carbon footprint.

To ensure a comprehensive review, studies were not excluded due to minor or unavoidable methodological flaws. These methodological issues and their implications for the quality of the results are discussed in detail in the results and discussion section.

2.4.11.2 Results and discussion

2.4.11.2.1 Pallet material type and geographical distribution

Among the different pallet materials, wooden pallets are the most extensively studied, with 25 articles dedicated to them (accounting for 86%). This prevalence is partly due to historical factors and the dominant market share of wooden pallets (Alanya-Rosenbaum et al., 2021). For instance, in the US, wooden pallets constitute 88% of the pallet market (Bilbao et al., 2010). The geographical distribution of the studies shows a significant concentration in the United States (10 studies), followed by Spain (2 studies), Finland (2 studies), and Australia (2 studies). Other countries such as China, New Zealand, Portugal, Italy, Singapore, and South Korea are represented by a single study each. Additionally, 8 studies did not specify their geographical context (Fig. 7). The findings from this systematic literature review are primarily presented in an aggregated format to enable easier comparison across various datasets. Specific results are highlighted only in cases where aggregation is not feasible, such as when there are limited case studies for a particular type of pallet, or when it is necessary to emphasise certain points or substantiate claims. For impact categories that are highly influenced by local or regional conditions, generalisation is avoided to ensure accuracy and relevance.

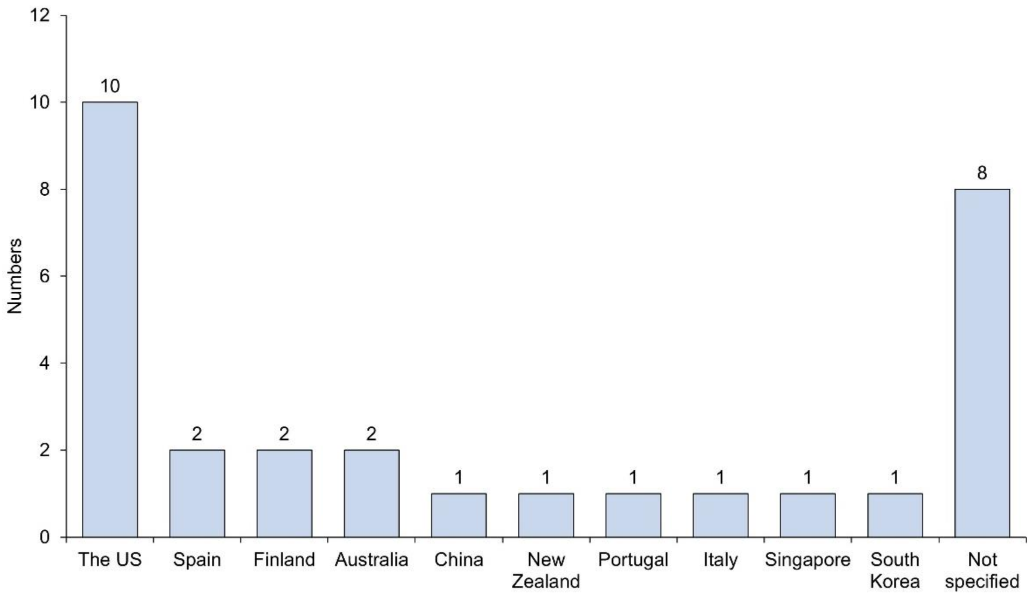


Fig. 7 Geographical distribution of pallet LCA studies identified in the reviewed literature

Wooden pallet. The key findings regarding wooden pallets emphasise their significant carbon footprint, with 8 out of the 25 articles specifically addressing carbon emissions. These studies consistently highlight the considerable carbon emissions associated with wooden pallets, considering factors such as raw material extraction, manufacturing, and EoL disposal. Carrano et al. (2014) provided a foundational analysis of the carbon emissions of wooden pallets from cradle to grave. Subsequent studies by Carrano et al. (2015) introduced an optimisation model aimed at minimising carbon emissions, considering specific handling/loading and EoL scenarios, revealing that significant reductions could be achieved through efficient logistics and material use. However, these studies are geographically limited, drawing on data from facilities in the northeastern and southeastern US, which cannot accurately represent conditions in China. Also, other impact categories are not included, hindering the assessment from a holistic perspective.

In Spain, García-Durañona et al. (2016) focused on the production stage, noting that it contributed significantly to the overall environmental impact. However, their study lacked a full lifecycle perspective and transparency regarding data collection. Alanya-Rosenbaum et al. (2021) considered the entire lifecycle of wooden pallets, providing a more holistic assessment of environmental impact categories including GWP, AP, EP, OD and PS from cradle to grave. They utilised primary data from U.S. pallet manufacturers collected in 2016 to calculate the total global warming impact, which was determined to be 10.4 kg CO_2 e per 45.4 tons of product delivered using wooden pallets. The manufacturing stage was identified as the most significant contributor to this impact, followed by the raw material supply stage.

The research on wooden pallets predominantly focuses on carbon emissions, with less attention given to other environmental impacts such as water usage, EP and toxicity. The reliance on regional data, particularly from the northeastern and southeastern US, limits the generalisability of findings to other regions with different environmental conditions and industrial practices. Moreover, the transparency and age of the data used are critical issues, as outdated data may not reflect current manufacturing practices or technological advancements (Bicalho et al., 2017).

Plastic pallet. In contrast to wooden pallets, individual studies on plastic pallets are scarce (only 13 articles), with most research focusing on comparative analysis between plastic and wooden pallets (accounting for 77%). The gradual increase in market share for plastic pallets has not yet eclipsed the predominance of wooden pallets. Comparative studies have primarily concentrated on the carbon footprint, with most findings indicating a higher carbon footprint for plastic pallets than wooden pallets due to greater resource and energy consumption during the raw material and production stages. 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 over 100 trips from a cradle-to-grave perspective. However, this study lacked comprehensive environmental impact assessments and the EoL flows are not based on real data collected from field studies. Instead, they used assumptions for EoL flows. Anil et al. (2020) conducted a detailed cradle-to-grave LCA to compare treated wooden pallets and plastic pallets within the grocery industry, evaluating the effects of various phytosanitary treatments. However, the relevance of this study to China is limited as some of the treatment methodologies, particularly methyl bromide fumigation, are no longer used due to toxicity concerns. The study relied on data from Anil's master's thesis (2010), which is now outdated. The LCI data for wooden pallets' EoL was sourced from Bush and Araman (2009), and the plastic pallet EoL was assumed full recycling. The LCI of hardwood lumber production was based on Bergman and Bowe (2008). The data needs updating, and the thesis lacks transparency regarding dataset sources, hindering reliability checks. Kočí (2019) expanded the environmental impact categories to include GWP, FPMF, FD, FC, FE, FEu, HT, IR, LU, ME, MEu, MD, POF, SOD, TA and TE. The study 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 life cycle. For wooden pallets, significant environmental impacts were associated with disposal, transport to processing, and production processes. For plastic pallets, the most impactful processes included melting and moulding of the plastic, primary plastic production, and transport to processing. However, this research also lacked transparency regarding the LCI data, limiting the reliability and reproducibility of the findings.

The research on plastic pallets, which includes 13 articles (Fig. 8), is less comprehensive than that on wooden pallets. The primary focus on carbon footprint overlooks other critical environmental impacts, such as toxicity, and resource depletion. The assumptions used in LCI data introduce uncertainties, and the lack of updated real-world data means that these studies might not accurately represent the environmental performance of plastic pallets in practice.

Other types of pallets. Studies on alternative pallet materials, including paper and steel, are relatively scarce with only 6 articles addressing these materials. Bengtsson and Logie (2015) extended beyond wooden and plastic pallets to include other materials such as cardboard pallets, considering manufacturing processes in both China and Australia. This study applied the

LCA methodology to evaluate environmental performance from cradle to grave, covering various stages such as materials supply, manufacturing, distribution, use, maintenance, reuse, recycling, and disposal. However, the results presented were limited to only two impact categories: GWP and FD. This narrow focus raises questions about the comprehensiveness and robustness of the assessment, as other significant environmental impacts were not analysed. Moreover, the study lacked transparency regarding the datasets used. It did not clarify whether the data were obtained from Ecoinvent databases, fieldwork, or other sources. This lack of clarity makes it difficult to verify the accuracy and reliability of the data. Additionally, the study did not specify the timeframe during which data were collected. Without this information, it is challenging to assess the relevance of the data, which are crucial for ensuring consistency and validity in LCA studies. Consequently, the absence of detailed information about data sources and collection periods undermines the overall reliability and credibility of the study's findings.

Choi et al. (2020) compared the environmental impacts of disposable wooden pallets and reusable steel cradles in South Korea. However, the study lacked uncertainty analysis and only considered primary materials and manufacturing processes. Recycled materials and transportation were excluded from the analysis, limiting the study’s reflection of real-world conditions. Zacchei et al. (2022) conducted an LCA study to assess the environmental impacts of new steel pallets compared to wooden, plastic, and aluminium pallets, including raw material extraction, manufacturing, transportation, and EoL treatment stages. The research concluded that new modular metal pallets offer satisfactory performance in terms of resistance and stiffness and present a more environmentally friendly option due to their recyclability and durability. However, the unclear data collection timelines and the presentation of environmental impact results as figures without numerical values, complicate comparison with other studies. Khan et al. (2021) presented an LCA study comparing the environmental impacts of wooden, plastic, and wood-plastic composite pallets in Finland. The study indicated that wood-plastic composite pallets had the lowest environmental impact in categories such as ADP, AP, EP, GWP and OD. The study concluded that wood-plastic composite pallets could be a better choice over plastic pallets and, in most instances, over wooden pallets. Nevertheless, the study did not specify the data collection timeframe, making it difficult to assess the reliability of the data. These studies lack the data transparency and the uncertainty analysis, limiting the robustness of their results.

Korol et al. have continuously investigated the environmental impacts of various materials used in pallet production, focusing on plastic pallets made from different biocomposites and traditional composites. In their 2016 study, they employed the ReCiPe LCIA method to compare the environmental impacts of pallets made from PP, glass fibres, and natural fibres, such as cotton, jute, and kenaf, using the EUR-pallet as a benchmark. The findings indicated that biocomposites and composites reinforced with cotton and glass fibres had the highest environmental impact, whereas kenaf and jute fibres had the lowest. However, it was not possible to definitively identify the most environmentally friendly material (Korol et al., 2016). The study lacked data provision and uncertainty analysis. In 2019, they assessed the water footprint of various materials, revealing that cotton fibres had the highest water footprint due to irrigation needs, while PP and its glass fibre composites had the lowest. This suggested that bio-based plastics and composites might not be as environmentally friendly as commonly assumed in terms of water usage (Korol et al., 2019). In 2020, they evaluated the carbon, ecological, and water footprints of PP-based composites reinforced with cotton, jute, and kenaf fibres, finding that natural fibres reduced the carbon footprint but significantly increased the water footprint due to cultivation and irrigation demands (Korol et al., 2020). Across these studies, Korol et al. underscore the importance of comprehensive environmental footprint evaluations when assessing bio-based or natural fibre-reinforced composites, highlighting the need for careful material selection and suggesting future research directions. However, these studies did not provide specific data, lacked representativeness of material type, did not perform uncertainty analysis, and were limited to cradle-to-gate system boundaries, failing to offer a complete environmental impact analysis.

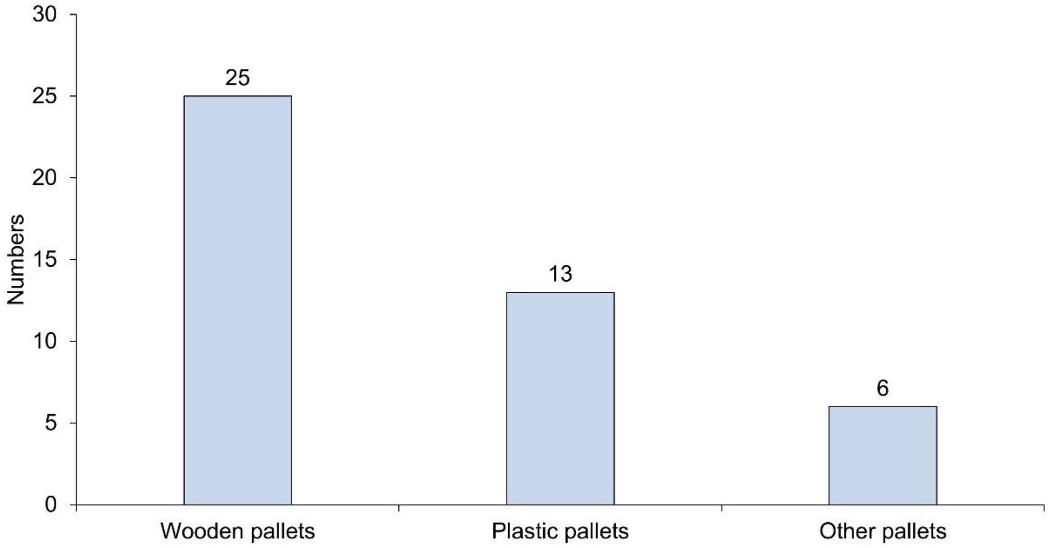


Fig. 8 Pallet material types identified in the reviewed literature

In conclusion, the current body of literature on the environmental impacts of pallets is notably limited and predominantly centres on the carbon footprint of wooden pallets, primarily in the context of the United States. This narrow focus has resulted in a significant gap in the LCI database for pallets, particularly in China, where five types of pallets which together accounted for more than 99% of the pallet market in 2020, are widely used but have not been comprehensively evaluated. The reliance on assumptions or outdated data, especially for wooden pallet EoL scenarios based on 2009 U.S. data, underscores the urgent need for updated and region-specific research. Moreover, the ability to directly compare the existing studies is often impeded by variations in system boundaries and levels of transparency. To achieve a more accurate and holistic environmental assessment of pallet use in China, it is imperative that future research addresses these gaps, incorporates a broader range of pallet types, and enhances the transparency and consistency of LCA research.

2.4.11.2.2 Life cycle stages

Several studies have quantified the carbon footprints of pallets focusing on the specific life cycle stage. Ng et al. (2014) calculated and compared the carbon footprint of pallets made from virgin and recycled wood, focusing on the production stage, and found that recycled wood had lower carbon emissions than virgin softwood. Tornese et al. (2016) focused on estimating the carbon footprints of the pallet remanufacturing phase and found that the main sources of carbon equivalent emissions from remanufacturing were the materials used in the operations. García-Durañona et al. (2016) considered other impact categories, such as AP, EP and HT, to provide a more holistic picture of pollution, and used these categories to assess the environmental impacts of the production stage of wooden pallets in Spain. However, the absence of uncertainty analysis in the study makes it difficult to ascertain the robustness and reliability of the data. Alanya - Rosenbaum et al. (2022) assessed the environmental burden of wooden pallet repair and remanufacturing stage in the US. For the EoL phase of pallets, because of the lack of data, the majority of research used the data from the questionnaires collected by Buehlmann et al. (2009) from 2003 to 2004 in North Carolina. Many studies focus on specific life cycle stage, often neglecting a holistic view that includes all stages from raw material extraction to disposal. This fragmented approach can lead to a potential burden shifting between stages. Additionally, the reliance on outdated data compromises the accuracy of the assessments. Some studies have extended the system boundary to encompass the entire life cycle of pallets. However, these studies primarily focus on the carbon footprint, neglecting multiple impact categories. This narrow focus prevents the identification and mitigation of potential trade-offs that could arise from considering only one impact category.

2.4.11.2.3 The LCA process

This section highlights important methodological flaws in the examined studies and analyses important discoveries that are unique to pallet LCA studies. The methodological problems found in four stages of LCA are summarised as follows in Fig. 9: The following issues have been raised: i) incomplete and missing goal and scope descriptions; ii) unclear FUs and incomplete system boundaries; iii) poorly presented inventories; and iv) unstated impact assessment techniques and omission of uncertainty analysis. These errors impair the reproducibility of the LCA results and introduce uncertainty into them.

Incomplete and missing goal and scope descriptions. About 17% of the reviewed studies have failed to define their goals and scopes (Table A. 2 in Appendices). Some studies that lack a defined goal for the LCA utilise broad aims or objectives to convey the study's purpose (e.g., Bilbao et al., 2011), while others need to be summarised to identify goals and scopes (e.g., Bilbao et al., 2010; Kočí, 2019) The absence of a clear and precise goal and scope definition hampers the identification of the target audience and the effective application of the LCA results for subsequent monitoring and evaluation in comparison to baseline conditions. According to the evaluation of the reviewed studies, their goals can be categorised as follows:

- To assess the carbon footprint of wooden pallets (e.g., Carrano et al., 2014);
- To assess the carbon footprint of a specific stage of wooden pallets (e.g., García-Durañona et al., 2016);
- To develop an LCI parametric model of wooden pallets (e.g., Niero et al., 2014);
- To quantify the environmental impacts of wooden pallets and identify key environmental hotspots within the supply chain for potential system improvements (e.g., Alanya-Rosenbaum et al., 2021);

- To compare the carbon footprint of different types of pallets (e.g., Weththasinghe et al., 2022);
- To compare the environmental impact of different types of pallets (e.g., Anil et al., 2020; Kočí, 2019).

In addition to the main goal of performing LCA, about 14% of the studies have multiple goals beyond the evaluation of environmental impacts, varying depending on the target audience and intended use of results. For instance:

- To investigate the environmental effects of optimising a unit load by increasing the stiffness of the pallets' top deck boards and reducing the board grade of its corrugated boxes (Kim et al., 2023);
- To evaluate the impact of preemptive remanufacturing policies on the economic and environmental performance of wooden pallet logistics (Tornese et al., 2019).

Unclear FUs and incomplete system boundaries. About two-thirds (66%) of the studies adopt a cradle-to-grave approach, covering the entire lifecycle of the product. However, a significant portion (34%) do not, potentially overlooking important lifecycle stages. 7% of studies exhibit unclear FUs, indicating that these studies fail to effectively establish the basis for comparison and impact assessment. The normalisation and comparison of LCAs of pallets with identical functions are based on FUs and reference flows, which also help to define the interpretation of the findings. FUs should contain the system's function; otherwise, they turn into reference flows (Bjørn et al., 2018a; Laurent et al., 2013).

Alanya-Rosenbaum et al. (2021) proposed a novel FU for the environmental assessment of pallets, calculated at 10.4 kg CO_2 e per 45.4 tons of pallet loads of product delivered using wood pallets, rather than the previously used FUs which did not fully consider the pallet’s functionality or load-bearing capacity. This shift in perspective allows for a more accurate environmental assessment, highlighting the influence of the RSL and load-bearing capacity on the total environmental impact. The study found that the manufacturing stage contributed the most to the total global warming impact, followed by the raw material supply stage. This approach contrasts with previous studies, where 50% used "one piece of wooden pallet" as the FU (Carrano et al., 2014; García-Durañona et al., 2016), which did not consider the pallet's functional performance. Additionally, 30% of studies used "trips" (Carrano et al., 2015; Khan et al., 2021), overlooking the impact of varying load-bearing capacities. Other studies focused on transporting certain tonnes of cargo without accounting for the different load-carrying capacities or RSLs of various pallet types (Gasol et al., 2008). Therefore, Alanya-Rosenbaum et al.'s FU is more reasonable and comprehensive, as it incorporates the critical factors of load capacity and service life, leading to a more robust and accurate environmental impact assessment.

Poorly presented inventories. Foreground data exhibit a high degree of specificity when they are derived from direct sources such as personal measurements, interviews, or surveys. In contrast, their specificity is reduced when they are obtained from secondary sources, including other LCA studies, national statistical data, and reports from the industry (Bjørn et al., 2018b). Conversely, background data and processes are predominantly drawn from LCI databases. These databases compile average industry data that is specific to particular countries or regions, or they may include global datasets that are applicable worldwide. A substantial majority (72%) of studies utilise primary data. However, only 34% of studies clearly present their data inventory, and an even smaller percentage (24%) describe the data timeframe, indicating significant gaps in data transparency. In the realm of LCA studies, a significant deficiency in data transparency can lead to a cascade of drawbacks (Bicalho et al., 2017). Firstly, the credibility of study outcomes is compromised when primary data is not presented transparently, thereby impeding the verification process by other researchers. The lack of a clear data inventory and the absence of a specified data timeframe can further complicate comparative analysis across studies, as temporal variations in data may skew the interpretation of environmental impacts. This opacity in data presentation hinders the replicability of studies. The lack of transparency can also lead to misallocation of resources, as it may not accurately reflect the areas requiring the most attention for sustainability improvements. Moreover, the potential for innovation is stymied when data is not openly shared, limiting the opportunity for a thorough analysis of existing processes. Public trust in the industry's sustainability claims may also erode if LCA studies are perceived as opaque or unreliable. To mitigate these issues, it is imperative for researchers to enhance data transparency, ensuring a clear and accessible presentation of their methodologies and findings, thereby fostering trust and enabling more effective decision-making for sustainable practices.

Unstated impact assessment techniques and omission of uncertainty analysis. A notable percentage of studies (38% and 17%, respectively) lack the information on the LCA software, and the databases used, which can affect the reproducibility and transparency of the studies. The Ecoinvent database is prominently featured as a key source of background data in 66% of the studies. It is exclusively used in nearly 11 studies, and is also combined with other databases such as U.S. Life Cycle Inventory (in 3 studies). Regarding the LCA software, SimaPro is the most widely adopted, with 52% of the studies employing it for their analysis. GaBi is used in 10% of the studies. Approximately 24% of the studies perform their LCA calculations manually using equations, which typically allows for the assessment of a limited number of impact categories. Open-source software such as OpenLCA which could potentially reduce uncertainties in calculations where commercial software is unaffordable, is not mentioned as being used in the reviewed studies. Furthermore, studies that use free databases do not indicate whether they also employed free software for their modelling process. Furthermore, while some studies explicitly state the software versions used, 14% of the studies do not provide this level of detail, which may introduce some level of uncertainty in the assessment of representativeness and comparability of the data across studies.

A majority (62%) of the studies specify their LCIA method, ensuring clarity and transparency in impact assessment. However, 38% of the studies do not specify their LCIA methods, which can lead to potential inconsistencies and challenges in comparing results across different studies. In the analysed literature, a notable 21% of the studies have employed the ReCiPe method for their impact assessment. This highlights its significant role and widespread acceptance in environmental impact studies. Additionally, other databases and methods have been utilised. For instance, the TRACI method is used in 10% of the studies, demonstrating its relevance in the field. Similarly, the CML method has been applied in another 21% of the research, indicating its importance within the domain. The GHG Protocol, known for its comprehensive approach to assessing carbon footprints, has been the method of choice in one study (Weththasinghe et al., 2022). Furthermore, a small fraction of studies, approximately 3%, have adopted less common methods such as the EPS 2000 Default Method, showing the diversity of approaches in LCIA. It is noteworthy that around 21% of the studies do not specify the method used for their environmental impact assessments. This lack of specification can hinder the reproducibility and credibility of the findings.

Furthermore, an important aspect of LCIA is conducting an uncertainty analysis, which can help understand the robustness of the results. However, less than half (45%) of the studies conduct an uncertainty analysis, indicating a significant area for improvement in future research. The absence of uncertainty analysis presents several disadvantages. Without it, the results may convey a false sense of precision, failing to account for the variability and potential errors inherent in the data and methodological assumptions. This oversight can undermine confidence in the findings and their applicability to real-world scenarios, potentially leading to misguided decisions and policies based on incomplete or misleading information.

Normalisation and weighting are optional steps in the LCIA phase. 14% of the studies conducted normalisation (Bengtsson and Logie, 2015; Khan et al., 2021; Korol et al., 2016; Lee and Xu, 2004), with half of these studies utilising the ReCiPe methodology. Additionally, 10% of the studies performed weighting, and 67% of them employed the ReCiPe methodology (Bengtsson and Logie, 2015; Korol et al., 2016). Normalisation involves calculating the magnitude of category indicator results relative to a reference information set, such as regional or global averages. This step helps in understanding the relative significance of the impacts by comparing them to a common baseline. However, normalisation has its disadvantages, including the potential for bias introduced by the choice of normalisation references, which can alter the conclusions drawn from the LCIA phase, and the lack of a holistic view, as it focuses on relative rather than absolute values. Weighting involves converting and possibly aggregating indicator results across impact categories using numerical factors based on value choices, aiming to simplify the interpretation of LCA results by providing a single score that reflects the overall environmental impact. However, weighting also has its drawbacks, such as the inherent subjectivity in the selection of weighting factors, which reflects value judgments that can influence the results and conclusions of the LCA, and the potential for aggregation issues, which can obscure the details of individual impact categories, leading to a loss of important information and a less holistic assessment of environmental impacts (ISO 2006b). Both normalisation and weighting are useful for simplifying and communicating LCA results, but they must be applied with caution to avoid misinterpretation and ensure robust decision-making.

In summary, the reviewed studies on pallet LCA exhibit several methodological flaws that impede the accuracy and reliability of their findings. Key issues include incomplete goal and scope descriptions, unclear FUs and system boundaries, poorly presented inventories, and a lack of specified impact assessment techniques and uncertainty analysis. These deficiencies challenge the reproducibility of the studies and introduce uncertainties. While some studies have made efforts to address these problems, such as adopting more comprehensive FU and using primary data, there remains a need for greater transparency and consistency in LCA methodologies. Enhancing data transparency, explicitly stating all methodological choices, and conducting uncertainty analysis are crucial steps for improving the robustness and credibility of pallet LCA studies. Future research could aim to standardise practices to facilitate comparability and foster more reliable sustainability assessments in the pallet industry.

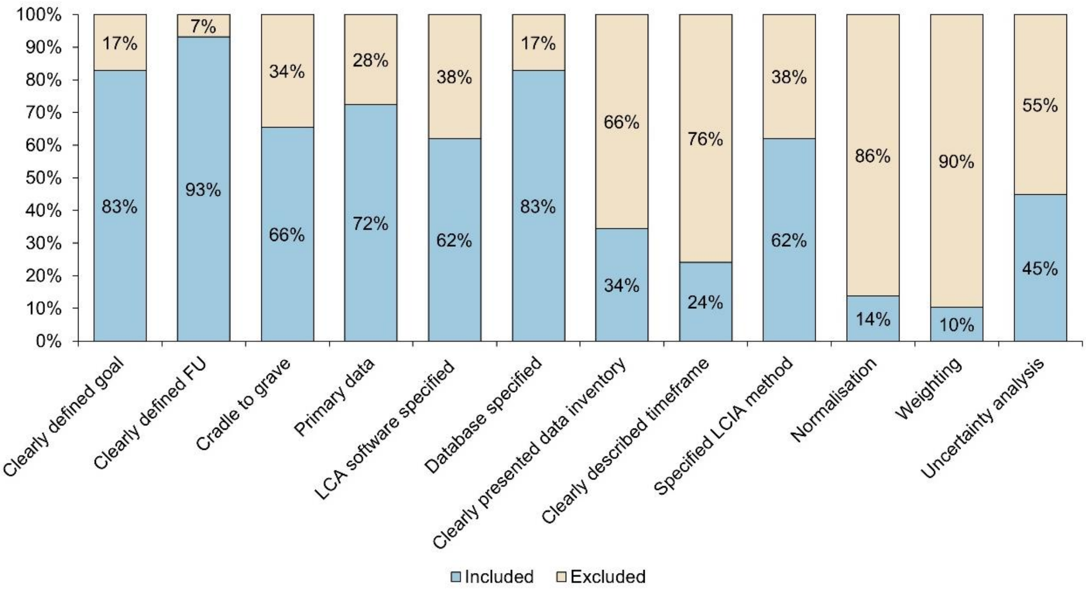


Fig. 9 Major methodological flaws found in the papers that were examined

Life cycle impact assessment. In addition, the analysis of LCAs in the pallet industry reveals a diverse consideration of environmental impact categories across the reviewed studies. While GWP is the most commonly analysed impact, reflecting a broader trend in LCA studies driven by global climate change mitigation targets (UNFCCC, 2015), a significant variation exists in the number of other impact categories considered. GWP is addressed in 86% of the reviewed articles, highlighting the emphasis on climate change potential. However, concentrating solely on GWP does not capture the full environmental performance of pallets and can lead to an incomplete understanding and potential burden shifting.

28% of the studies focus solely on GWP, and the remaining studies conduct partial assessments covering selected categories. Notably, most of the studies performing partial assessments do not provide a justification for their limited scope, which can impact the reliability and interpretation of the results. Approximately 59% of the studies perform assessments which cover a wide range of impact categories. These assessments offer a more holistic perspective on the environmental impacts of pallet systems. For example, AP is considered in 9 articles due to its importance in assessing environmental impacts such as acid rain and soil acidification. AP is a critical measure because acidification can lead to detrimental effects on soil quality, forest health, and aquatic ecosystems, ultimately impacting biodiversity and human health. EP is studied in 8 articles, highlighting the need to understand nutrient loading and its effects on aquatic systems. EP is particularly relevant for evaluating the impacts of nutrient runoff from agricultural and industrial activities, which can cause excessive growth of algae in water bodies. FD is addressed in 8 articles, which is crucial for assessing the depletion of non-renewable fossil resources. FD measures the availability of fossil fuels, which is essential for understanding the sustainability of energy and material use in pallet production and the broader implications for energy security and climate change mitigation. Other impact categories are also explored, including HT in 8 articles, and FPMF in 5 articles. HT considers the impacts of toxic substances on human health, including carcinogenic and non-carcinogenic effects, through different exposure pathways such as inhalation, ingestion, and dermal contact. FPMF focuses on the generation of fine particles during the life cycle of pallets, which is important for understanding the air pollution-related health impacts of pallet manufacturing and transportation processes.

Overall, considering these impact categories alongside GWP provides a more comprehensive and balanced evaluation of the environmental performance of pallet systems. Such holistic assessments can help identify trade-offs and synergies among different environmental impacts, guiding more sustainable practices in pallet production, use, and disposal.

2.4.11.3 Conclusions, research gaps, and recommendations for future research

The current body of literature on LCA pertaining to pallets primarily focuses on the carbon footprint of wooden pallets, particularly within the United States. However, this emphasis has resulted in a significant research gap regarding the environmental impacts of various pallet materials—wooden, plastic, steel, paper, and fly ash—within the context of China. Given the substantial market presence of these pallet types in China, it is imperative that future studies address this disparity to provide a comprehensive understanding of their environmental footprint.

The identified research gaps include the limited consideration of a broad spectrum of environmental impact categories beyond GWP. To achieve a holistic understanding of their environmental footprint, it is essential to incorporate a comprehensive set of impact categories, such as AP, EP, FD, HT, and FPMF, among others. Moreover, there is an urgent need to fill the data gap for LCA studies specific to Chinese pallets. This requires the collection and analysis of up-to-date, region-specific data that accurately reflects current practices in pallet production, usage patterns, and EoL scenarios within China. Such region-specific data is crucial for enhancing the relevance and applicability of research findings. Another direction is to adopt a cradle-to-grave approach, encompassing the entire lifecycle of pallets from raw material extraction to disposal or recycling. This approach is vital for identifying lifecycle stages with the highest environmental burdens and assessing potential burden shifts. The use of a clearly defined FU is another critical aspect for future research. The FU should encapsulate the pallet's functional performance, including load-bearing capacity and service life, to ensure accurate assessment of its environmental impacts based on actual utility. In addition, the variability in system boundaries and FUs across the reviewed studies poses a significant challenge to directly comparing their findings. Therefore, achieving comparability of environmental impact results across different types of pallets necessitates the adoption of consistent system boundaries and FUs. Consistency in system boundaries ensures that all relevant stages of a pallet's lifecycle, from raw material extraction to disposal or recycling, are uniformly included in the assessment. Similarly, using a consistent FU is essential for accurately quantifying and comparing the environmental performance of pallets based on their intended use and service life. Besides, to enhance the robustness and credibility of future LCA studies, it is crucial to clearly state methodological choices, including the specific LCA software and databases employed, and to conduct uncertainty analysis. This transparency is essential for ensuring result reproducibility and facilitating more reliable sustainability assessments in the pallet industry.

In conclusion, addressing these research gaps and adhering to these recommendations will contribute to a more comprehensive understanding of the environmental impacts associated with pallets. This knowledge is crucial for guiding sustainable practices in pallet design, production, use, and EoL management, thereby supporting the transition toward a more environmentally conscious supply chain.

2.5 Circular economy

CE is a step-stone towards sustainability (Kravchenko et al., 2019), and aims to enable the economic system to thrive in the long run (BSI, 2017). Sustainability which is defined as not compromising the life of future generations, has attracted more attention. Since the formation of the United Nations Global Compact (2000), sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Keeble, 1988). Various policies have been established to address environment burden caused by human consumption. The UN has set SDG12 to encourage sustainable consumption and production in 2015. Particularly, SDG12 aims to increase the sustainability and efficiency of natural resource consumption by 2030. CE can reduce the stress on the natural environment through more circular use of materials, whilst enabling the economic system to thrive in the long run (BSI, 2017).

The Circularity Gap Report states that in 2019, the world economy used more than 100 billion tonnes of materials (Circle Economy, 2022). This linear model of production and consumption has severe consequences for the planet and its resources. To address this challenge, CE has been proposed as an alternative system that can reduce waste, emissions, and resource use while enhancing economic growth and social well-being. In addition, CE is regarded as one of the responses which can alleviate the burden on the natural environment, whilst enabling the economic system to thrive in the long run (BSI, 2017). For instance, adopting CE practices could raise EU GDP by 3.9% by 2030 (Domenech and Bahn-Walkowiak, 2019). Similarly, CE targets can help achieve SDGs and foster more equitable societies (Morseletto, 2020). It is often known that CE stimulates economic growth by generating new ventures and employment possibilities.

2.5.1 The development of CE definition

The concept of CE has a rich history spanning several decades, originating from early discussions on industrial ecology and resource efficiency in the mid-20th century (Ekins et al., 2020). Scholars like Boulding in his seminal 1966 paper laid the philosophical and practical groundwork for understanding the CE, emphasising the importance of closed-loop systems and sustainable resource management (Boulding, 1966). Building on this foundation, pioneers such as Stahel and Reday-Mulvey in the early 1980s explored practical strategies for extending product lifecycles and promoting recycling as a means to minimise waste and resource depletion (Stahel, 1982; Stahel and Reday-Mulvey, 1981).

Pearce and Turner's influential 1990 textbook provided a comprehensive framework for conceptualising the circular relationship between the economy and the environment, emphasising the importance of considering both exhaustible and renewable resources within the context of sustainability (Pearce and Turner, 1990). Despite these early contributions, widespread recognition and adoption of the CE concept did not occur until the EMF landmark publications in 2013, which helped propel the idea into mainstream business and policy discussions. Since then, the concept has continued to evolve, with ongoing contributions from academia, industry, and policymakers shaping its understanding and implementation across various sectors (EMF, 2013). Today, CE represents a holistic approach to sustainable resource management, aiming to minimise waste, promote resource efficiency, and foster economic growth while preserving environmental integrity for future generations.

CE was initially defined as extending the product service life, but later it became a general term that encompasses 3R strategies. Stahel and Reday (1976) proposed a loop economy and show how extending the product-life can save energy and generate jobs by using manpower instead (Clift and Druckman, 2015). Stahel (1982) highlighted a self-sustaining system with spiral-loops that reduced the material and energy flows to maximise the overall product lifespan, which involve reusing, repairing, reconditioning/rebuilding, and recycling of goods and materials. Stahel and Clift claimed that the CE is a subset of performance economy (Clift and Druckman, 2015; Stahel, 2010), and further argued that CE emphasises the circularity of material flows, while the performance economy prioritises the quality and value of in-use stock. Cooper (1999) expands the content of CE and suggests that CE is a generic term which covers all activities, including reducing, reusing, and recycling. Meanwhile, the importance of sustainable development has been recognised in the definition of CE (Cooper, 1999; Shen, 2007; WCED 1987, p. 43; Wu, 2005).

3R CE strategies have been improved to 4R strategies by including

recovery. McDonough and Braungart (2010), Nakajima (2000) and Pitt (2011) shift the focus of CE to restoration of the environment approach which can be waste-free. UNEP (2006) adds new factor, redesign, in CE's definition to call for designing out waste. Thus, the definition of CE is comprised of redesign and restoration. Geng and Doberstein (2008) and Mentink (2014) define CE as the realisation of closed material loops in the entire economic system. Yuan et al. (2006) propose 3Rs, i.e., reduce, reuse and recycle, as the key strategies of CE's definition (Korhonen et al., 2018). Hu et al. (2011) emphasise that resource productivity and eco-efficiency improvements are vital to CE, and 4Rs (reduce, reuse, recycle and recover) is the way to achieve CE.

Economic benefits have been incorporated into the CE definition to complement the environmental benefits. Recently, many organisations have tried to explicitly define CE. Among these definitions, the EMF's definition is widely accepted, since both the economic and environmental benefits are included based on regeneration (EMF 2013, p. 7; Lieder and Rashid, 2016). CE is viewed as a model to achieve the decoupling of the economic development from the depletion of resource (EMF, 2013; Lieder and Rashid, 2016; Liu et al., 2009; Xue et al., 2010). EMF compares CE with the linear economy model, also known as "cowboy economy" (Boulding and Jarrett, 1966) which refers to the industrial process that turns natural resources into waste (Lieder and Rashid, 2016). The linear economy damages the natural environment in two ways, including directly reducing natural capital through unsustainable harvesting and mining, and reducing the value through pollution emitted by waste generated through the whole product life cycle (Murray et al., 2017). In contrast, CE promotes renewable energy consumption (EMF, 2013), and proposes restoration and regeneration as a substitute for the EoL concept (Nguyen et al., 2014).

Social welfare has been added to the CE definition to balance the environmental and economic benefits. The Institut de l'économie circulaire and the Netherlands have directly adopted EMF' s definition in 2013 (Institut de l'économie circulaire, 2013; Government of the Netherlands, 2014). Moreover, several organisations have introduced modified CE definition. CE is viewed as an economic system which focuses on increasing the resource use efficiency, reducing the negative effects on the environment while increasing the human welfare (Bonet et al., 2014; Geldron, 2013). This definition points out the function of CE, which means that CE is a bridge between sustainable development and ecological transition. However, this definition lacks consideration of many important aspects, such as restorative, design and loops aspects, systemic etc. Therefore, in 2014, the EDDEC Institute adds new factors, such as eco-design and industrial ecology into CE's definition (EDDEC, 2014), which is agreed by ICCE (ICCE, 2015) and ACCENTURE (2014). The IPAG Business School defines CE from a novel perspective, and is the only organisation who considers social aspect. IPAG views CE as a new management style which promotes the local economic development and increase the employment while reducing the impacts on the eco-system (Bonet et al., 2014). ACCENTURE (2014) narrows the range of CE's definition and focuses on companies' circularity. It suggests that all the cycles alongside the value chain should become circular and attain the CE business model. In 2015, CIGAIG concludes that the CE concept is in line with umbrella concept, which is first introduced by Hirsch and Levin (1999) (CIGAIG, 2015). The umbrella concept is a general term or notion that is applied haphazardly to include and explain a variety of distinct events (Hirsch and Levin, 1999). CIGAIG considers CE as a new discipline, which has blurred boundaries, various conceptual sources and has both broad and narrow aspects, leading to no commonly accepted definition for CE. Therefore, CIGAIG suggests using umbrella concept to describe CE. CIGAIG defines CE from two dimensions, including the environmental dimension, and the economic dimension which is business vision. However, this definition omits the social dimension of sustainability. Murray et al. (2017) add social dimension on the basis of the conceptual umbrella. Sustainability includes three aspects: economic, environment and social aspects. However, CE ignores social dimension, focusing on improving the redesign of production and recovering the environment (Murray et al., 2017; Schröder et al., 2020). It is still unknown how CE can promote inter-generational equity and social justice. Lacking social dimension will lead to some unintended consequences, such as unethical behaviours (Murray et al., 2017). Also, estimating the negative effects on the environment caused by CE approach is of vital importance. For example, the green fuel movement has led to deforestation of Borneo, damaging the habitats for many species (Bonet et al., 2014). Another contribution that they make is to extend the use of CE in sustainable business (Murray et al., 2017). Blomsma and Brennan (2017) add two new aspects, "catalytic function and the predictable developmental trajectory" in CE's definition to enable CE to better fit in the umbrella concept. They also point out the importance of social aspect in CE's definition.

3R CE strategies have now being upgrading to 10R strategies. CE has garnered significant interest from both scholars and professionals (Blomsma and Brennan, 2017; Geng and Doberstein, 2008; Liu et al., 2009). The traditional 3R strategies framework, reduce, reuse and recycle, has been further expanded to 10R strategies (Kirchherr et al., 2017; Pan et al., 2022; Superti et al., 2021; Wen et al., 2023). Specifically, the reduce path is further upgraded into rethink, reduce and refuse. The reuse path is further expanded into repurpose, remanufacture, reuse, refurbish and repair. Recycle and recovery are further extensions of the recycling path.

The Chinese government is pursuing CE strategies to promote the green transformation of industries. In order to facilitate and encourage the implementation of CE, the Chinese central government has made it a national regulatory policy priority and implemented a number of regulations. The first regulatory action was the "Cleaner Production Promotion Law" that came into effect in 2003 (Ministry of Commerce People's Republic of China, 2007). The National Development and Reform Commission held the first national CE work conference in 2004. This was followed by the amended Law on Pollution

Prevention and Control of Solid Waste that became effective in 2005. In the same year, the State Council issued "Several Opinions on Accelerating the Development of Circular Economy". In 2006, China officially incorporated CE into the “Eleventh Five-Year Plan”. China was also the first to enact a specific law on CE in 2008 (Moraga et al., 2019), which was fully implemented in 2009 (CIRAIG, 2015; Zhao, 2020). The “Circular Economy Promotion Law” legally confirms that the advancement of CE is a useful strategy for China’s economic and social progress. CE refers to the reduction, reuse and resources utilisation during the production and consumption process in the "Circular Economy Promotion Law”. This law promotes sustainable development, preserves the environment, improves resource use efficiency, and fosters the adoption of the CE (Geng et al., 2012). One of the objectives for creating a moderately wealthy society by 2020 was identified by the 18th National Congress of the Communist Party of China in 2012. This included the initial establishment of a system for recycling resources. In the 12th Five-Year Plan for National Economic and Social Development, China has expressed its commitment to vigorously promote CE. In the opinions of the Central Committee of the CPC and the State Council on Accelerating the Promotion of Ecological Progress, efficient recycling of resources and strict protection of eco-environment form the basis of sustainable development of the society. The State Council issued the "Circular Economy Development Strategy and Immediate Action Plan" in 2013. The 19th National Congress of the Communist Party of China made a proposal to advance green development and promote comprehensive resource conservation and recycling in 2017. The State Council issued the "Guiding Opinions on Accelerating the Establishment of a Green and Low-Carbon Circular Development Economic System", and the National Development and Reform Commission issued the "14th Five-Year Plan for Circular Economy Development" in 2021. There, the Chinese government has placed great emphasis on the promotion of CE in various industries in China.

2.5.2 Current studies of environmental impacts of CE strategies on pallet industry

CE can operate in three scales: small, medium and large scales (Geng et al., 2012). The small-scale circular mode refers to the internal cycle of the enterprise, which requires corporations to minimise the material and energy use of products and services, decrease the emission of pollutants, strengthen the ability to recycle materials; maximise the sustainable utilisation of renewable resources, enhance product durability and raise the service intensity of products and services under the concept of eco-efficiency introduced by WBCSD (1992). The material circulation that connects various factories or departments to create an industrial symbiosis of resource sharing and by-product exchange is referred to as the medium-scale circular mode. The social embodiment of CE is the large-scale circular mode. It describes the process of creating a circular society by recycling resources throughout all economic and social domains (Zhao et al 2019). Therefore, the 10R CE strategies can be applied at different scales, both for pallet products and for the pallet industry.

The 10R CE framework consists of 10 strategies: recycle, reuse, recover, reduce, repair, repurpose, remanufacture, refuse, rethink and refurbish. These principles can help the pallet industry to extend its life cycle, close the material loops, and reduce the waste and emissions. For example, repairing damaged pallets can extend their service life and prevent them from being discarded. Recycling or recovering the materials from waste pallets can potentially save resource and energy input. By applying the 10R framework, the pallet industry can achieve a more circular and sustainable system that benefits both the economy and the environment. However, each type of pallet requires different CE strategies to reduce the environmental burdens and resource consumption accordingly, since they have different characteristics, such as material composition and waste management method, etc. Therefore, identifying the specific CE strategies that are suitable for each type of pallet, and evaluating the potential of these measures on mitigating the negative impacts is crucial to achieving the green transformation of the pallet industry.

2.5.2.1 Results and discussion

2.5.2.1.1 CE strategy and pallet material

The literature on the environmental impact reduction potential of CE strategies on pallets is fragmented. Based on the literature review results from Section 2.4.11, 20 articles focusing on the environmental impacts of CE strategies on pallets were identified (Table A. 3 in Appendices). The majority of the studies focus on CE strategies for wooden pallets, comprising 16 articles (80%). This is followed by plastic pallets, with 9 articles (45%) (Fig. 10). This distribution is consistent with the findings from the pallet LCA literature review. The distribution of the literature reflects the market share of pallet types, with wooden pallets being the most prevalent, followed by plastic pallets.

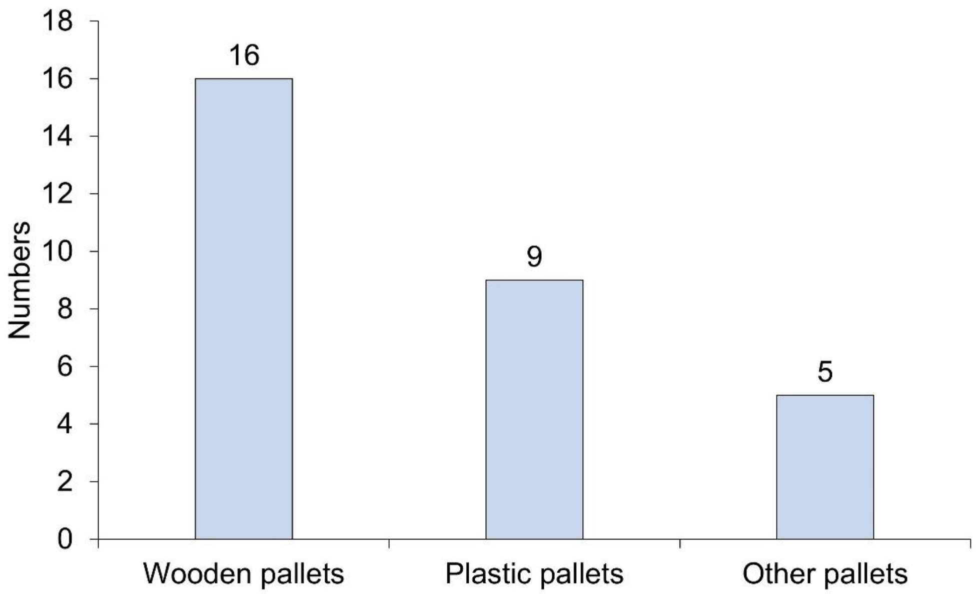


Fig. 10 Pallet material types identified in the reviewed pallet CE literature

The primary CE strategies investigated in the studies are recycling, reuse, rethink, repair, and remanufacturing. 6 studies focus on recycling strategy (e.g., Ng et al., 2014), analysing the environmental impacts of producing pallets from recycled materials as opposed to virgin materials, and highlighting potential reductions in carbon emissions and resource use. 5 studies concentrate on reuse strategy (Fig. 11), driven by the establishment of pallet sharing systems in markets such as the United States and Australia, which facilitate the reuse of pallets. In China, governmental regulations, such as the 14th Five-Year Plan for Logistics (General Office of the State Council of China, 2022), aim to advance the development of a pallet sharing system to enhance CE development, primarily emphasising pallet reuse. Rethink strategy is explored in studies such as Korol et al. (2020), investigating the environmental impacts of using new materials for pallet production and assessing how these materials can improve environmental performance from a cradle-to-gate perspective. Repair strategy, discussed in studies such as Park et al. (2018), involves the maintenance and repair of wooden pallets due to their detachable structure, which allows for the replacement and repair of damaged components. This can significantly extend their lifespan and reduce the need for new pallet production, thereby lowering overall environmental impacts. Remanufacturing strategy, explored in studies such as Alanya-Rosenbaum et al. (2022), evaluates the potential environmental benefits of using waste pallets as input materials for remanufacturing new pallets. Remanufacturing can substantially reduce environmental impacts by minimising the need for virgin materials and decreasing waste.

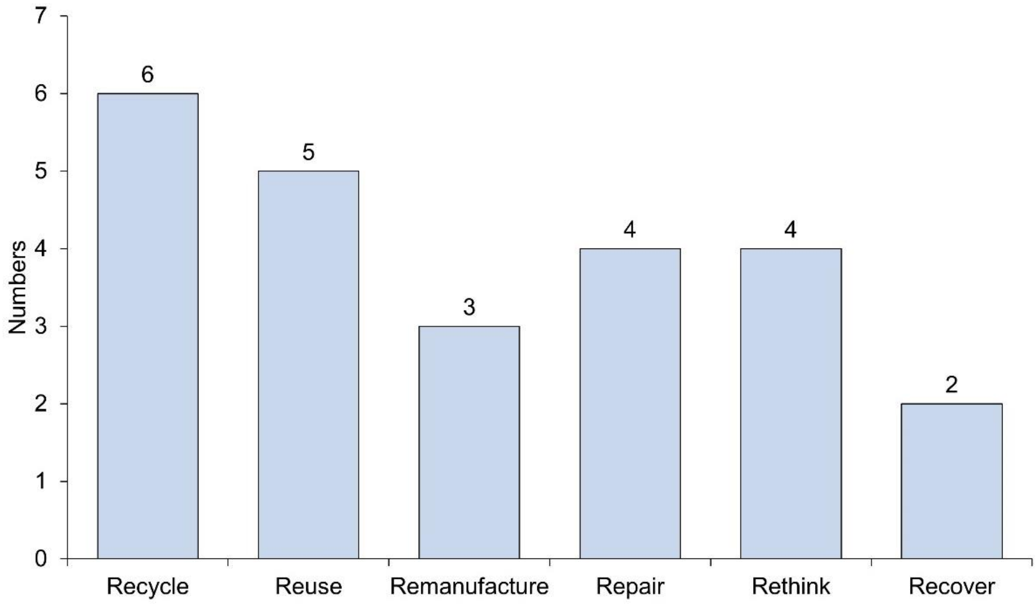


Fig. 11 Specific CE strategies of pallets identified in the reviewed literature

Recycle. Ng et al. (2014) focused on the carbon emissions of the production stage for wooden pallets. Their study found that pallets made from technical wood had lower carbon emissions compared to those made from virgin wood. However, this study was limited to Singapore. Khan et al. (2021) expanded the scope by including various sources of waste materials. They compared composite pallets made from plastic waste and wood with virgin wooden pallets and plastic pallets. Their findings indicated that wood-polymer composite pallets could be a preferable option over plastic pallets and, in most cases, over wooden pallets. However, this study was limited to Finland. Kočí (2019) compared the environmental impacts of pallets made from recycled plastic granulates with those made from new plastic materials. The study concluded that pallets made from secondary plastics showed lower resource consumption compared to those made from primary plastics. Specifically, secondary plastic pallets exhibited lower impacts in most categories such as GWP and FPMF. The environmental impacts lie in the processes involved in converting waste materials into secondary plastic materials. However, it did not provide LCI data or present data age, which limits the reproducibility and reliability of the results.

Reuse. Carrano et al. (2015) analysed the reuse strategy by comparing different pallet management modes to determine the carbon reduction potential, based on frameworks developed by Bilbao et al. (2011) and Bilbao et al. (2010). However, Carrano et al. (2015) did not collect actual data on the EoL flows of pallets to reflect the real situation in the US. Additionally, the data collection period was unclear, making it uncertain if the data age was consistent and reasonable. Bengtsson and Logie (2015) compared the environmental impacts of different types of pallets used in one-way and pooled (reusable) pallet systems. They found that pooled softwood pallets had a lower environmental impact compared to one-way pallet alternatives in many typical applications, due to reduced material needs and the ability to reuse the pallet multiple times before servicing. Pooled plastic pallets, however, had a higher environmental impact than pooled wooden pallets, primarily due to the energy required for their production. The study favoured the use of pooled softwood pallets for their environmental benefits and suggested that one-way pallets needed significant reuse to compete environmentally. However, the study provided data on wood and plastic pallets manufactured in China but lacked data on paper pallets and had an incomplete LCI, preventing comprehensive calculations. Additionally, the EoL scenarios were assumed, and the data collection period was not specified, making the data age uncertain. Gasol et al. (2008) developed an LCI analysis to compare the environmental impacts of wooden pallets with low and high usage rates. This research included more environmental impact categories, such as AP and HT. However, the study did not perform an uncertainty analysis for input parameters, and the final disposal of pallets was assumed to be recycling (85%), incineration (9%), and landfill (6%) based on stakeholder statements, without presenting the data collection process to ensure reliability. Buehlmann et al. (2009) surveyed 103 known pallet recycling operations in North Carolina between 2003 and 2004, receiving 34 responses. They investigated the EoL destination of wooden pallets in the US, and subsequent studies on wood pallet EoL data have largely been based on this article (Anil, 2010; Anil et al., 2020).

Remanufacture. Previous research has evaluated the potential of remanufacturing strategy to reduce the environmental impact of wooden pallets (Alanya-Rosenbaum et al., 2022; Tornese et al., 2016). Tornese et al. (2016) assessed the carbon footprint of remanufacturing wooden pallets using a FU of one piece of wooden pallet. However, their analysis was limited to carbon footprint and used a gate-to-gate system boundary, which means that the influence of the remanufacturing strategy on the entire lifecycle of pallets was not explored. The same limitation exists in the study by Alanya - Rosenbaum et al. (2022). Although they used the same FU as Tornese et al. (2016), they included additional environmental impact categories such as AP, EP, OD and

PS and OD. Tornese et al. (2019) found that preemptive remanufacturing plans can reduce remanufacturing emissions in all scenarios, with an average reduction of 39.18% for stringer pallets and 29.02% for block pallets. Ng et al. (2014) demonstrated that the carbon emissions of technical wood pallets (3.547 kg CO_2 eq.) are lower than those of virgin softwood pallets (4.009 kg CO_2 eq.). However, the time frame of their data is unclear, and the EoL stage was not based on actual collected data. Furthermore, Ng et al. did not specify how the EoL was assumed in their study. Additionally, research by Khan et al. (2021) found that using secondary plastics to manufacture pallets results in lower environmental impacts compared to pallets made from virgin plastics.

Repair. The existing research has evaluated the potential of repair strategy to reduce the environmental impact of wooden pallets (Clarke et al., 2005; Park et al., 2018), based on the limited LCI data (Park et al., 2018). Araman and Bush (2015) reported that repairing used pallets for reuse is the most common strategy adopted by pallet recyclers. This approach can lower costs by selling repaired pallets at reduced prices and avoiding landfill fees (Buehlmann et al., 2009). Moreover, repaired pallets can retain satisfactory physical performance comparable to new pallets (Clarke et al., 2005). Repairing pallets also helps comply with recycling regulations, such as the North Carolina House Bill 1465 enacted in 2005, which prohibits the disposal of wooden pallets in landfills within North Carolina (Park et al., 2016). Park et al. (2018) calculated the carbon footprint of pallet repair based on gate-to-gate LCI data for the repair process, following the methodology developed by Park et al. (2016). However, their study only accounted for the carbon footprints of the repair stage, without considering the reduction of carbon footprints over the entire lifecycle of wooden pallets due to repair. Additionally, their study focused on the US, and the input and output data cannot reflect the situation in China. Carrano et al. (2014) considered both the carbon emissions of repair and the reduction of carbon emissions over the entire lifecycle of wooden pallets. However, their study had three limitations: (1) they did not provide or cite specific LCI information, which affects the reliability and comparability of their data; (2) they only used US data, which may not be representative of other regions; and (3) they only assessed carbon emissions, neglecting other impact categories necessary for a comprehensive evaluation of environmental effects, as these may reveal different or conflicting results (Gasol et al., 2008). Considering other environmental impacts can reveal trade-offs and synergies between different environmental aspects of the product. It can also help identify the significant environmental hotspots and improvement opportunities across the product's life cycle stages, such as production, use, and EoL. The study by Alanya-Rosenbaum et al. (2021) assessed additional environmental impacts of wooden pallets in the US and identified pallet repair as a critical component of the wooden pallet supply chain with a low environmental footprint, enabling mitigation of the overall impact by extending the service life. The study suggests that future improvements in the environmental performance of the wooden pallet industry can be achieved by focusing on increasing the number of repairs and optimising load-carrying capacity. However, this study provides gate-to-gate industry-average LCI data collected from US repair/remanufacturing facilities in 2018, with a lack of data for pallets in China. Similarly, Gasol et al. (2008) provided LCI data for the wooden pallet repair process, but their study was geographically restricted to Spain and only covered wooden pallets.

Rethink. 4 articles explore the environmental impact of rethinking strategy for pallet production. Kim et al. (2023) examined the environmental impact of optimising a unit load by decreasing the board grade of the pallets' corrugated boxes and stiffening the top deck boards of the pallets. This research aimed to enhance the structural performance of wooden pallets to improve their sustainability. The other 3 articles focus on developing new materials for manufacturing plastic pallets. For instance, Korol et al. (2016) examined the potential of producing plastic pallets from biocomposites and composites based on PP, GF, and natural fibers, such as CF, JF, and KF. The use of these alternative materials aims to reduce the environmental footprint of plastic pallets by leveraging renewable and less energy-intensive resources compared to traditional virgin plastics. These studies highlight the importance of material innovation and structural optimisation in reducing the environmental impacts of pallets. By improving the design and material composition of pallets, these rethink strategies offer promising pathways to enhance the sustainability of pallet production and usage.

Recover. Four primary EoL scenarios for pallets have been identified and incineration with energy recovery can have negative environmental impacts, as highlighted by Carrano et al. (2014). Besides, practices such as using pallets as fuel or for recycling can offer substantial environmental benefits, including significant reductions in GHG emissions (Alanya-Rosenbaum et al., 2021).

In conclusion, the majority of existing research focuses on evaluating the environmental impacts of individual CE strategy, particularly in terms of carbon emissions. Notably, 35% of these studies do not adopt a full life cycle perspective, which limits their ability to provide a comprehensive assessment of environmental impacts. Additionally, the existing literature often overlooks the potential benefits of combining comprehensive CE strategies and is largely focused on contexts outside of China. Previous studies have investigated various CE strategies for different types of pallets, including wood, plastic, and composite materials. However, there is a notable gap in the literature regarding the comprehensive assessment of combined CE strategies and their applicability to wood, plastic, paper, steel, and fly ash pallets across their full life cycle in the Chinese pallet industry. This will hinder the identification of sustainable pathways for the green transition of China's pallet industry, and a holistic understanding of how various CE strategies can be integrated to enhance environmental performance.

2.5.2.1.2 The LCA process

This section points out significant methodological shortcomings in the reviewed studies and discusses key findings unique to pallet CE LCA research. Fig. 12 summarises the methodological issues identified across the four stages of LCA as follows: i) incomplete or missing goal and scope definitions; ii) incomplete system boundaries; iii) inadequately presented inventories; and iv) failure to state impact assessment methods and omission of uncertainty analysis. These flaws hinder the reproducibility of LCA results and introduce uncertainty.

Incomplete or missing goal and scope definitions. Incomplete and missing goal and scope descriptions are evident in some of the reviewed studies. Approximately 20% of these studies lack a clearly defined goal and scope for the LCA (see Table A. 3 in the Appendices), relying instead on broad aims or objectives to communicate their purpose (e.g., Tornese et al., 2016). Others require summarisation to extract and clarify their goals and scopes (e.g., Kočí, 2019). The absence of a clear and precise goal and scope definition hinders the identification of the target audience and impedes the effective application of the LCA results for subsequent monitoring and evaluation against baseline conditions. Based on the evaluation of the reviewed studies, their goals can be categorised as follows:

- To assess the carbon footprint of a specific CE strategy for a particular type of pallet from gate-to-gate perspective (e.g., Tornese et al., 2016);
- To quantify the environmental impacts of a specific CE strategy for a particular type of pallet from gate-to-gate perspective (e.g., Alanya-Rosenbaum et al., 2022);
- To assess the environmental impact of pallets, focusing on repair and EoL CE strategies for wooden pallets (e.g., Alanya-Rosenbaum et al., 2021).

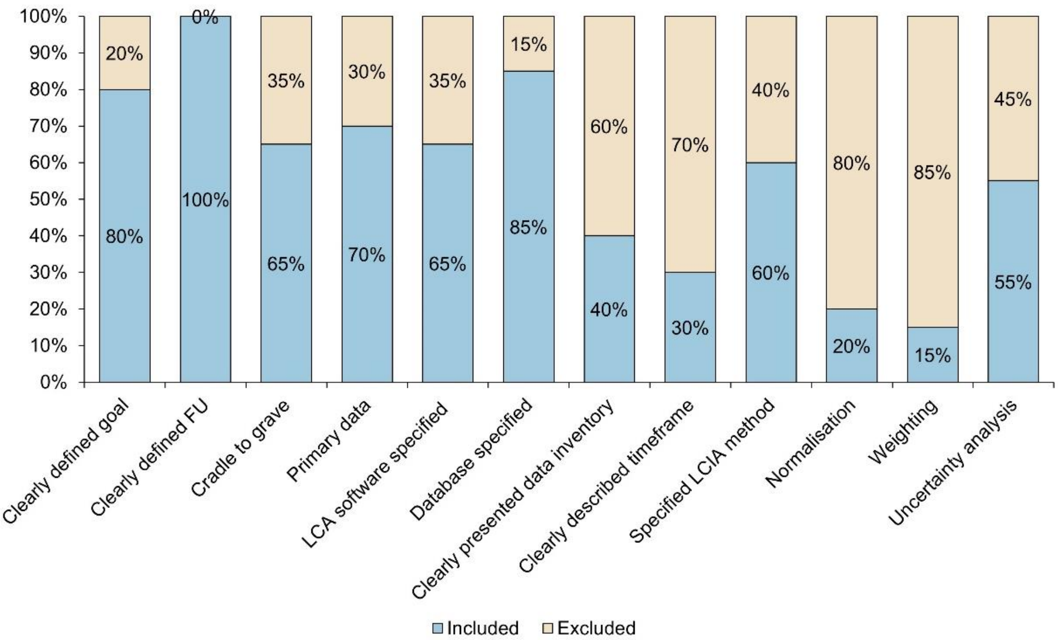


Fig. 12 Major methodological flaws found in the pallet CE LCA papers that were examined

Incomplete system boundaries. Approximately 65% (13 out of 20) of the studies have addressed the full life cycle of pallets, from cradle to grave. However, many of these studies focus solely on calculating the environmental impact of a specific CE strategy at a particular stage, without accounting for the overall reduction in environmental impact achieved through the implementation of these strategies. This approach limits the comprehensive understanding of the benefits provided by CE strategies, as it does not consider the broader context of environmental impacts across the entire life cycle.

Inadequately presented inventories. 70% of studies utilise primary data. However, only around 40% (8 out of 20) of the studies have clearly presented their data inventory. Approximately 30% (6 out of 20) of the studies have clearly described the age of the data. This lack of transparency can hinder the reproducibility and reliability of the studies, as well as the ability to critically assess the quality and relevance of the data used. Clear and comprehensive data inventories are crucial for ensuring the robustness and credibility of research findings.

Failure to state impact assessment methods and omission of uncertainty analysis. A significant portion lacks the critical information, with

35% not specifying the software and 15% not specifying the databases, which can adversely affect the reproducibility and transparency of their findings. The Ecoinvent database is prominently used as a primary source of background data in 65% of the studies, exclusively featured in nearly 7 studies, and combined with other databases such as the U.S. Life Cycle Inventory in 2 studies. Notably, 5% of the studies do not specify any databases used. Regarding LCA software, SimaPro is the most frequently adopted, with 50% of the studies employing it for their analysis. GaBi is used in 15% of the studies. Additionally, about 20% of the studies perform their LCA calculations manually using equations, which typically limits the assessment to a smaller number of impact categories. 15% of the studies do not specify the software used. Furthermore, while some studies explicitly state the software versions used, 23% do not provide this detail, potentially introducing uncertainty in the representativeness and comparability of the data across studies.

In the examined studies, 60% (12 out of 20) have specified the LCIA method used, while 40% have not, potentially leading to inconsistencies and challenges in comparing results across different studies. Among the methods detailed, the ReCiPe method is employed in 20% of the studies, showing its significant role and widespread acceptance in environmental impact assessments. Additionally, the TRACI method is utilised in 15% of the studies and the CML method is applied in 10% of the research, indicating their importance in the field. The GHG Protocol, noted for its comprehensive approach to assessing carbon footprints, is used in one study (Weththasinghe et al., 2022). Furthermore, a small fraction of studies, around 5%, have adopted alternative methods such as the EPS 2000 Default Method (Lee and Xu, 2004), showing the diversity of approaches in LCIA. Notably, approximately 25% of the studies do not specify the method used for their environmental impact assessments, which can hinder the reproducibility and credibility of their findings.

An essential aspect of LCIA is conducting an uncertainty analysis to gauge the robustness and reliability of the results. About 55% (11 out of 20) of the studies include an uncertainty analysis. The absence of such analysis presents significant drawbacks. Without it, results may give a false sense of precision, failing to account for the variability and potential errors inherent in the data and methodological assumptions. This oversight can undermine confidence in the findings and their applicability to real-world scenarios, potentially leading to misguided decisions and policies based on incomplete or misleading information.

Normalisation and weighting are optional steps in the LCIA phase. According to the literature review, 20% of the studies conducted normalisation, with half of these studies employing the ReCiPe methodology. Additionally, 15% of the studies performed weighting, with 67% of them using the ReCiPe methodology (Bengtsson and Logie, 2015; Korol et al., 2016). Normalisation and weighting are valuable for simplifying and conveying LCA results, but they must be used carefully to prevent misunderstandings and guarantee sound decision-making. Normalisation has disadvantages, including potential bias from the choice of normalisation references, which can influence the conclusions drawn from the LCIA phase, and a lack of a holistic view since it focuses on relative rather than absolute values. Weighting also has drawbacks, such as inherent subjectivity in selecting weighting factors, which reflect value judgments that can influence the results and conclusions of the LCA, and potential aggregation issues, which can obscure details of individual impact categories, leading to a loss of important information and a less holistic assessment of environmental impacts (ISO 2006b).

Life cycle impact assessment. The analysis of LCA within the pallet industry reveals a diverse approach to environmental impact categories across the reviewed studies. While GWP is the most frequently analysed impact, reflecting a broader trend in LCA studies driven by global climate change mitigation targets (UNFCCC, 2015), there is significant variation in the number of other impact categories studied. GWP is addressed in 90% of the reviewed articles, underscoring the focus on climate change potential. However, a sole concentration on GWP fails to capture the full spectrum of environmental performance for pallets, leading to an incomplete understanding and potential burden shifting. Specifically, 35% of the studies focus exclusively on GWP, approximately 55% of the studies conduct assessments that encompass a wide range of impact categories, offering a more holistic perspective on the environmental impacts of pallet systems. These comprehensive assessments include impact categories such as AP, EP, FD, and HT. By addressing a broader array of environmental impacts, these studies provide a more complete understanding of the ecological footprint of pallet systems, which is crucial for making informed decisions and developing sustainable practices within the industry. The diverse approaches in assessing environmental impacts highlight the need for more transparent reporting practices. Ensuring comprehensive coverage of various impact categories and providing clear justifications for the chosen scope of assessment are essential for enhancing the credibility and comparability of LCA studies in the pallet industry. This, in turn, will support more robust decision-making and contribute to the development of strategies that effectively mitigate a wide range of environmental impacts.

2.5.2.1.3 Conclusions, research gaps, and recommendations for future research

In summary, the current literature on the environmental impacts of CE strategies for pallets is limited and primarily focuses on a single strategy such as repairing, remanufacturing, reuse, and recycling, predominantly for wooden pallets, without identifying corresponding strategies for each pallet type, leading to the gap regarding comprehensive assessment of combined CE strategies and their applicability to wood, plastic, paper, steel, and fly ash pallets across their full life cycle in the Chinese pallet industry. This narrow focus neglects other types of pallets and comprehensive CE strategies for the green transformation of the entire pallet industry. Additionally, existing studies tend to concentrate solely on the products themselves, without considering the broader industry structure or other critical aspects of the pallet industry as a whole. There is also a noticeable lack of LCI data and analysis concerning the pallet market in China. Given China's unique situation in terms of pallet types, market structure, and environmental regulations, this is a significant oversight. Furthermore, a substantial portion of the studies focus exclusively on GWP, neglecting other important environmental impact categories such as AP, EP, FD, and HT. Therefore, there is a need for a comprehensive and holistic study of CE for pallets in China that covers multiple types of pallets and CE strategies, and considers the entire pallet supply chain based on the primary data collected in China.

To address these gaps, future research could consider expanding the scope of research to include comprehensive combined CE strategies that consider various types of pallets beyond wooden ones. This should include plastic, paper, steel, and fly ash pallets to provide a more inclusive understanding of the industry. Conducting studies that consider the entire pallet supply chain, including production, distribution, usage, and EoL management, is essential. Detailed primary data collection specific to the Chinese pallet market should be undertaken, encompassing diverse pallet types, market structures to reflect the unique context of the region. Additionally, expanding the environmental impact assessment to include a wide range of impact categories is crucial. Future studies should not only focus on GWP but also include AP, EP, FD, HT, and other relevant impact categories to provide a more comprehensive evaluation of environmental performance. Improving transparency in data collection and reporting methodologies will enhance the comparability and reliability of LCA studies. By addressing these gaps and following the recommended approaches, future research can contribute significantly to the development of sustainable and efficient CE strategies for the pallet industry, particularly in nations, such as China that are currently underrepresented in the literature. This will support the green transformation of the pallet industry and promote broader environmental sustainability.

Chapter 3 Methodology

MFA depicts the pathways of pallet streams, identifying the hotspots for waste prevention and reduction. However, MFA fails to evaluate pallets in view of the environmental impacts (Allesch and Brunner, 2015). LCA allows evaluating the environmental effects under the current practice and under the CE principles, 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 LCI for LCA (Brunner and Rechberger, 2016). Therefore, integrating MFA and LCA can provide a more comprehensive view of 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).

3.1 Research questions

(1) The production and consumption scale of pallets in China continues to grow. Where do the pallets entering the Chinese socio-economic system come from? And where do they go? How to establish a systematic method to quantitatively track the sources, sinks and pathways of pallets?

(2) The whole life cycle of pallets will cause environmental impacts. What are the hotspots that cause environmental effects? How to identify and evaluate the environmental impacts of different types of pallets in the whole life cycle?

(3) How to establish a framework to facilitate the green transformation of the pallet industry?

3.2 Material flow analysis

3.2.1 System boundary and model structure

The system boundary is China, covering the production, manufacturing, use, recycling and waste management phases (Fig. 13). Four types of pallets, including wooden pallets, plastic pallets, paper pallets, steel pallets, contributing for 99% of market share in 2020 are considered separately. The remaining types of pallets including fly ash pallets, 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.

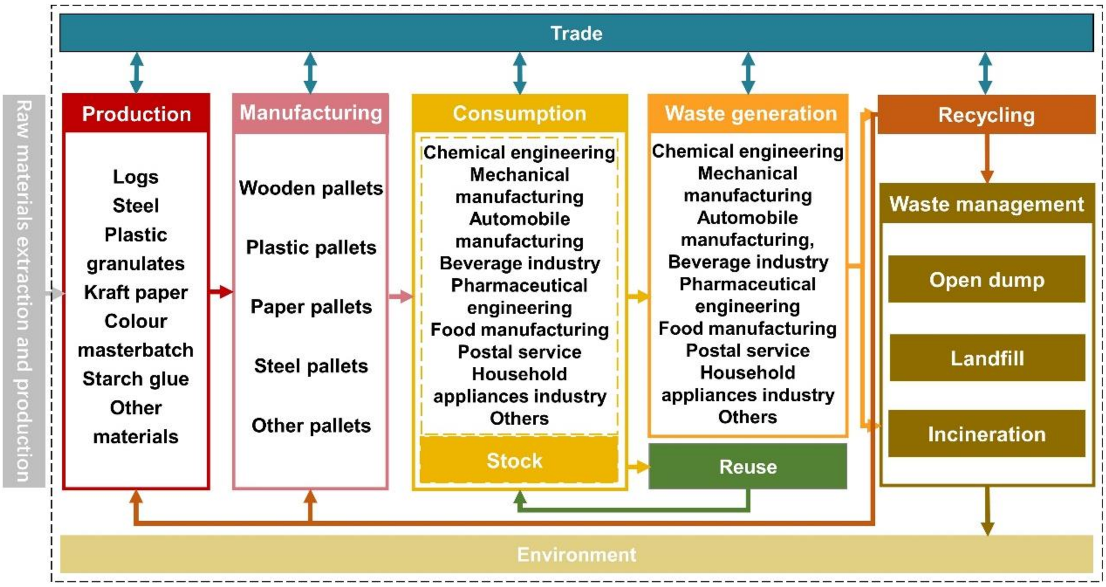


Fig. 13 Schematic diagram of pallet flows and stocks in China. Stages are represented by boxes, and flows are shown by arrows. The system boundary is depicted as a black dotted

box.

3.2.2 Flows and stocks

3.2.2.1 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 2:

$$A_{p,n} = P_{p,n} + S_{p,n-1} + I_{p,n} - E_{p,n} \tag{2}$$

3.2.2.2 Lifetime distribution

Pallet products have a limited lifespan and are eventually discarded. Some of the discarded pallets are recycled, while others are disposed of. 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 pallet 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 MFA 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:

$$C(x) = \int_{n-1}^{n} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)} dx \tag{3}$$

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

$$ChE_{p,n} = c_i \times A_{p,n} \quad (4)$$

$$MeM_{p,n} = m_i \times A_{p,n} \quad (5)$$

$$AuM_{p,n} = a_i \times A_{p,n} \quad (6)$$

$$BeI_{p,n} = b_i \times A_{p,n} \quad (7)$$

$$PhE_{p,n} = p_i \times A_{p,n} \quad (8)$$

$$FoM_{p,n} = f_i \times A_{p,n} \quad (9)$$

$$PoS_{p,n} = s_i \times A_{p,n} \quad (10)$$

$$HoA_{p,n} = h_i \times A_{p,n} \quad (11)$$

$$Oth_{p,n} = t_i \times A_{p,n} \quad (12)$$

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 $Oth_{p,n}$ represent the number 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.

3.2.2.3 Recycling and waste management

Without considering the import and export conditions, let the production of each type of pallet 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:

$$W(x) = \sum_{n=n_{min}}^{n=n_{max}} (P_{p,x-n} \times C_{p,n}) \quad (13)$$

Waste management

$$INC = \sum_{n=n_{min}}^{n=n_{max}} (P_{p,x-n} \times C_{p,n}) \times n_i \quad (14)$$

$$LAN = \sum_{n=n_{min}}^{n=n_{max}} (P_{p,x-n} \times C_{p,n}) \times l_i \quad (15)$$

$$OPE = \sum_{n=n_{min}}^{n=n_{max}} (P_{p,x-n} \times C_{p,n}) \times o_i \quad (16)$$

$$REC = \sum_{n=n_{min}}^{n=n_{max}} (P_{p,x-n} \times C_{p,n}) \times r_i \quad (17)$$

where *INC*, *LAN, OPE* and *REC* represent 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.

3.2.2.4 After-use stocks

The after-use stock of pallets refers to pallets after the active use status that is providing services to the society. The after-use pallet is acquired as an accumulation within the economy, which is 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:

$$S_{p,n} = P_{p,n} + S_{p,n-1} + I_{p,n} - E_{p,n} - \sum_{n=n_{min}}^{n=n_{max}} (P_{p,x-n} \times C_{p,n}) \quad (18)$$

3.2.3 Data sources

In order to collect reliable data on the pallet industry in China, field studies are conducted at 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. 14). Data on the main pallet material type, production volume, the market share of different pallet material types and waste disposal rates are collected. A purposive sampling method is then used to select 20 companies from data sources. The representative companies are chosen based on their size, location and technology representativeness, etc. to ensure a diverse and representative sample. Field trips are conducted to collect primary data covering the entire pallet supply chain for 2020 from these companies. The data were then analysed using descriptive and inferential statistics. 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 the production process would be excluded from the study, because these input items have a very limited impact on the overall results, and the related data are unable to be published due to confidentiality reasons (Wei et al., 2022). The secondary sources are academic papers that report the raw materials consumption data for different types of pallets in other countries or regions (Alanya-Rosenbaum et al., 2021; Anil et al., 2020), which are used to cross-check the primary sources. Also, data from secondary sources are collected to complement unavailable primary data, such as the EoL treatment of plastic pallets. The data are reviewed by experts, who have extensive knowledge and experience in the pallet industry and the entire supply chain. The data inventory has been presented in the following tables 1-6.

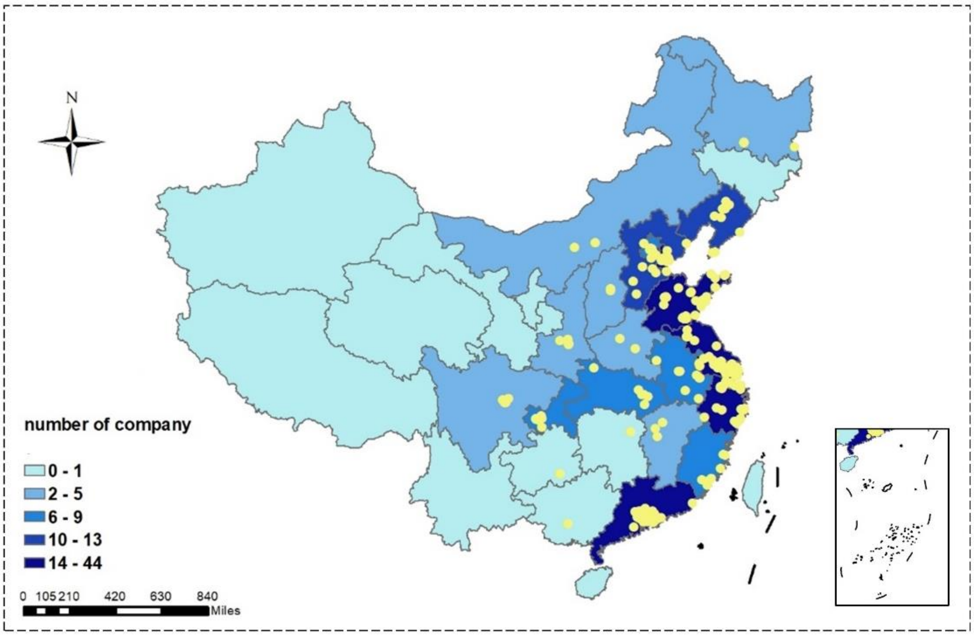


Fig. 14 Member companies in China of CFLP

3.2.4 Data inventory

In the production stage, the main input variables, raw materials input and the pre-consumer waste, are collected from field studies. Pre-consumer waste which are produced centrally on the factory assembly line, are usually used as raw materials on the spot or collected into the energy recovery system (Table 1).

Table 1

Detailed data of the raw materials input (kg)

Type	Wooden pallets	Plastic pallets	Paper pallets	Steel pallets	Other pallets
Logs	1.07E+10				
Steel nails	4.08E+07				3.67E+05
Colour masterbatch		2.03E+07			
HDPE		1.06E+08			

granulate				
PP granulate	9.63E+08			
Cornstarch gum		3.81E+07		
Kraft paper		1.14E+08		
PE			1.02E+07	
Steel screws			243440	
Steel plate			4.53E+08	
Other materials				6.77E+07

For the manufacturing stage, the main input variables are the domestic production of pallets ($P_{p,n}$), the last-year stock ($S_{p,n-1}$) and the manufacturing scrap as shown in Table 2.

Table 2

Detailed data of the pallets production (kg)

Wooden pallet	$P_{p,n}$	6.29E+09
	$S_{p,n-1}$	2.68E+10
	Manufacturing scrap	4.44E+09
Plastic pallet	$P_{p,n}$	1.09E+09
	$S_{p,n-1}$	4.64E+09
	Manufacturing scrap	1.31E+06
Paper pallet	$P_{p,n}$	1.28E+08
	$S_{p,n-1}$	5.44E+08
	Manufacturing scrap	2.46E+07
Steel pallet	$P_{p,n}$	4.08E+08
	$S_{p,n-1}$	1.74E+09
	Manufacturing scrap	5.53E+07
Other pallets	$P_{p,n}$	6.80E+07

	$S_{p,n-1}$	2.90E+08
	Manufacturing scrap	2.72E+04

For the use stage, the top-down method is adopted to provide a complete information on the flows and stock in the entire economic system. The main input variables are product split ratios and sector split ratios. The inter-economy flows of pallet products are considered by application area, such as chemical engineering, machinery manufacturing and beverage manufacturing industry. The sector split ratios represent the proportion of different sectors in the consumption of each type of pallet, and they are collected from field studies. The product and sector split ratios are cross-checked by experts from CFLP, who have in-depth knowledge and experience in the pallet industry. The top-down approach can provide a comprehensive estimation of the pallet stock, which avoids the incompleteness of the bottom-up approach that relies on specific case studies. The pallet stock is also assessed by using a lifetime distribution function, which accounts for the variation of pallet lifetime and usage patterns (Table 3 and Table 4).

Table 3

Pallet use by sector (kg)

Type	**Wooden pallet**	**Plastic pallet**	**Paper pallet**	**Steel pallet**	**Other pallets**
Chemical engineering	1.38E+10	9.92E+08	2.86E+08	1.29E+09	
Mechanical manufacturing	9.64E+09				
Automobile manufacturing	2.75E+09			2.15E+08	
Beverage industry	1.38E+09				
Net export	5.55E+07				
Pharmaceutical engineering		1.49E+09			

Food manufacturing		1.49E+09		1.07E+08	
Postal service		9.92E+08		1.07E+08	
Household appliances industry			2.86E+08		
Others				4.30E+08	3.06E+08

Table 4

Pallet stocks by sector (kg)

Type	Wooden pallet	Plastic pallet	Paper pallet	Steel pallet	Other pallets
Chemical engineering	1.65E+10	1.15E+09	3.36E+08	1.29E+09	
Mechanical manufacturing	1.16E+10				
Automobile manufacturing	3.31E+09			2.15E+08	
Beverage industry	1.65E+09				
Net export	5.55E+07				
Pharmaceutical engineering		1.72E+09			
Food manufacturing		1.72E+09		1.07E+08	
Postal service		1.15E+09		1.07E+08	
Household appliances industry			3.36E+08		
Others				4.30E+08	3.58E+08

The post-consumer pallet waste is calculated based on the apparent pallet use and the life time distribution model (Table 5).

Table 5

Pallet wastes by sector (kg)

Type		Wooden pallet	Plastic pallet	Paper pallet	Steel pallet	Other pallets
Chemical engineering	Incineration	1.47E+09	4.22E+07	1.45E+07		

	Recycling	1.23E+09	3.84E+07	2.54E+07	1.74E+05
	Landfill	5.51E+07	7.05E+07	8.81E+06	
	Open dump		2.46E+06	7.92E+05	
Mechanical manufacturing	Incineration	1.03E+09			
	Recycling	8.60E+08			
	Landfill	3.86E+07			
Automobile manufacturing	Incineration	2.94E+08			
	Recycling	2.46E+08			2.91E+04
	Landfill	1.10E+07			
Beverage industry	Incineration	1.47E+08			
	Recycling	1.23E+08			
	Landfill	5.51E+06			
Pharmaceutical engineering	Incineration		6.33E+07		
	Recycling		5.76E+07		
	Landfill		1.06E+08		
	Open dump		3.68E+06		
Food manufacturing	Incineration		6.33E+07		
	Recycling		5.76E+07		1.45E+04
	Landfill		1.06E+08		
	Open		3.68E+06		

	Open dump					
Postal service	Incineration		4.22E+07			
	Recycling		3.84E+07		1.45E+04	
	Landfill		7.05E+07			
	Open dump		2.46E+06			
Household appliances industry	Incineration			1.45E+07		
	Recycling			2.54E+07		
	Landfill			8.81E+06		
	Open dump			7.92E+05		
Others	Landfill					5.24E+07
	Recycling				5.81E+04	

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 and n_i, l_i, o_i, and r_i represent the ratios of incineration, landfill, open dump and recycling for pallet waste (Table 6).

Table 6

Detailed data of the EoL treatment ratios

Type	Wooden pallet	Plastic pallet	Paper pallet	Steel pallet	Other pallets
n_i	0.534	0.275	0.293		
r_i	0.446	0.25	0.513	1.00	
l_i	0.02	0.459	0.178		1.00

o_i	0.016	0.016

Assumptions used to build the MFA model of the pallet market in China, such as the negligible losses, exclusion of minor raw materials, lifespan of different types of pallets, are shown in Table 7.

Table 7

Assumptions and sources of the MFA model of China's pallets

Assumptions	**Reference**
Pallet losses during use resulting from degradation, abrasion or other dissipative phenomena are assumed to be negligible.	Ciacci et al. (2017); Ryberg et al. (2019)
This study omits any raw materials that make up less than 1% of the mass of the pallets, such as additive, adjuvant, paint, etc.	Hsu et al. (2021); Wei et al. (2022)
Only the residence time in the use stage is considered, and the pallet flow within and between other stages is assumed to be instantaneous.	Zhou et al. (2013)
The data availability of all kinds of ratios used by this study could not cover all the years, so the missing data was calculated using interpolation method.	Hashimoto et al. (2007); Hu et al. (2010); Kawecki et al. (2021)
The lifespans of pallet products are assumed to be the same from 2003 to 2020.	Jiang et al. (2020); Liu, Y. et al. (2020)
The shares of EoL management of waste plastic and paper pallets in China are the same as general waste plastics and general waste paper EoL flows.	Ciacci et al. (2017); Jiang et al. (2020); Liu, M. et al. (2020)

3.2.5 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. 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). Emphasis has been placed on parameters identified as having the highest degree of uncertainty. 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).

3.3 The green transformation framework[1]

This study aims to provide a comprehensive framework to improve the environmental performance of the pallet industry in China, thereby contributing to the green transformation of the pallet logistics. The framework is composed of three scenarios which represent the pallet system as in China today, the establishment of a pallet sharing system and the adoption of CE strategies. The framework is validated by adopting LCA and scenario analysis. The framework is presented and explained in Section 3.3.

3.3.1 The structure of the framework

This thesis develops a comprehensive green transformation framework for identifying the stages involved in mitigating environmental impacts within the realm of pallet logistics in China. The framework is constructed through the data basis provided from MFA and the formulation and comparison of three distinct scenarios: the base case scenario, reflecting the current state of the pallet system in China; the sharing system scenario, which introduces a pallet sharing system; and the CE scenario, which incorporates additional strategies aligned with CE principles. To validate this framework, the methodology of LCA is

[1]Section 3.3 is largely reproduced from:
Zhang, T., Wen, Z., Tan, Y., Ekins, P., 2024. Circular economy strategies for the booming industrial pallet use in China. *Sustainable Production and Consumption*, 46, 244-255.

employed, combing field studies and robust modelling. The initial phase involves a thorough evaluation and comparison of environmental impacts for five types of pallets across three distinct scenarios. However, it fails to account for real-world market conditions, such as the market share distribution among different types of pallets. Subsequently, utilising the insights derived from these assessments, a detailed analysis of the environmental impacts of the Chinese pallet market across three scenarios is undertaken, offering practical implications for the pallet industry in China. This research would provide valuable insights into the challenges associated with reducing the environmental impacts of pallet logistics, thereby contributing to the sustainable development of the industry in the Chinese context.

The presented framework, delineated through an illustrative flowchart (Fig. 15), offers guidance on the assessment and enhancement of the environmental performance within the realm of pallet logistics in China. The framework comprises four key steps: data collection, scenario settings, evaluation and comparison of environmental impacts, and a discourse on barriers and strategies aimed at mitigating environmental impacts. Data collection involves comprehensive information on the Chinese pallet market, encompassing production details for each pallet type, such as material specifications, market shares, and current production, usage, and disposal practices.

Given the potential of the sharing economy and CE to curtail resource utilisation and waste generation, the framework establishes three scenarios. These scenarios progress from the base case, representing the current system characterised by single-use and disposal of pallets, to the system sharing scenario, where pallets are leased and collected for reuse. The sharing system scenario envisions a comprehensive transition of the entire pallet industry to a sharing system, representing the second phase aimed at diminishing environmental impacts. This system reduces pallet demand by fostering shared usage among different entities, facilitating multiple trips per pallet. The framework further extends to the CE scenario, wherein pallets are managed under a sharing system, incorporating combined CE strategies. It goes a step further by reducing resource and energy consumption during the life cycle, while concurrently elevating pallet recycling and energy recovery rates at the EoL stage. These three scenarios collectively serve as evaluative tools to assess the potential for environmental impact reduction within the Chinese pallet industry. Comparative analyses of environmental impacts across the scenarios enable a comprehensive understanding of the industry's transformation potential.

In addition, environmental impact assessments are conducted at multiple levels, encompassing both product and national scales. Product-scale evaluations involve quantifying the environmental impacts of five distinct pallet types—wooden, plastic, steel, paper, and fly ash pallets, providing insights into the environmental implications of diverse material compositions. At the national scale, market share information is integrated, allowing for the quantification of environmental impacts related to the three scenarios within the Chinese pallet industry. This analysis yields practical implications for the industry's transition. In the context of the sharing system scenario, additional data on the reuse times of different pallet types is collected. For the CE scenario, the identification of specific CE strategies for each pallet type becomes imperative. This comprehensive study contributes insights into the environmental sustainability of pallet logistics in China, offering valuable perspectives at both product and national scales.

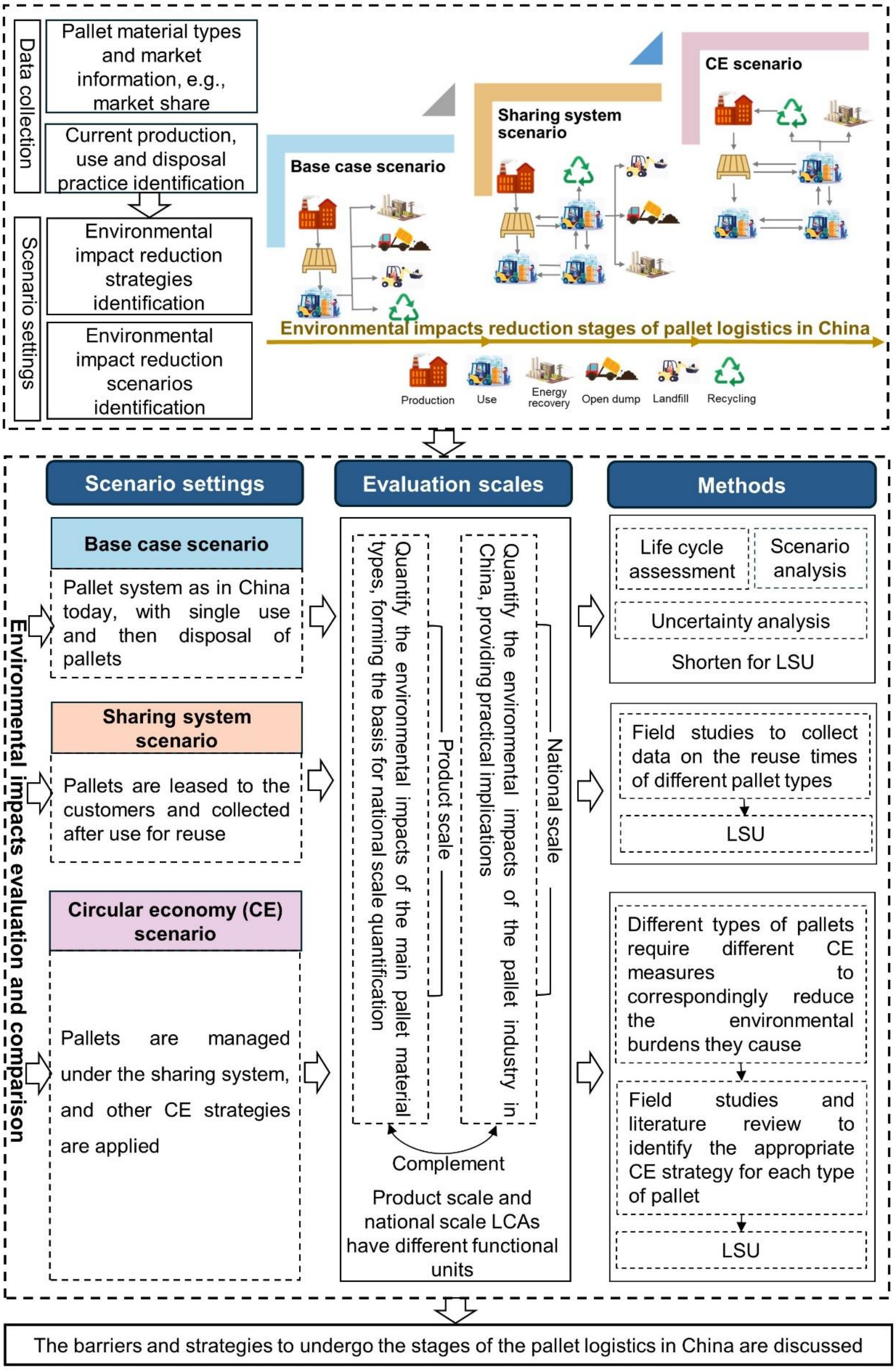


Fig. 15 The structure of the green transformation framework

3.3.2 Scenario settings

The base case scenario reflects the current situation of pallet industry in China, where pallets are utilised in a single-use manner and subsequently disposed of. The sharing system scenario assumes that the whole pallet industry transfers to the sharing system, which is the second stage towards green transformation. The sharing system reduces the number of pallets required for transportation, as pallets are shared among different users and reused for multiple trips. The CE scenario assumes that the CE strategies are applied in the market with the pallet sharing system established. The CE scenario further reduces the resource and energy consumption in the entire lifecycle stage and increases the recycling rate and energy recovery rate of pallets at the EoL stage (Table 8). The three different scenarios are used to evaluate the potential of green transformation in the pallet industry in China, by comparing the environmental impacts of pallet industry under each scenario.

Table 8

Scenario settings in the green transformation framework

Scenario	Content
Base case scenario	Pallet system in the current situation, with single use and then disposal of pallets
Sharing system scenario	Pallets are leased to the customers and collected after use for reuse
CE scenario	Re-use as in scenario 2, plus other CE strategies

3.3.2.1 Base case scenario

The “single-use” strategy is a form of open-loop supply chain where pallets are sold to the consumers for single use and then discarded or recycled at the end of their life cycle (Deviatkin et al., 2019). This strategy has some advantages, such as high availability and flexibility, but it also has some disadvantages, such as low quality, and lack of standardisation. Based on field studies covering the pallet supply chain, the process of production, distribution, use and EoL stage of the five types of pallets in China have been identified.

3.3.2.1.1 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; 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 moulding machine. After the mixture is turned into a melt at a high temperature, the melt is injected into the mould of the plastic tray by an injection device, and it is formed after four stages of filling, pressure holding, cooling and demoulding. The demoulded pallet is processed and trimmed manually to obtain the required plastic pallets.

Paper pallet. Paper pallets are made by gluing corrugated cardboard and kraft 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 steel pallets 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 under high temperature and high pressure. To achieve the required surface effect, a powder coating is sprayed onto the workpiece's surface. The powder is then heated to the designated temperature and allowed to melt and level for the appropriate amount of time before solidification.

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

3.3.2.1.2 Distribution stage

Pallet distribution stage refers to the process of supplying empty pallet products to the users who need them for loading and transporting various types of goods. Pallet distribution stage can employ different methods, such as direct delivery, depot delivery, or third-party delivery. In direct delivery, the pallet supplier delivers the pallet products directly to the user’s location. In depot delivery, the pallet supplier delivers the pallet products to a depot or warehouse, where the user can pick them up. In third-party delivery, the pallet supplier uses a third-party logistics provider to deliver the pallet products to the user. Each method has its own benefits and drawbacks, depending on elements such as cost, speed, availability, and reliability. 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), which is considered in this study.

3.3.2.1.3 Use stage

The process of the pallet use 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 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). Under the base case scenario, pallets are single-used and then disposed. Wooden, plastic, paper, steel and fly ash pallets have the carrying capacity of 1, 1.5, 1, 2 and 1.5 tonnes, respectively.

3.3.2.1.4 EoL stage

Pallet EoL stage is the stage in which pallets that are beyond use or repair are either recycled or disposed of. EoL stage can employ different methods, such as recycling, open dump, incineration and landfill (Alanya-Rosenbaum et al., 2021; Weththasinghe et al., 2022). Recycling refers to reusing the materials from the pallets to make new products or pallets. Open dump is the method of discarding the pallets in an open area without any treatment or control. Incineration is the method of burning the pallets to reduce their volume and weight, and to recover energy. Landfill is the method of burying pallets in a designated area with some environmental protection measures. Each method has its own environmental impacts or benefits, depending on factors such as emissions, resource consumption, waste generation, and energy recovery. The choice of alternative waste treatment methods are aimed to encourage pallet industry to adopt more sustainable waste management practices that enable a

CE for waste pallets, and provide guidance on reducing environmental impacts of pallet industry (Korhonen et al., 2018).

The establishment of base scenarios for EoL management of different pallet material types is a critical aspect of assessing the environmental impact and sustainability of pallet use in logistics. The base scenarios for the EoL management of different pallet material types are established by using data collected from field studies. In the absence of specific field data, including plastic and paper pallets, literature rates for EoL are often relied upon to construct these scenarios. Based on field studies to the wooden pallet recycling centre which has more than 100 waste wooden pallet collection companies, 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 (Table 9). In the case of steel pallets, field studies indicate that the presence of waste pickers in China plays a significant role due to the availability of cheap labour. Waste pickers actively collect materials with economic value, including discarded steel. Since scrap steel holds intrinsic value, it is highly possible that waste pickers will retrieve and sell it to recycling centres when they encounter dumped steel pallets. Consequently, it is reasonable to assume a 100% recycling rate for steel pallets.

However, to enhance the robustness of the results, sensitivity analysis has been employed by testing lower recycling rates, from 90% to 70%. This approach ensures that the findings remain valid even under varying recycling scenarios. The collection rate during the recycling process is for a material type only. For example, one tonne of waste paper can produce 0.8 tonnes of pulp (Liu et al., 2020). The collection rates are set at 90% for waste steel, 85% for waste plastic, and 85% for waste fly ash pallets as referenced from GaBi database (Thinkstep, 2021).

Table 9

EoL flows of five types of pallets

Pallet type	EoL flows	Reference
Wood	33.3% of waste wooden pallets are dismantled to repair or remanufacture other pallets, 53.4% are used as biomass fuel, 11.3% are recycled to produce wood shavings, and 2.0% are landfilled	Field study
Plastic	25% of plastic pallets are recycled, 27.5% are incinerated for energy recovery, 45.9% are landfilled, and 1.6% are open dumped	Jiang et al. (2020)
Paper	51.3% of waste paper pallets are recycled, 29.3% are incinerated as fuel, 17.8% are landfilled, and 1.6% are leaked into the environment	Liu et al. (2020)
Steel	Steel pallets are 100% recycled	Field study
Fly ash	Fly ash pallets are 100% landfilled.	Field study

3.3.2.2 Sharing system scenario

The concept of pallet sharing within a closed-loop supply chain, commonly known as the "pallet sharing system", or alternatively referred to as leased pallet pooling or a closed-loop pallet system, is characterised by the leasing of pallets to clients and their subsequent collection after use for reuse. The “pallet sharing system” strategy is derived from the principles of CE and shared economy, which aims to reduce waste and optimise resource utilisation by sharing and reusing products (Elia and Gnoni, 2015). Pallet sharing system refers to a system that uses standardised pallets that are compatible with different kinds of goods and equipment. The system implements consistent pallet operations throughout the supply chain, such as loading, unloading, stacking, and storing and circulates pallets along with goods without changing pallets in the middle of the supply chain, which maintains the pallet-goods unit status and reduces handling time and damage risk. Used pallets are collected at the end point of the supply chain. After inspection and appropriate maintenance, the pallets enter the sharing system network for reuse by other customers (Bilbao et al., 2010). The essence of pallet circulation and sharing is to transport goods with pallets in a more efficient way. The system aims to solve the problems of repeated pallet exchange in the traditional pallet management strategies, which can cause low operation efficiency and easy damage of goods in the logistics process (Glock, 2017).

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 consulting pallet manufacturers who have performed rigorous tests and the users who possess rich pallet use experience. Then the RSL numbers are cross-checked with academic papers (Alanya-Rosenbaum et al., 2021; Anil et al., 2020). The data are also reviewed with experts from CFLP, who have extensive knowledge and experience in the pallet industry. Wooden, plastic, paper, steel and fly ash pallets have an RSL of 15, 70, 4, 100, 15 trips, respectively based on field studies. These RSL numbers are reasonable with reference to the existing research (Anil et al., 2020; Deviatkin et al., 2019; 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.

Since the sharing economy can facilitate a transition in collective consumption pattern (Zhou et al., 2020), a pallet sharing system has the potential to increase the circularity of the industry. Currently, the pallet sharing system has been adopted in Europe and the US. However, 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 to CFLP, the number of shared pallets only represented 1.8% of the total pallet holdings in China, indicating that the majority of pallets were still managed under the single use system. This suggests that there is a great need and potential for studying the environmental implication of pallet sharing systems in China and exploring the factors and challenges that affect their development. Moreover, there is a lack of empirical studies and data on the environmental effects of different pallet management strategies in China, which hinders the comparison and evaluation of their environmental benefits and trade-offs.

3.3.2.3 CE scenario

CE has garnered significant interest from both scholars and professionals (Blomsma and Brennan, 2017; Geng and Doberstein, 2008; Liu et al., 2009). Particularly, the Chinese government has actively embraced CE strategies to drive the environmentally conscious transformation of industries. The conventional 3R (reduce, reuse, recycle) framework has undergone substantial expansion, evolving into a comprehensive 10R strategies model (Kirchherr et al., 2017; Pan et al., 2022; Superti et al., 2021; Wen et al., 2023) (Fig.16). Specifically, the reduce pathway has been elaborated to include rethink, reduce, and refuse. The reuse pathway has been extended to encompass repurpose, remanufacture, reuse, refurbish, and repair. The recycling path now incorporates recycle and recovery as additional dimensions.

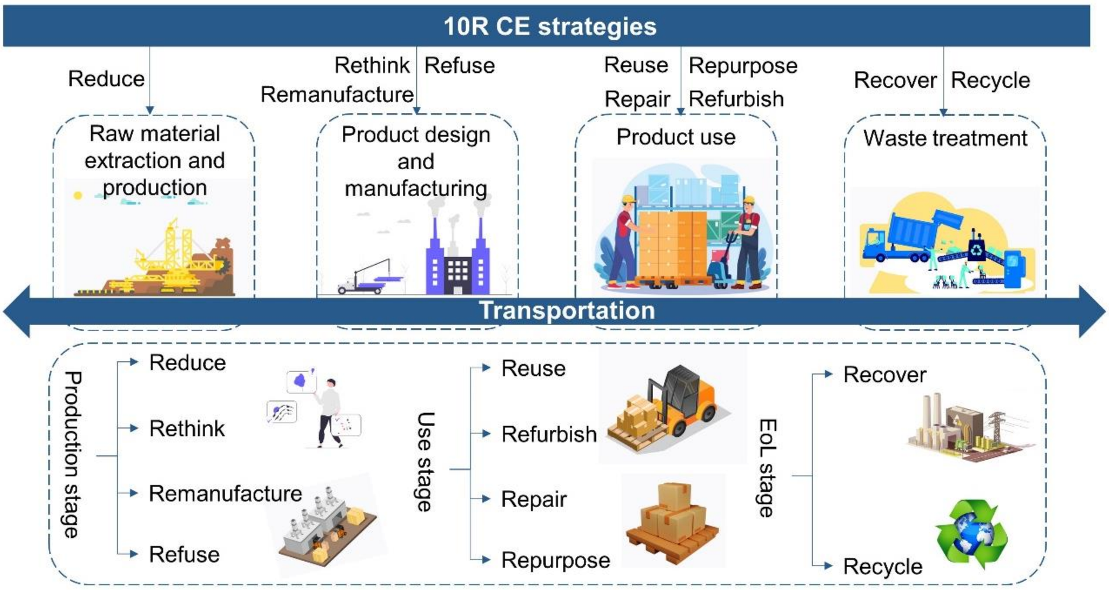


Fig. 16 Framework for 10R strategies of CE

Various pallet types require specific CE measures to efficiently mitigate the corresponding environmental impacts they generate. The essential step towards achieving a transformation in environmental impact reduction within the pallet industry involves the careful identification of the suitable CE strategies for each pallet type. This identification process is accomplished through field studies, ensuring a thorough understanding of the unique characteristics and life cycle implications associated with different pallet types.

Production stage. The remanufacture strategy involves the production of new pallets utilising recovered boards or components obtained from dismantled pallets (Pan et al., 2022). This process includes the provision of used pallets, the collection and transportation of these used pallets, and the subsequent operations involved in pallet remanufacturing. Retailers provide used pallets, which are then gathered and transported to facilities for dismantling.

The reduce strategy refers to reducing both the consumption of raw materials and electricity produced from fossil fuels throughout the whole life cycle of pallets. This involves the substitution of conventional electricity with renewable energy source, solar thermal (AC, compact linear fresnel reflector concentrated solar power technology), in five types of pallets (Buonocore et al., 2016; Williams et al., 2012). Additionally, recycled materials are employed as substitutes for new materials as part of the reduce strategy.

Use stage. The reuse strategy entails the establishment of a pallet sharing system, with wooden, plastic, paper, steel and fly ash pallet having a RSL of 15, 70, 4, 100 and15 trips, respectively.

The repair strategy involves the restoration of pallet components, including the repair of connections and the replacement of damaged blocks and boards, ensuring the maintenance of strength and structural integrity, which can increase the service life of pallets (Coughlan et al., 2018). This process encompasses the supply, collection, and transportation of used pallets, followed by repair operations. To make repaired pallets, damaged components are fixed using either new wooden boards or reclaimed boards from dismantled pallets. The CE scenario allows for the repair of wooden and fly ash pallets due to their assembly method, involving nailing the boards together, allowing for the replacement of deckboards and stringers during disassembly (Kočí, 2019). However, the repair strategy is not applicable to plastic, steel, and paper pallets, as they are manufactured through injection moulding, welding, and pressing processes, respectively. In this study, it is assumed that pallets recovered from repair or remanufacturing facilities have no additional environmental burdens, since their effects have already been allocated to pallets, except for the energy, water and materials inputs for the repair or remanufacturing process, and transportation to the facility (Alanya-Rosenbaum et al., 2022; Park et al., 2018).

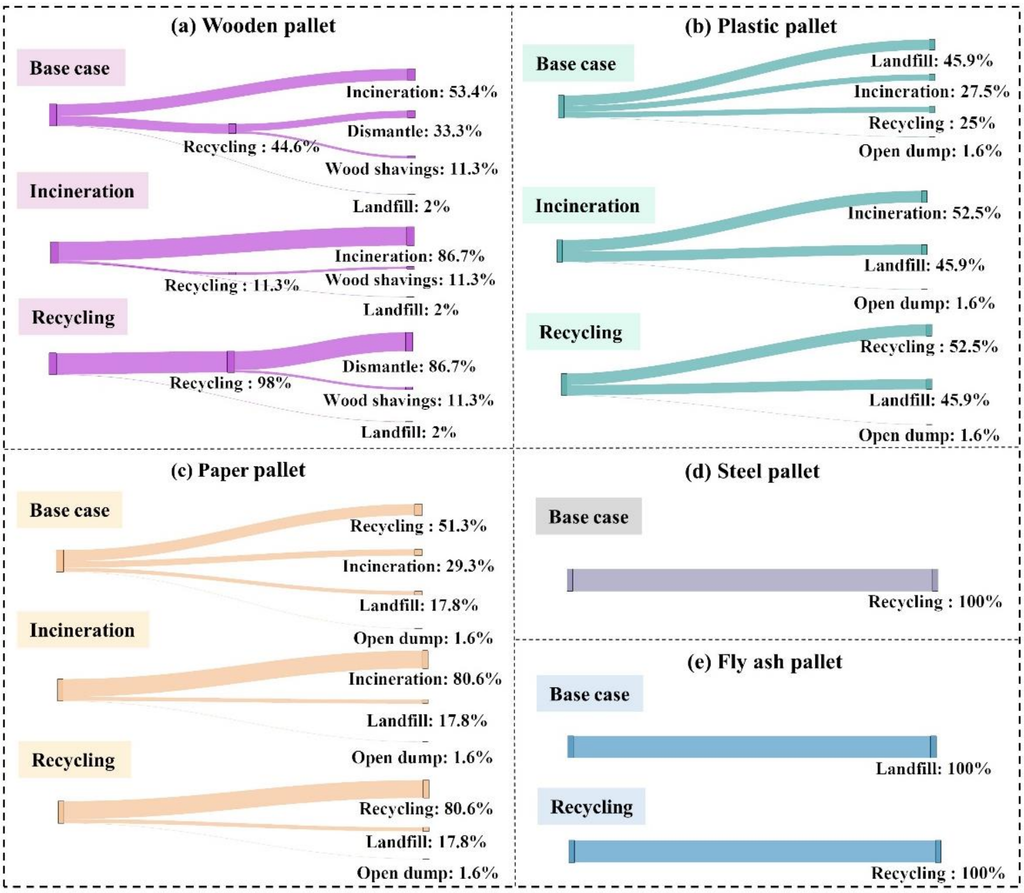


Fig. 17 Scenario settings for EoL flows of five pallet material types

EoL stage. Alternative EoL scenarios are considered to assess the potential environmental benefits and burdens of different EoL treatments, in order to encourage the pallet industry to adopt more sustainable waste management practices that enable a CE for waste pallets, and provide guidance on reducing environmental impacts of pallet industry (Korhonen et al., 2018). Scenario analysis will be performed 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 amount of energy can be recovered in the form of electricity or 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. In the incineration and recycling scenarios, 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 10). 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. 17).

Table 10

EoL scenario settings for five types of pallets

	Scenario	**EoL path**	**Avoided burden included**
Wooden pallets	Base case	33.3% are dismantled to be reused as boards, 53.4% are recycled to make biomass fuel, 11.3% are recycled to make wood shavings, and 2.0% are landfilled	● Dismantled boards replace virgin logs as raw materials ● Biomass fuel used for boiler ● By-products from production process are used as fuel

			● Recycled wood shavings replace virgin lumber
	Recycling	86.7% of wooden pallets are dismantled to be reused as boards, 11.3% are recycled to make wood shavings, and 2.0% are landfilled.	● Dismantled boards replace virgin logs as raw materials ● By-products from production process are used as fuel ● Recycled wood shavings replace virgin lumber
	Incineration	86.7% of wooden pallets are collected to make biomass fuel for energy recovery, 11.3% are recycled to make wood shavings, and 2.0% are landfilled	● Biomass fuel used for boiler ● By-products from production process are used as fuel ● Recycled wood shavings replace virgin lumber
Plastic pallet	Base case	25% recycling, 27.5% incineration for energy recovery, 45.9% landfill, 1.6% open dump	● Recycled plastics replace virgin plastic granulates ● Electricity recovered from plastic incineration
	Recycling	52.5% recycle, 45.9% landfill, 1.6%	● Recycled plastics

		open dump	replace virgin plastic granulates
	Incineration	52.5% fuel, 45.9% landfill, 1.6% open dump	● Electricity recovered from incineration
Paper pallet	Base case	51.3% recycle to make pulp, 29.3% incinerate as fuel, 17.8% landfill, 1.6% leak in the environment	● Fuel used for boiler ● Recycled pulp replaces virgin paper
	Recycling	80.6% recycle to make pulp, 17.8% landfill, 1.6% leak in the environment	● Recycled pulp replaces virgin paper
	Incineration	80.6% incinerate as fuel, 17.8% landfill, 1.6% leak in the environment	● Fuel used for boiler
Steel pallet	Base case	100% recycling	● Recycled steel replaces virgin steel ● By-products from steel pallet production replace virgin steel
Fly ash pallet	Base case	100% landfill	● No benefits
	Recycling	100% recycling	● Recycled materials replace virgin inputs

3.3.3 Life cycle assessment

3.3.3.1 Goal and scope

LCA is adopted to evaluate and compare the environmental impacts under three scenarios, validating the framework across both product scale and national scale. 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 (Fig. 18). The production stage stems from the extraction of primary resources, such as oil extraction in the manufacture of plastic granulates. The infrastructure construction and the transportation of raw materials are excluded in the study (Zhang et al., 2021). 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. In the traditional system, pallets are single used, which is also the prevalent pallet management system in China. The EoL stage includes different treatment methods based on the current waste treatment flows. The assessment complies with international LCA standards (ISO, 2006a, b). The modelling of LCA is conducted using the Gabi software (Version: 9.1). Detailed explanations of scenario settings are shown in Table 14.

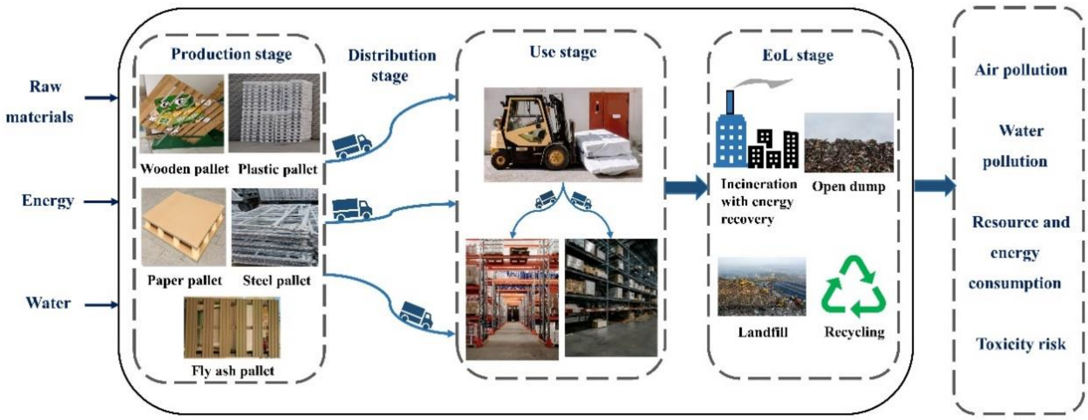


Fig. 18 System boundary of environmental impact assessment for pallets

3.3.3.2 Life cycle inventory

3.3.3.2.1 Data inventory

The Foreground system encompasses all activities from the receipt of raw materials at factories to the disposal of waste pallets. All activities within the Foreground system occur on-site at pallet production companies. The Background system includes all activities involved in providing materials and energy necessary to support the operational processes conducted in the Foreground. The detailed descriptions of lifecycle stages and scenario settings have been presented in Section 3.3.2. The LCI data are generated through collecting data from manufactures, literature or from the available databases. In order to collect reliable data on the pallet industry in China, the author conducts field studies on CFLP, which is the largest and most authoritative pallet organisation in China, to identify 20 representative pallet production companies. These field studies include the largest companies in each pallet type category, including wooden, plastic, paper, steel, and fly ash pallet manufacturers and production data are collected from them. The background processes such as electricity and water are used from Gabi and Ecoinvent database. The data inventory and detailed data sources have been presented in Appendix B.

3.3.3.2.2 Allocation

In line with the principles of LCA, the study identifies environmental benefits associated with the EoL phases of different pallet types. Specifically, recycling and energy recovery through incineration are EoL strategies that not only manage waste but also generate recycled materials and energy. The system expansion approach is adopted to take the avoided burden from material recycling and energy recovery into account (Eriksson et al., 2010;

Frischknecht, 2010). The substitution is applied in the reference system to prevent the production of functional equivalents. The environmental effects and credits resulting from system expansion is shown in Fig. 19. The product system is credited for the electricity and heat produced by the combustion of waste pallets. The conventional energy generation methods, electricity grid mix and natural gas, are regarded as the avoided energy sources for the incineration credits (Pellengahr et al., 2023). Besides, when recycled materials are used in manufacturing, it prevents the environmental impacts that would have been caused by the extraction and processing of virgin materials. This measure acknowledges the environmental benefits of substituting recycled materials for virgin ones, and gained credits for avoiding virgin materials production (Sambucci et al., 2023).

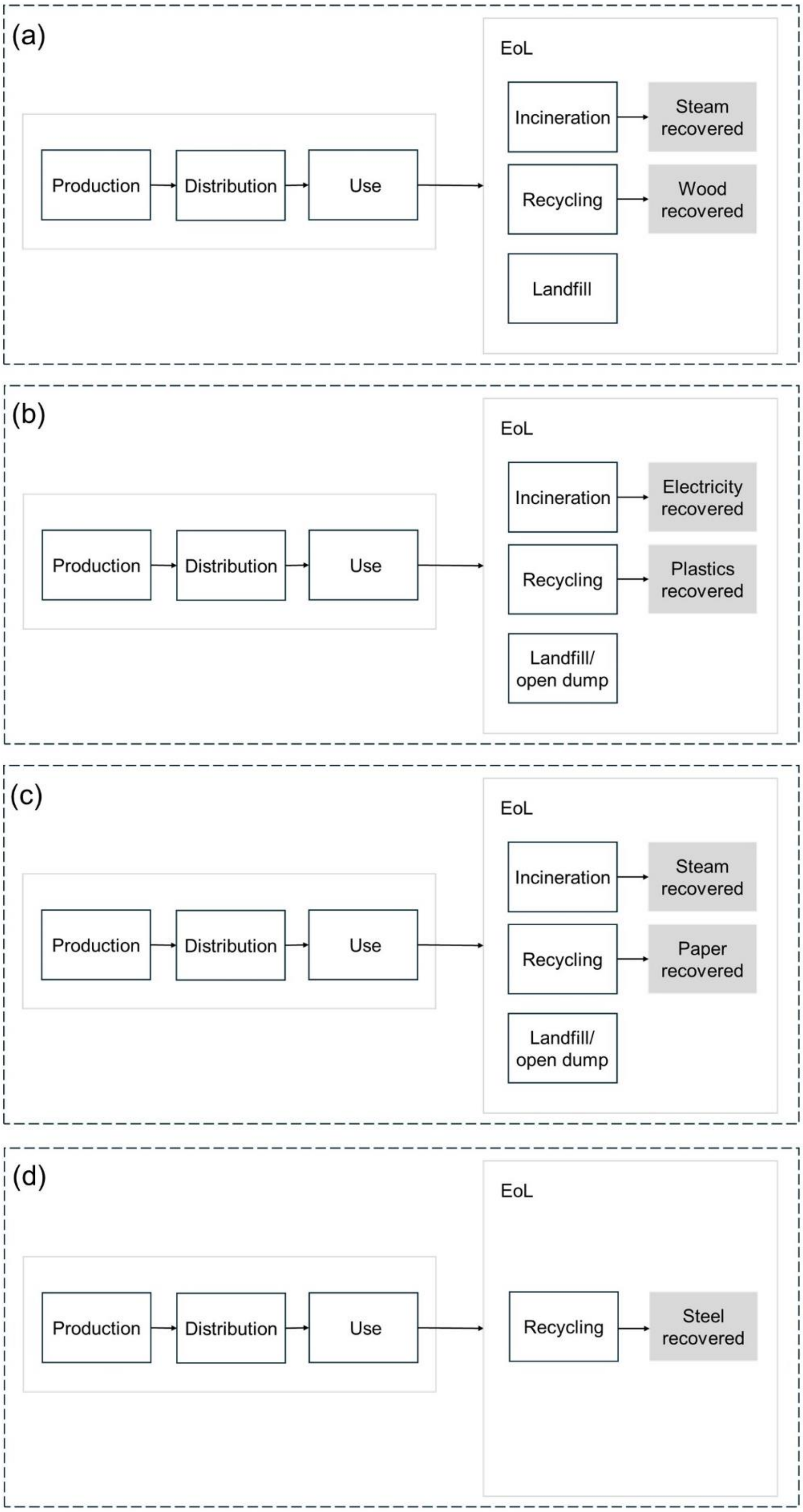


Fig. 19 System boundary for the base scenario (a) wooden pallet; (b) plastic pallet; (c) paper pallet; (d) steel pallet.

3.3.3.3 Life cycle impact assessment

The whole life cycle of pallets involves the consumption of resources and energy, which can cause air pollution, such as GHG emissions, dust and 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 five sets of environmental impact categories: air pollution, water pollution, soil pollution, resource and energy consumption, and toxicity risks. Specifically, air pollution set includes GWP, FPMF, IR, and POF. Water pollution and soil pollution is assessed through FEu and TA respectively. The category of resource and energy consumption incorporates FC, FD, and MD. Toxicity risks are evaluated using HT, TE, and FE (Table 11). The additional potential impact categories have been excluded because the numerical values associated with these supplementary impact categories are relatively minor and do not significantly influence the final outcomes of this study, according to a broader LCA that have been conducted. Consequently, in the thesis, the above-mentioned impact categories that have prominent results are focused, which enable a comprehensive examination of environmental impacts. In order to make the environmental impacts comparable, the ReCiPe 2016 v1.1 Midpoint (H) is adopted.

Table 11

The selected ReCiPe 2016 v1.1 Midpoint (H) impact categories, units and respective descriptions (Huijbregts et al., 2016).

Name	**Unit**	**Explanation**
GWP	kg CO_2 eq.	The potential to contribute to global warming over a specified timeframe
FPMF	kg $PM_{2.5}$	Primary and secondary aerosols in the atmosphere

	eq.	are produced by air pollution
IR	kBq Co-60 eq.	In addition to the nuclear fuel cycle, which involves the mining, processing, and disposal of waste, other human activities that produce anthropogenic radionuclide emissions include burning coal and extracting phosphate rock
POF	kg NO_x eq.	The capacity to use photochemical reactions to potentially aid in the creation of ground level ozone
TA	kg SO_2 eq.	The acidity of the soil is altered by inorganic material deposition from the atmosphere, such as phosphates, nitrates, and sulphates
FEu	kg P eq.	The potential to cause excessive nutrient enrichment in freshwater ecosystems
FC	m^3	The amount of freshwater withdrawn or consumed
FD	kg oil eq.	The depletion of finite fossil fuel resources
MD	kg Cu eq.	The depletion of finite metal resources
HT	kg 1,4-DB eq.	The potential to cause harm to human health through various exposure pathways
TE	kg 1,4-DB eq.	Chemicals that persist in the environment, accumulate within the human food chain, and exhibit toxicity can harm ecosystems
FE	kg 1,4-DB eq.	

Normalisation and weighting are optional steps in LCA study. Normalisation entails determining the magnitude of category indicator results in relation to a reference dataset, such as regional or global averages. However, normalisation has its drawbacks, including the risk of bias introduced by the selection of normalisation references, which can influence the conclusions drawn from the LCIA phase, and the lack of a comprehensive perspective, as it emphasises relative rather than absolute values. Weighting involves converting and potentially aggregating indicator results across different impact categories using numerical factors based on value judgments, with the goal of simplifying the interpretation of LCA results by offering a single score that represents the overall environmental impact. Nevertheless, weighting also has its limitations, such as the inherent subjectivity in choosing weighting factors, which reflect value-based decisions that can affect the outcomes and conclusions of the LCA, and the potential for aggregation challenges, which can obscure the details of individual impact category, leading to a loss of crucial information and a less comprehensive assessment of environmental impacts (ISO 2006b). Therefore, to provide a holistic analysis of each environmental impact category, the steps of normalisation and weighting are not applied in this study, which allows for a critical assessment of how each pallet type or scenario performs across various impact categories without oversimplification, enabling more robust and informed decision-making based on the specific environmental burdens identified. In summary, while normalisation and weighting can be useful for simplifying LCA results, this thesis avoids these steps to provide a holistic understanding of the environmental impacts of different types of pallets under each scenario.

3.3.3.4 Uncertainty 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 (Zhao et al., 2019). The data collected from the production process are subject to more uncertainty because of the fluctuations exist among multiple pallet producing plants, which may have different production technologies, capacities, efficiencies, and environmental performances (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 the uncertainty analysis. The input data for the production stage are assumed to follow normal distributions, which are characterised by their mean values and standard deviations. The Monte Carlo method is applied to the input data for the production stage using 10,000 sampling values. The probability distribution histograms and 95% confidence intervals are constructed based on simulations (Li et al., 2022).

3.3.3.5 Product scale

The reference flow represents the particular product flow aligned with the FU of the analysed product system. The FU serves as a quantified depiction of the function or service offered by the product. This reference flow is employed to standardise the product system, bringing it to an equivalent level of function or service, facilitating comparisons with other product systems. This study selects “one tonne of cargo delivered using pallets” as the FU. This FU is used to more accurately describe the function of pallets in comparison to other studies, through taking RSL and load bearing capacity of pallets into consideration. The FU is based on the 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. This study assumes that pallets are always loaded to full capacity (Zhang et al., 2023). The RSL and load bearing capacity are used to determine the number of pallets needed to meet the FU (Alanya-Rosenbaum et al., 2021):

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

The LCA study conducted at the pallet product scale offers a comparative analysis of the environmental impacts associated with various material types across the three scenarios. The assumptions made in the LCA study are outlined in both Table 12 and Table 13. However, the LCA study at the product scale overlooks the influence of real-world market conditions, i.e., market share. To address this limitation and provide a more comprehensive understanding, the LCA study is extended to the national scale under the three scenarios. This broader perspective aims to offer a more holistic and practical depiction of the environmental implications associated with pallet logistics.

Table 12

Specifications, RSL, and FUs of pallet designs at product scale

Pallet material type	Load capacity (tonnes)[a]	RSL (trips)[a]	Number of pallets required (base case scenario) (piece)	Number of pallets required (sharing system scenario) (piece)	Number of pallets required (CE scenario) (piece)
Wooden pallet	1	15	1	0.07	0.07
Plastic pallet	1.5	70	0.67	0.01	0.01
Paper pallet	1	4	1	0.25	0.25
Steel pallet	2	100	0.50	0.01	0.01
Fly ash pallet	1.5	15	0.67	0.04	0.04

[a] Load capacity and RSL as specified by manufacturer.

3.3.3.6 National scale

The product-scale LCA primarily evaluates the environmental impacts associated with the production, distribution, use, and disposal of a single product. It aims to identify environmental hotspots across the entire lifecycle, compare the environmental impacts of different material types and assess the influence of various stages of green transformation on a single product. However, this approach fails to consider real-world market conditions, such as market share and the potential for the adoption of sustainable practices within the pallet industry. To address this limitation, the LCA is expanded to the national scale, providing a more comprehensive analysis of pallet logistics and the potential environmental benefits across different stages of the green transition.

At the national level, the study examines the environmental impacts of the entire pallet market in China under three scenarios. First, the conventional pallet logistics system is assessed as the baseline, reflecting current practices. Next, the adoption of a pallet-sharing system is considered, where companies reuse pallets across various supply chains, thereby optimising logistics and reducing the reliance on single-use pallets. Finally, the study explores the adoption of CE strategies, extending beyond pallet sharing to incorporate more CE strategies throughout the pallet lifecycle, such as repair, recovery, and recycling. The FU for the national scale LCA is selected based on the overall load capacity carried during the useful life of a pallet in the entire pallet market in China, which is estimated to be 1.74 billion tonnes of cargo delivered in 2020, reflecting the purpose of pallets to handle, store, and transport cargo (Table 13). This FU allows for a fair and consistent basis for comparing the environmental impacts of the Chinese pallet industry under the three scenarios to explore the stages in the established green transformation framework. The system boundary is from cradle to grave as illustrated in Fig. 18.

This study provides a more comprehensive quantification of the environmental benefits at each stage of the green transition, viewed from a market perspective, through extending the LCA to the national scale. It offers a holistic understanding of how transitioning from conventional systems to pallet-sharing and ultimately to CE models can influence the environmental impacts of the pallet industry as a whole. This broader perspective delivers valuable insights for policymakers and industry leaders, facilitating informed decision-making that promotes the sustainable transformation of logistics and supply chain systems.

Table 13

Specifications, RSL, and FUs of pallet designs at national scale

Pallet material type	Market share	Load capacity (tonnes)[a]	RSL (trips)[a]	Number of pallets required (base case scenario) (million pieces)	Number of pallets required (sharing system scenario) (million pieces)	Number of pallets required (CE scenario) (million pieces)
Wooden pallet	74%	1	15	1126.66	76.47	76.47
Plastic pallet	16%	1.5	70	243.33	3.54	3.54
Paper pallet	5%	1	4	76.40	19.38	19.38
Steel pallet	4%	2	100	60.83	0.62	0.62
Fly ash pallet	1%	1.5	15	15.23	1.03	1.03

[a] Load capacity and RSL as specified by manufacturer.

Chapter 4 Results and discussion

The structure of the results section is organised into two main components. Section 4.1 presents the results from the MFA, which examines the current state of the pallet supply chain, focusing on material flows, resource use, and waste generation for different pallet types. This section highlights key points for waste reduction and resource optimisation, providing a detailed overview of the efficiency and circularity of material usage across various pallet systems.

Section 4.2 focuses on the outcomes of the green transformation framework, which identifies the environmental hotspots for each type of pallet, i.e., wooden, plastic, paper, steel and fly ash pallets, and compares their environmental impacts. This section also evaluates how different stages of the green transition—ranging from conventional practices to pallet sharing and CE strategies—affect environmental performance at both the product and national scales. The results provide critical insights into the potential environmental benefits of adopting sustainable practices across the pallet market in China.

4.1 Results and discussion on the circularity of the pallet industry in China[2]

4.1.1 Pallet flows

The consumption of raw materials for manufacturing pallets amounted to 12.51 Mt in 2020 (Fig. 20), 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

[2] Section 4.1 is largely reproduced from:

Zhang, T., Wen, Z., Tan, Y., Shi, X., Sun, Y., Ekins, P., 2024. Advancing circular economy of pallets: a comprehensive evaluation framework. *Resources, Conservation and Recycling*, 211, 107874

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, which accounts for 36% of the total material inputs and 41% of total waste, indicating the low efficiency of resource use. This is mainly because of the high waste generation 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).

4.1.2 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), 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. Within the chemical engineering 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 had 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 required 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.

4.1.3 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.

The current disposal situation of waste pallets is far from circular and sustainable, as the entire life cycle of pallets has led to significant amount of waste that require proper disposal. A large proportion of plastic, paper and fly ash pallets are still landfilled, accounting for 45.9%, 17.8% and 100% respectively, which poses serious threats to the environment and human health. 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. Landfill can cause leachate contamination of groundwater, methane emissions that contribute to climate change, loss of natural habitats for wildlife, and degradation of land value for nearby communities (Yadav et al., 2020). Moreover, some pallets are openly dumped in the environment, which can cause visual pollution, fire hazards, soil erosion, and harm to animals that ingest or get entangled in them (Zhang et al., 2021). On the other hand, a significant mass of plastic, steel and paper pallet waste was sent for recycling, which shows some progress towards a more circular approach. However, the recycling rate of wooden pallets in China was 44.6% which is significantly lower than that of the US, and recycling losses due to inefficient collection, segregation processes of different materials significantly compromise the potential benefits of recycling, indicating that establishing an effective waste collection system for pallets is vital to avoid the mismanagement of pallet waste. Besides, 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. Therefore, there is an urgent need to establish a closed-loop recycling system for waste pallets in China. This would involve improving the collection and segregation processes, reducing the cross-contamination and losses of recyclable materials, increasing the demand and quality of secondary materials, and developing innovative technologies for material recovery and energy conversion. In addition, a tracking system for pallets can be implemented to avoid their abandonment in the environment and to monitor their use and disposal patterns.

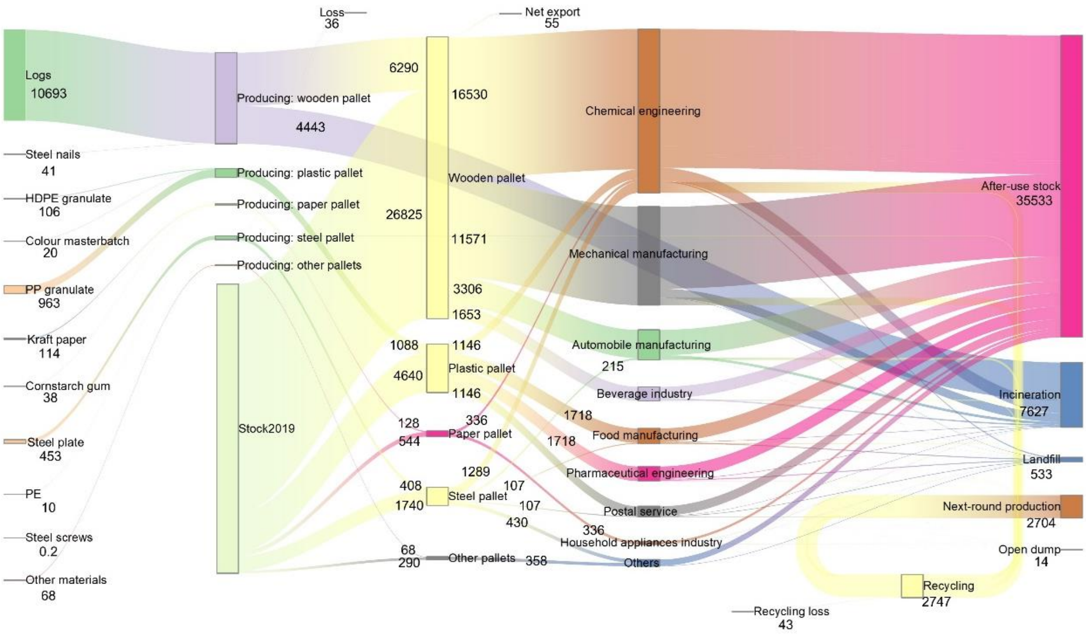


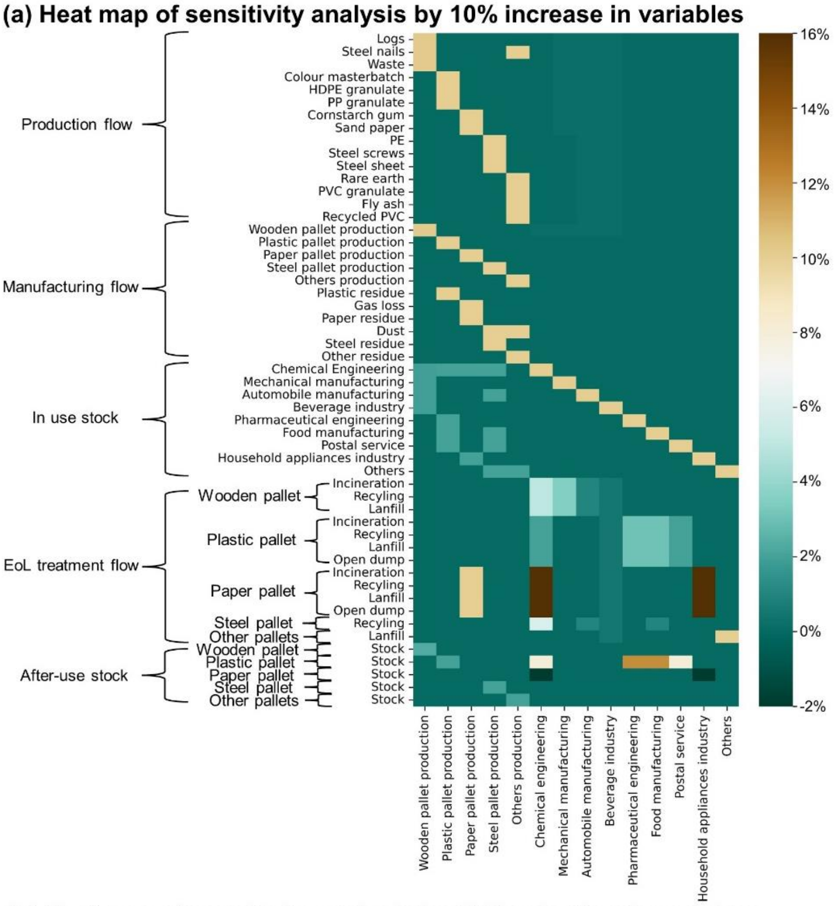
Fig. 20 Pallet flows and stocks in use in China in 2020 (unit: Kt)

4.1.4 Sensitivity analysis

The sensitivity refers to how much a model's outcomes are affected by changes in its parameters or inputs. High sensitivity means small adjustments in a parameter can significantly impact the results, while low sensitivity indicates that changes have minimal effect. Sensitivity analysis is conducted to assess the influence of individual parameter changes on the model's overall output, helping identify the most critical factors.

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. 21a). 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, showing moderate sensitivity to sector fluctuations (Fig. 21b).

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



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

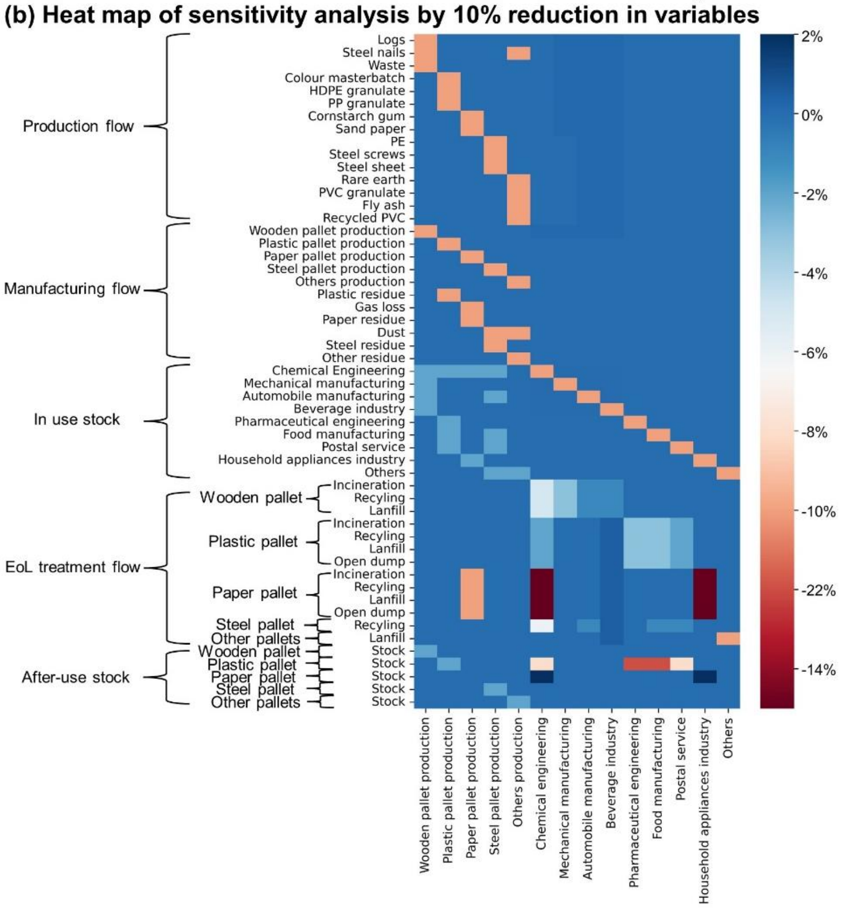


Fig. 21 Sensitivity analysis of the MFA model. The horizontal axis displays the key variables through the pallet life cycle. The vertical axis displays the results of flows and stocks under each change. The colour presents the magnitude of the implications under changes of +10% (a) and -10% (b).

4.1.5 Summary

According to the baseline approach projection by the OECD, there is an anticipated increase in total resource utilisation from 79 Gt in 2011 to 167 Gt by the year 2060 (Ekins et al., 2020). The pallet industry, which facilitates more than 80% of global trade, is also a major consumer of resources and a source of environmental impacts. The evaluation of material consumption and waste generation of China's pallets industry, forms the basis for understanding the current sustainability status and identifying the hotspots for improving the resource efficiency. However, the material flows of pallets in China have been widely overlooked. This section conducts MFA of pallets in China considering the complex interactions among products, sectors, and waste management systems in the entire supply chain. Results show that the pre-consumer waste generated accounts for 36% of the total material inputs, indicating the low efficiency of resource use. In addition, the current disposal practices of waste pallets are far from circular, as significant amount of waste are landfilled or open dumped, causing serious environmental and social consequences.

4.2 Results and discussion on the green transformation framework of the pallet industry in China[3]

The results section is structured into two parts to comprehensively elucidate the environmental implications of pallet logistics under varying scenarios. The initial segment focuses on presenting the environmental impacts of five pallet material types across three scenarios, aiming to assess environmental hotspots and compare environmental effects of different material types in each scenario. Thus, the outcomes in the first part serve as enlightening guidance for making strategic adjustments to the market structure of pallet materials, promoting the adoption of material type with less environmental impact under each scenario. In the second part of the results, a broader perspective is adopted to show the environmental impacts across the entire pallet industry in China under the three scenarios. This part provides a thorough understanding of the potential reduction in environmental impacts within the entire industry, contributing valuable insights for sustainable practices and industry-wide environmental improvements.

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[3] Section 4.2 is largely reproduced from:
Zhang, T., Wen, Z., Tan, Y., Ekins, P., 2024. Circular economy strategies for the booming industrial pallet use in China. *Sustainable Production and Consumption*, 46, 244-255.
Zhang, T., Wen, Z., Fei, F., Kosajan, V., Tan, Y., Xu, M., Ekins, P., 2023. Green transformation strategy of pallet logistics in China based on the life cycle analysis. *Science of The Total Environment*, 903, 166436.

4.2.1 Environmental impact results at product scale under three stages

4.2.1.1 Environmental impacts for five types of pallets under the base case scenario

4.2.1.1.1 Wooden pallet

The production stage of wooden pallets involves the extraction of raw materials and the processing of these materials into pallet components and assembled pallets. This stage has the highest contributions to MD and IR, with 90% and 98% of the total impacts respectively, as shown in Fig. 22 (a). The primary reason is the high demand for metal resources and the associated emissions from mining and smelting activities (Burchart-Korol, 2013). Nails which are used to assemble wooden pallets are one of the major contributors to these impacts, as they require a large amount of steel and zinc. In the steel production process, raw materials such as iron ore, coal, and limestone may contain naturally occurring radioactive nuclides, which can be released into the environment during smelting. This is particularly relevant during sintering and blast furnace ironmaking, where emissions, wastewater, and solid waste may contain elevated levels of radioactive nuclides. The release of these substances poses potential risks to the environment and public health. Solid waste, such as sintering dust and blast furnace sludge, may accumulate higher concentrations of radioactive nuclides and therefore requires careful management. In addition, logs contribute 73% in FEu, as they require the use of chemical fertilisers and pesticides during tree planting, which can cause soil contamination and leaching of nutrients (Zhang et al., 2021). Electricity is consumed in the sawing process, which contributes 70% in FC and 95% in TE in the logs treatment stage. The source of electricity can affect the magnitude of these impacts, according to the fuel mix and the efficiency of power generation.

The use stage of wooden pallets is the most important contributor to most of the environmental impact categories, from 58% in FE to 90% in FD, because of the use of electricity consumed during service life. Electricity is needed for operating pallet handling equipment. The generation of electricity, particularly from fossil fuels, is a major source of resource depletion. Additionally, the toxicity associated with electricity use can stem from thermal pollution due to cooling water discharges from power plants, as well as from spills and leaks during the extraction and transportation of fossil fuels, which can lead to water contamination and disrupt aquatic ecosystems. Transportation in the use phase can cause emissions of GHGs, NO_x and particulate matter, which can affect GWP, POF, FPMF and HT (Weger et al., 2021). Consequently, the use phase of wooden pallets is a critical juncture for environmental impact mitigation strategies, highlighting the need for sustainable energy sources and efficient handling equipment to reduce the environmental effects of pallet usage.

The EoL stage of wooden pallets accounts for 100% negatively to GWP category, because of the avoided impacts from using dismantled board and incinerating waste wood (Alanya-Rosenbaum et al., 2021; Gasol et al., 2008). Dismantled board can be used as a substitute for virgin wood. This can reduce the demand for primary resources and related effects on the environment. Incinerating waste wood can generate heat that can displace fossil fuels and reduce their depletion and emissions (Ng et al., 2014). The EoL stage also involves landfilling of some waste wood that cannot be reused or recycled. Landfilling can cause emissions of methane (Sathre and O’Connor, 2010), which can increase GWP.

4.2.1.1.2 Plastic pallet

The environmental impact analysis of plastic pallets shows that the production stage has the highest impact on most of the categories, except for FEu and POF, where the use stage is more significant. The production stage involves the use of large amounts of materials and energy, such as PP and electricity. The production stage contributes 69% to GWP and 50% to TA (Fig. 22 (b), mainly due to the emissions of GHGs and acidifying substances, such as CO_2 and SO_2, from PP and polyester production. Focusing on the production stage, the main impact is caused by the manufacturing of PP granulates (from 52% in TA to 84% in FD), which makes up 88% of all materials consumed in pallets. PP granulates are the largest contributor (accounting for 73%) to GWP through the extraction and transportation of fossil fuels and the refining and manufacturing processes. The production of these granulates also generates a large amount of plastic waste that can leak into the environment and cause long-term toxicity risks to ecosystems and human health (Rillig, 2012). Moreover, plastic waste that enters the ocean, waterways and natural landscapes poses a long-term toxic threat (Wagner et al., 2014). 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 consumption is another important factor that affects the environmental impacts of plastic pallets, especially in FPMF, where it accounts for 49%. This is mainly due to the emission of primary and secondary aerosols in the generation of electricity from coal (Cho and Strezov, 2020; Weththasinghe et al., 2022). Electricity also contributes 17% to GWP. The direct emissions from the pallet manufacturing plants are relatively low (2%) in POF, but they still release NMHC during the production process.

The use stage of plastic pallets has the highest impact on POF, accounting for 66%. This is because the use stage entails the transportation of goods using trucks that operate on diesel fuel. The combustion of diesel fuel produces a large amount of toxic substances and particulate matter, such as PAHs, heavy metals, and BC (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).

The EoL stage has a negative contribution to nine environmental impact categories, meaning that it reduces the overall environmental burden of plastic pallets. This is because of the energy recovery process that recovers some of the embodied energy in plastic waste and displaces some fossil fuels from the energy mix. Moreover, the recycling process that uses waste plastics to replace virgin materials also reduces the demand for fossil fuels and avoids some emissions from PP production. However, these benefits are limited by the potential emissions from waste open dump, incineration and landfilling. The EoL stage of plastic pallets has the highest impact on FEu, accounting for 87%. The improper disposal of waste plastic pallets can result in leaching or emission of pollutants into water (Harris et al., 2021), soil and air (Allouzi et al., 2021; Chae and An, 2018; MacLeod et al., 2021), such as heavy metals (Cheng et al., 2010), chlorides, sulphates, dioxins and phthalates (Al-Harahsheh et al., 2019; Law and Rochman, 2023). These pollutants can impair water quality and pose risks to aquatic life and human health (Geyer et al., 2017; Reddy et al., 2022).

4.2.1.1.3 Paper pallet

The environmental impact analysis of paper pallets shows that the use stage and the production stage are significant sources of environmental impacts for most categories, while the EoL stage has environmental benefits in most of the impact categories. The use stage involves the operation of forklifts that consume electricity to carry cargo. The use stage contributes the most to seven impact categories, ranging from 70% contributions in FPMF to 86% contributions in POF (Fig. 22 (c)). The main reason for this is the emission of pollutants, such as SO_2, NO_x, NMHC and BC, from electricity generation and consumption. These pollutants can cause acidification, photochemical smog and toxicity risks to ecosystems and human health.

A significant quantity of resources and energy are used during the production stage, such as paper, gum and electricity. The production stage contributes the most to the remaining categories, ranging from 68% positive contributions in FC to 99% positive contributions in FEu. The main reason is the use of pesticides or fertilisers during tree planting in the upstream process of paper production, which leads to an increase in the nutrient load of the water body (Zhang et al., 2021). These pesticides or fertilisers can cause eutrophication and toxicity risks to aquatic ecosystems and human health. The production stage also involves the chemical pulp process, which requires high temperatures and chemicals to dissolve lignin, hemicellulose and cellulose from wood chips, and separate the remaining cellulose fibres from the liquid (Thinkstep, 2021). The manufacturing of kraft paper has high environmental impacts on four air pollution categories, GWP (44%), FPMF (40%), IR (89%) and POF (67%), which is mainly because of the chemical pulp process (Bajpai, 2015). GHG is emitted when mixed wood chips and the pulping chemicals are heated (Thinkstep, 2021). The kraft pulping process requires high temperatures (usually from 165 to 175℃) which adversely affects the GWP (Kuparinen et al., 2019). 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 (Miner and Upton, 2002).

The EoL stage has environmental benefits for most of the environmental impacts, because of the avoided impacts from using recycled pulp and incinerating waste paper for energy recovery. The recycling or incineration process can reduce the demand for virgin materials and energy for new pallet production, as well as the waste and emissions for landfilling and open dump. However, the recycling or incineration process also consumes energy and resources, such as electricity, water and steam. The recycling or incineration process also generates waste and emissions, such as ash, dust and fumes (Liu et al., 2020). These waste and emissions can affect water quality and human health (Villanueva and Wenzel, 2007).

4.2.1.1.4 Steel pallet

The LCA results reveal that the production stage of steel pallets is the most environmentally detrimental, contributing to more than 68% of GWP, 91% in FC, and almost 100% in MD (Fig. 22 (d)). This is because the production stage requires the use of significant amounts of energy, water and raw materials, such as electricity, steel plates and polyethylene. The production stage also emits a large amount of GHGs (Burchart-Korol, 2013; Norgate et al., 2007), and releases radionuclides during the smelting process (Li et al., 2018). For the production stage, steel plate contributes 96% in GWP, since the production processes, such as crushing stage, emits large amounts of 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 plate accounts for 95% in POF result, because of the emission of VOCs during its production process. Steel plate contributes the most to the remaining environmental impact categories (from 77% in FC to almost 100% in MD).

The use stage of steel pallets has the highest impact on POF and HT, accounting for 68% and 63% respectively. This is because the use stage involves the transportation of goods using trucks that run on diesel fuel. The diesel fuel combustion generates a large amount of toxic substances and particulate matter, such as PAHs, heavy metals and BC (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, steel pallets also have some environmental benefits, especially when they are recycled at the EoL cycle. EoL stage brings out environmental benefits (Ayres, 1997), because waste steel pallets and by-products from steel pallets manufacturing process are recycled to make steel plates, which avoids the production of primary steel. Recycling steel pallets can save natural resources, energy, emissions, and landfill space. Recycling steel also reduces the need for mining new iron ore, which can have negative impacts on the environment such as deforestation, soil erosion, water pollution, and biodiversity loss (Norgate and Haque, 2010).

4.2.1.1.5 Fly ash pallet

The results indicate that the production stage of fly ash pallets has the highest impact on resource and energy consumption categories, accounting for almost 100% in FC and MD (Fig. 22 (e)). This is because the production stage involves the use of significant amounts of materials and energy, such as water, adjuvant, PVC, and electricity. The production stage also has a significant impact on GWP and TA, accounting for 50% and 64% respectively. The main contributors to these impacts are the adjuvant (52% in GWP and 74% in TA in the production) and PVC components (48% in FD) in the production stage. The adjuvant is a mixture of rare earth elements that are utilised to improve the strength and durability of the fly ash pallets. However, the extraction and processing of rare earth elements generate a large amount of GHG emissions and acidifying substances, such as CO_2 and SO_2 (Navarro and Zhao, 2014), as well as radioactive and heavy metal emissions in the atmosphere, soil, plants, groundwater, and rivers around mining sites (He et al., 2004), which becomes the main reason for contributing the most to toxicity risk, ranging from 58% in FE to 74% in TE. Besides, 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 (Liang et al., 2014; Thinkstep, 2021) also contributes to these impacts. The PVC is a polymer that is used as a raw material and mixed with the adjuvant to improve the durability and strength of fly ash pallets. However, the production of PVC also emits a large amount of GHGs and other pollutants, such as dioxins and phthalates (Costner et al., 1995).

The use stage of fly ash pallets has the highest impact on FE and POF, accounting for 53% and 67% respectively. This is because the use stage entails the transportation of goods using trucks that operate on diesel fuel. The combustion of diesel fuel generates toxic substances and particulate matter, such as PAH_s, heavy metals, and BC (Ali et al., 2021). These substances can have detrimental effects on terrestrial and aquatic ecosystems and human health (Pope III and Dockery, 2006; Soni et al., 2018).

The EoL stage of fly ash pallets has the highest impact on FEu, accounting for 87%. This is because the EoL stage involves the landfilling of fly ash pallets that are not collected or recycled. The landfilling of fly ash pallets can lead to leaching of pollutants into groundwater and surface water, such as heavy metals, chlorides, sulphates, and organic compounds (Chichester and Landsberger, 1996; Mahajan et al., 2022; Onay and Pohland, 1998). These pollutants can impair water quality and pose risks to aquatic life and human health.

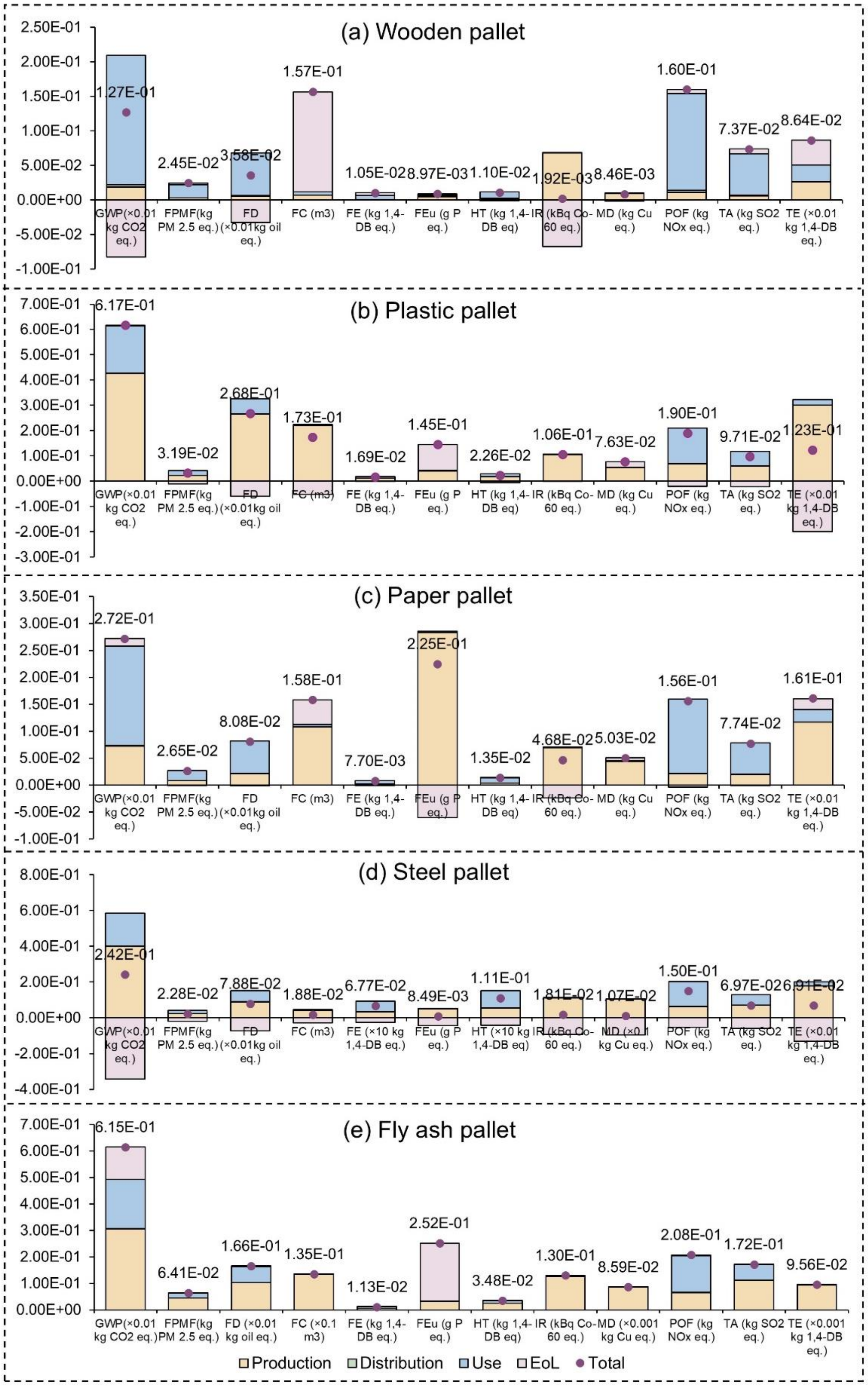

Fig. 22 Environmental impacts of five types of pallets under base case scenario. Some of the results have been scaled to fit within certain parameters, and the real values can be

calculated by applying the corresponding multipliers indicated in brackets. (a) wooden pallet; (b) plastic pallet; (c) paper pallet; (d) steel pallet; (e) fly ash pallet.

4.2.1.1.6 Sensitivity and uncertainty analysis under the base case scenario

This analysis provides further insight into how environmental impacts change as the recycling rate of steel pallets decreases from 100% to 70%, with the remaining fraction being sent to landfill. This adjustment accounts for real-world limitations, such as collection inefficiencies that reduce recyclability. Landfilling remains a common waste disposal method for materials that cannot be economically or technically recycled, and thus, a portion of steel waste may end up in landfills (Wang, P. et al., 2017). The EoL scenario for steel pallets is assumed to involve 100% recycling due to the high economic value of scrap steel and the active role of waste pickers in China, who collect and sell discarded materials to recycling centres. However, to increase the robustness of the results, a sensitivity analysis was conducted by testing lower recycling rates, ranging from 90% to 70%. This approach highlights the potential environmental risks associated with reduced recycling rates.

The results demonstrate that all environmental impact indicators worsen as the recycling rate decreases, reinforcing the critical importance of maintaining high recycling levels. Lowering the recycling rate increases the environmental burden across the studied categories (Fig. 23). In terms of air pollution, GWP, FPMF, IR, and POF show significant increases as the recycling rate decreases. GWP rises from 24.25 kg CO_2 eq. at 100% recycling to 34.62 kg CO_2 eq. at 70% recycling, representing a 42.79% increase. This trend is driven by higher energy consumption and emissions during the landfill processes. FPMF grows by 25.51%, from 0.02 kg $PM_{2.5}$ eq. to 0.03 kg $PM_{2.5}$

eq., reflecting the increase in particulate emissions from waste handling. The most changes are observed in IR, which increases by 156.64%, which can be linked to the increased use of energy sources that involve radioactive materials in waste processing. The relatively smaller rise in POF, increasing from 0.15 kg NO_x eq. to 0.17 kg NO_x eq., suggests that while the POF is impacted, it is less sensitive to the recycling rate in comparison to other air pollution indicators.

For water and soil pollution, FEu and TA demonstrate moderate increases as recycling rates decline. FEu experiences a substantial increase of 159.59%. This sharp rise indicates that landfill processes contribute significantly to nutrient leaching. TA has a more modest rise, from 0.07 kg SO_2 eq. to 0.09 kg SO_2 eq., reflecting an overall increase of 26.47%, suggesting the increased release of acidifying substances into the environment.

In the category of resource and energy consumption, FD rises from 7.88 kg oil eq. to 10.07 kg oil eq., while FC grows by 45.29%, underscoring the increased need for virgin material extraction and water consumption with the decreased recycling rate. MD, however, exhibits the largest increase, jumping by 277.03%, from 0.11 kg Cu eq. to 0.41 kg Cu eq. This rise highlights the significant resource strain caused by reduced recycling rates, as more virgin metals are required to replace those lost to landfill. Toxicity risks also increase, with HT showing a smaller rise of 11.23%. TE, however, increases by 58.86%, and FE by 11.81%, indicating the growing risks to both human and ecological health from increased landfill activities.

Overall, the analysis highlights that reducing the recycling rate of steel pallets from 100% to 70% significantly elevates environmental impacts across all categories. Maintaining high recycling rates is therefore critical to minimising the environmental footprint of steel pallet disposal.

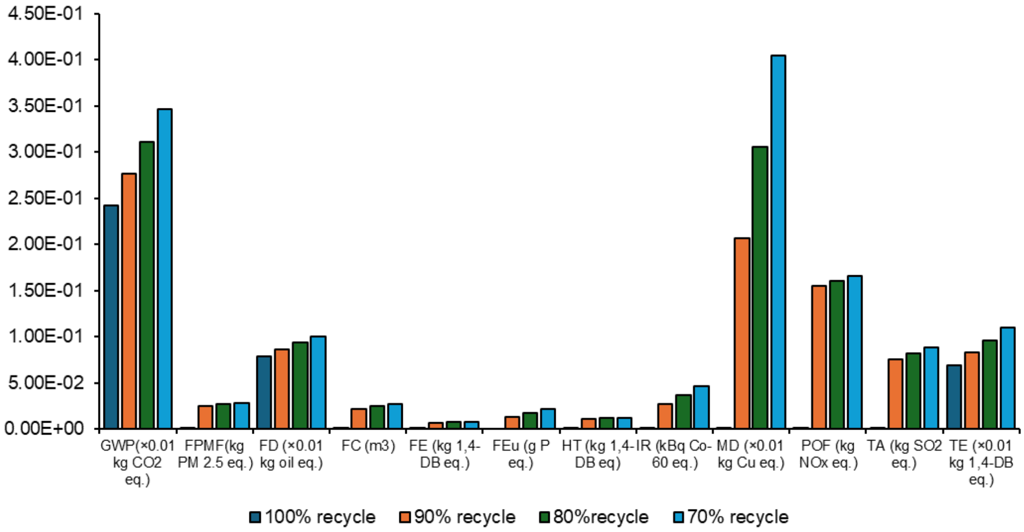

Fig. 23 Sensitivity analysis for the recycling rate assumption of steel pallets

The credibility of the Monte Carlo simulation-derived distributions based on 10,000 sampling values can provide a more comprehensive representation of the actual situation within the pallet industry (Zhao et al., 2019). To be specific, GWP results exhibit distinct profiles across various pallet materials under the base case scenario. Wooden pallets exhibit the lowest GWP (12.67 ± 0.09 kg CO_2 eq.), contrasting with plastic pallets, which register a GWP value of 61.68 ± 2.63 kg CO_2 eq. (mean ± SD). Additionally, steel, paper, and fly ash pallets yield GWP values of 24.25 ± 3.15, 27.21 ± 0.34, and 61.54 ± 1.27 kg CO_2 eq., respectively (Fig. 24). In terms of the FD category, wooden pallets demonstrate the least impact with a result of 3.58 ± 0.03 kg oil eq., followed by steel pallets at 7.88 ± 0.67 kg oil eq. Plastic pallets record the highest FD result (26.77 ± 1.83 kg oil eq.). The TE category reveals values of 6.91 ± 1.27 for steel pallets and 8.64 ± 0.15 kg 1,4-DB eq. for wooden pallets. Sensitivity and uncertainty analysis results for all impact categories can be found in Table C. 4 in Appendix C.

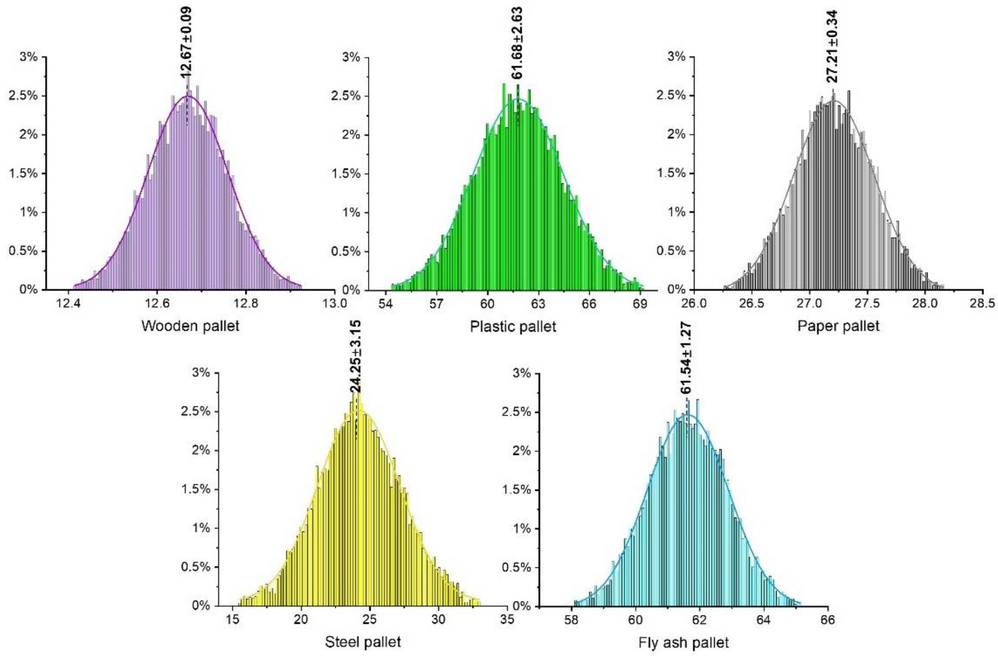

Fig. 24 Uncertainty analysis for five types of pallets under the base case scenario (unit: kg CO_2 eq.)

4.2.1.1.7 Comparison of environmental impacts of base case scenario

The environmental impacts of five different types of pallets—wooden, plastic, paper, steel, and fly ash—across the selected environmental impact categories under the base case scenario have been presented in this section. The analysis reveals significant variations in the environmental impact performance of the different pallet materials, influenced by factors such as the energy requirements of production processes, material composition, and EoL considerations. By examining these impacts in detail, this study provides valuable insights into the environmental trade-offs associated with each pallet type, highlighting opportunities for reducing the environmental burdens in logistics.

Air pollution. GWP results indicate that plastic pallets have the highest impact, contributing 61.68 kg CO_2 eq., primarily due to the reliance on petroleum-based materials that require intensive processing and energy use

(Fig. 25). Fly ash pallets also exhibit high GWP values (61.54 kg CO_2 eq.). This is due to the manufacturing and processing of adjuvants, which requires significant amounts of energy. Despite fly ash being a by-product of coal combustion, the energy required to handle this waste material is substantial. In contrast, wooden pallets have the lowest GWP (12.67 kg CO_2 eq.), attributed to the relatively low-energy processes involved in its production. Paper pallets and steel pallets fall between these extremes, with moderate GWP values (27.22 kg CO_2 eq. and 24.24 kg CO_2 eq., respectively), reflecting the intermediate energy requirements for paper pallets, and the highest carrying capacity of steel pallets.

In terms of FPMF, fly ash pallets also have the highest contribution (0.06 kg $PM_{2.5}$ eq.), as the handling of ash can release particulates, contributing to air quality degradation. Plastic and paper pallets follow closely (0.03 kg $PM_{2.5}$ eq.) due to emissions associated with fossil fuel-based production processes. Wooden pallets exhibit relatively lower FPMF values (0.02 kg $PM_{2.5}$ eq.), as their production processes are less dependent on fossil fuels and particulate-emitting activities. For IR, fly ash pallets are again the most impactful (0.13 kBq Co-60 eq.), mainly because fly ash often contains trace amounts of radionuclides from coal combustion. The release of these radionuclides during the lifecycle of the pallets contributes to IR. In comparison, wooden pallets have minimal IR contributions, as their natural, organic origin avoids the inclusion of radioactive substances. POF follows a similar trend. Fly ash pallets have the highest value (0.21 kg NO_x eq.), driven by the release of NO_x during the handling of ash and the energy required for its treatment. Plastic pallets show a comparable result (0.19 kg NO_x eq.), as the burning of fossil fuels in plastic production releases NO_x gases that contribute to ozone formation. Wooden pallets have a relatively low contribution to POF (0.16 kg NO_x eq.), reflecting the lower emissions associated with the use of renewable materials.

Water pollution. FEu is highest for fly ash pallets, as the disposal and treatment of fly ash can result in the release of phosphorus and other nutrients that leach into water systems, which can cause excessive growth of algae in freshwater ecosystems, contributing to eutrophication. Paper pallets also exhibit notable EP, as paper processing involves chemical pulp process, that can result in nutrient runoff. Plastic pallets show a moderate value, largely due to the additives and chemicals used in plastic production that can leach into water bodies.

Soil pollution. For TA, fly ash pallets again rank the highest (0.17 kg SO_2 eq.), because of sulfur oxides released during coal combustion. The sulfur content in the fly ash itself can also exacerbate this issue if not properly managed. Plastic pallets follow with a higher TA value (0.10 kg SO_2 eq.), as the combustion of fossil fuels during plastic production releases significant amounts of sulfur oxides. Wooden pallets and paper pallets show similar, lower impacts (0.07 kg SO_2 eq. and 0.08 kg SO_2 eq., respectively), as their production processes emit fewer acidifying compounds.

Resource and energy consumption. FC is particularly high for fly ash pallets (1.35 m^3), reflecting the significant water use in fly ash handling and treatment processes. Plastic pallets also have high FC (0.17 m^3), driven by the water demands of polymer production and cooling processes. Paper and wooden pallets have similar FC results (0.16 m^3) due to the relatively low water requirements in their production processes compared to other types of pallets. FD is highest for plastic pallets (26.77 kg oil eq.) and fly ash pallets (16.61 kg oil eq.), because fly ash treatment and plastic production are both energy-intensive and rely heavily on fossil fuels. In contrast, wooden pallets have the lowest FD impact (3.58 kg oil eq.) due to the renewable nature of wood and the lower energy demands of its production. MD shows the highest impact for fly ash pallets (85.93 kg Cu eq.) due to the presence of metals in fly ash and the industrial processes required for ash treatment. Steel pallets also have a high MD value (0.11 kg Cu eq.) due to the extraction and use of metals in their production. Wooden pallets, by comparison, have minimal MD impacts (0.01 kg Cu eq.) because of the low metal inputs during their lifecycle.

Toxicity risks. HT is highest for fly ash pallets (0.03 kg 1,4-DB eq.) due to the presence of toxic elements, such as heavy metals, in fly ash. These substances pose significant risks to human health if not properly managed. Plastic pallets also show high HT (0.02 kg 1,4-DB eq.), largely due to the chemical additives used in plastic production that can leach into the environment. Wooden pallets, with the lowest HT value (0.01 kg 1,4-DB eq.), are less harmful, as their natural composition results in fewer toxic byproducts during their lifecycle. TE is significantly higher for fly ash pallets (95.63 kg 1,4-DB eq.), as the toxic components of fly ash can leach into soil, affecting terrestrial ecosystems. Plastic pallets also pose a risk in this category (12.27 kg 1,4-DB eq.), due to the potential leaching of microplastics and chemicals into the environment. FE is highest for plastic pallets (0.02 kg 1,4-DB eq.) due to the potential leaching of harmful chemicals and microplastics into water systems. Fly ash pallets also have a notable impact (0.01 kg 1,4-DB eq.), as toxic elements from the ash can enter water systems through runoff. Wooden pallets have much lower FE impacts, indicating that their materials are less possible to cause harm in aquatic ecosystems.

Overall, fly ash pallets exhibit the highest environmental impacts across nine of the assessed categories, particularly in air pollution and toxicity risks. This is primarily due to the energy-intensive production processes and the hazardous substances associated with fly ash. The extraction and processing of the adjuvants used in fly ash pallets lead to significant GHG emissions, acidifying substances, as well as the release of heavy metals and radioactive emissions, all of which pose environmental risks. Plastic pallets also show substantial environmental burdens, especially in air pollution, resource and energy consumption categories. Plastic pallets also have a low recycling rate (25%) and are often disposed of in landfills (accounting for 45.9%) or open dumps (1.6%) which generates GHG emissions and toxic substances. In contrast, wooden pallets consistently demonstrate lower impacts across ten categories, owing to the renewable nature of the material and its relatively low resource and energy demands. Wooden pallets are made mainly from natural materials that require less processing than other materials. Moreover, wooden pallets have a high recycling rate (44.6%) and can be reused or converted into dismantled boards or wood shavings. Additionally, wooden pallets achieve a high energy recovery rate at the EoL stage, with 53.4% being converted into biofuel. Steel pallets have a high impact in the production stage, due to the high energy use and emissions associated with steel making. However, steel pallets also have a high recycling rate and can be recovered and remelted at the EoL stage, which creates environmental benefits that offset some of the impact from the production stage. Paper pallets have a low carrying capacity, which limits their applicability. Moreover, the energy recovery rate of paper pallets is only 29.3%, while 17.8% of the paper waste ends up in landfills, which increases their impact in the EoL stage.

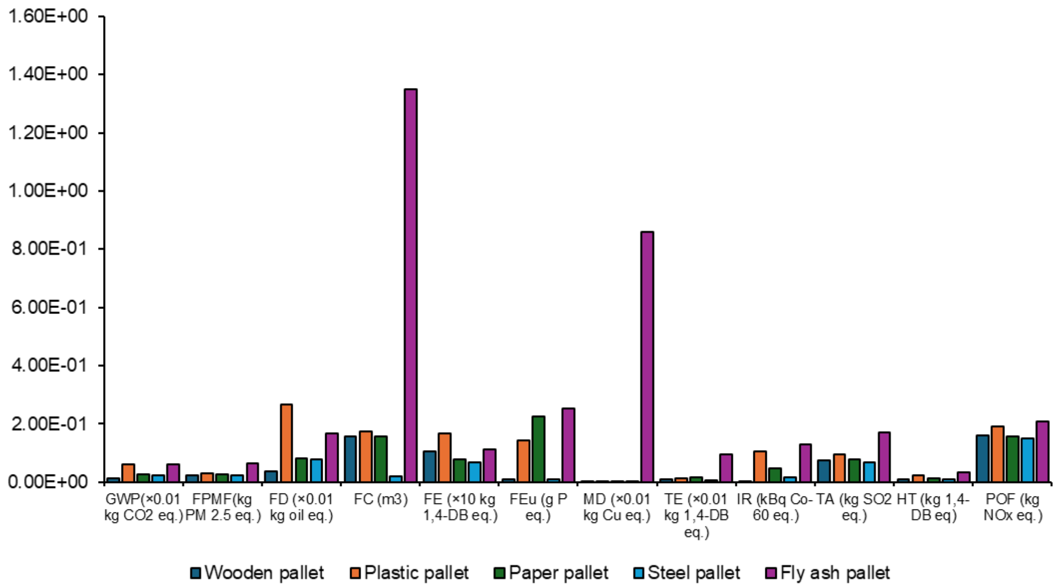

Fig. 25 Environmental impacts comparison for each type of pallet under base case scenario. Some of the results have been scaled to fit within certain parameters, and the real values can be calculated by applying the corresponding multipliers indicated in brackets.

4.2.1.1.8 Summary

This section provides a comprehensive analysis of the environmental impacts of five types of pallets—wooden, plastic, paper, steel, and fly ash—under the base case scenario. The results reveal that fly ash pallets have the highest results across nine categories, particularly in air pollution and toxicity risks, due to energy-intensive processes and hazardous materials. Plastic pallets also exhibit substantial environmental burdens, especially in air pollution, resource and energy consumption categories. Wooden pallets consistently demonstrate the lowest impacts, attributed to their renewable materials, low resource demands, and high recycling rates. Steel pallets show a balanced profile, with moderate impacts during production but significant recycling benefits at the end of life. Paper pallets perform moderately but are hindered by limited carrying capacity and a lower energy recovery rate, which increases their EoL impact. Overall, the analysis highlights the environmental trade-offs among different pallet types, with significant variations in environmental impact performance.

4.2.1.2 Environmental impacts under the sharing system scenario

4.2.1.2.1 Wooden pallet

The LCA results show that the use stage is the most dominant stage in terms of environmental impacts, accounting for the majority of the impacts on water pollution and toxicity risk categories, such as HT, FE and TE (Fig. 26 (a)). The use stage accounts for 57% of TE, 60% of FE and 84% of HT due to the additional resource and energy input for repairing wooden pallets. The production stage of wooden pallets in a sharing system accounts for 65% of IR, which is the highest among all stages. This is because the production stage involves the extraction and processing of nails, which require metal resources and emit radioactive substances. Nails are made of steel and zinc, which have high radiotoxicity potentials. The production stage also consumes water and causes eutrophication in freshwater bodies due to the application of chemicals during tree planting. The EoL stage of wooden pallets in a sharing system creates environmental benefits because of the avoidance of virgin material inputs and the recovery of energy. The EoL stage accounts for 100% negatively of GWP, because the EoL stage involves the recycling and incineration of waste wood for energy recovery, which can displace primary wood and fossil fuels. Recycling can save resources and reduce emissions from material production. Incineration can generate heat that can replace natural gas. The EoL stage also involves landfilling of some waste wood that cannot be reused or recycled. Landfilling can cause methane emissions, which increase GWP.

4.2.1.2.2 Plastic pallet

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. 26 (b)). The main reason for this is the extraction and processing of fossil fuels that are used as raw materials and energy sources for plastic pallet production.

The use stage is the most significant source of FPMF (51%), POF (67%) and TA (54%). The main reason for this is the emission of pollutants, such as SO_2, NO_x, NMHC, PAHs, heavy metals and BC, from diesel combustion and electricity generation (Sha et al., 2019). These pollutants can cause acidification, photochemical smog and toxicity risks to ecosystems and human health (Ali et al., 2021). For example, SO_2 and NO_x are the main acidifying substances that contribute to TA, which measures the potential impact of acidifying substances on soil and vegetation. NMHC and NO_x are the main precursors of ozone that contribute to POF, which measures the potential impact of ozone on human health and crops.

The improper management of plastic waste also poses a long-term threat to the environment (Barnes et al., 2009; Pinheiro et al., 2023), as landfilled plastics harm the ecosystem by decomposing into toxic substances that are absorbed by plants (Chae and An, 2018), or by leaching into microplastics that can persist for hundreds of years and accumulated in the food web (Galloway et al., 2017; Haward, 2018; Ivleva et al., 2017; Vanapalli et al., 2019). Plastic waste can also release toxic substances into water, soil and air, such as dioxins and phthalates (Lamb et al., 2018), posing risks to aquatic life and human health (Kamaruddin et al., 2017; Saikia and De Brito, 2012). However, EoL stage decreases the results of most environmental impacts, due to credits associated with energy recovery process and using waste plastics to replace virgin materials.

4.2.1.2.3 Paper pallet

The LCA results show that the use stage is the most significant source of environmental impacts for most categories, since the use stage entails the transportation of goods using trucks that operate on diesel fuel and the use of forklifts that require electricity. The use stage provides four services in the life cycle of paper pallets, which increases the electricity use. The use stage contributes to the highest proportion of the impacts on air pollution categories, ranging from 68% positive contribution for GWP to 87% for POF, except for IR (Fig. 26 (c)). The main reason for this is the emission of GHGs and other pollutants, such as CO_2, SO_2, NMHC and BC, from diesel combustion and electricity generation. These pollutants can lead to global warming, soil and water acidification, ozone formation and toxic impacts on the environment and human health (Ali et al., 2021; Pope III and Dockery, 2006; Soni et al., 2018; Weththasinghe et al., 2022).

The other environmental impacts are mainly in the production stage, which accounts for 99% positive contribution in FEu and 98% in IR. The main reason for this is the use of pesticides or fertilisers during tree planting in the upstream process of paper production, which leads to an increase in the nutrient load of the water body (Zhang et al., 2021). These pesticides or fertilisers can cause eutrophication and toxicity risks to aquatic ecosystems and human health. The production stage also involves the chemical pulp process, which requires high temperatures and chemicals to dissolve lignin, hemicellulose and cellulose from wood chips, and separate the remaining cellulose fibres from the liquid (Thinkstep, 2021). The chemical pulp process has high environmental impacts on IR, which measures the potential effect of radioactive substances on human health and ecosystems. The main reason for this is the emission of radioactive substances from heating and chemical reactions. These radioactive substances can cause IR and genetic damage.

4.2.1.2.4 Steel pallet

The LCA results reveal that the production stage is the dominant contributor to the environmental impacts of the steel pallets throughout their life cycle when they are implemented in a sharing system. The production process of steel pallets has the most significant impact on GWP (64%) and MD (almost 100%), because of the high energy use and emissions associated with steel making (Fig. 26 (d)). The consumption of steel plates requires the mining of iron ore, which is the main ingredient in the production of steel. The mining of iron ore is highly energy-intensive and causes air pollution in the form of NO_x, CO_2, CO, and SO_2 (Muller et al., 2014). Acid leakage from mines and heavy metal contamination of water are additional effects of iron ore mining. Acid drainage may persist for millennia following the cessation of mining operations (Kim and Worrell, 2002). The consumption of steel plates also requires the manufacturing of steel, a process renowned for its high energy consumption and significant CO_2 emissions, making it one of the most environmentally impactful industrial activities globally (Mathiesen and Mæstad, 2004; Wang, K. et al., 2007). Steel production requires significant amounts of coke which poses severe environmental harm. Air pollution from coke ovens, such as naphthalene, is highly carcinogenic and poses a serious health risk (Zeng et al., 2009). The coking process also generates wastewater that is extremely toxic and contains various organic compounds that can cause cancer, as well as cyanide, sulfides, ammonium and ammonia (Jing et al., 2014).

The steel pallets provide 100 services in their life cycle, which significantly increases the electricity consumption for forklifts. The electricity consumption for forklifts contributes to the GHG emissions and FD, while the transportation for trucks contributes to the air pollution and HT potential. However, the EoL stage brings out environmental benefits, because waste steel pallets and by-products from steel pallets manufacturing process are recycled to make steel plates, which avoids the production of primary steel.

4.2.1.2.5 Fly ash pallet

The LCA results show that when the fly ash pallets are established in a sharing system, the main environmental effects of the pallets throughout their life cycle are in the use stage. This is because the pallets provide 15 services in their life cycle, which greatly increases the electricity consumption for forklifts. The use stage accounts for 67% in POF and 35% in TA (Fig. 26 (e)). The reason for this is that the electricity consumption contributes to GHG emissions and ozone depletion, while the transportation emissions contribute to acidifying substances and particulate matter, such as SO_2, NO_x and BC (Ali et al., 2021; Soni et al., 2018). The production stage contributes the most to resource and energy categories, which accounts for almost 100% in MD, 99% in FC and 61% in FD. The reason for this is that the production stage involves material inputs such as PVC and water, as well as energy inputs such as electricity. The electricity generation relies on fossil fuels such as coal, which deplete non-renewable resources and emit GHGs.

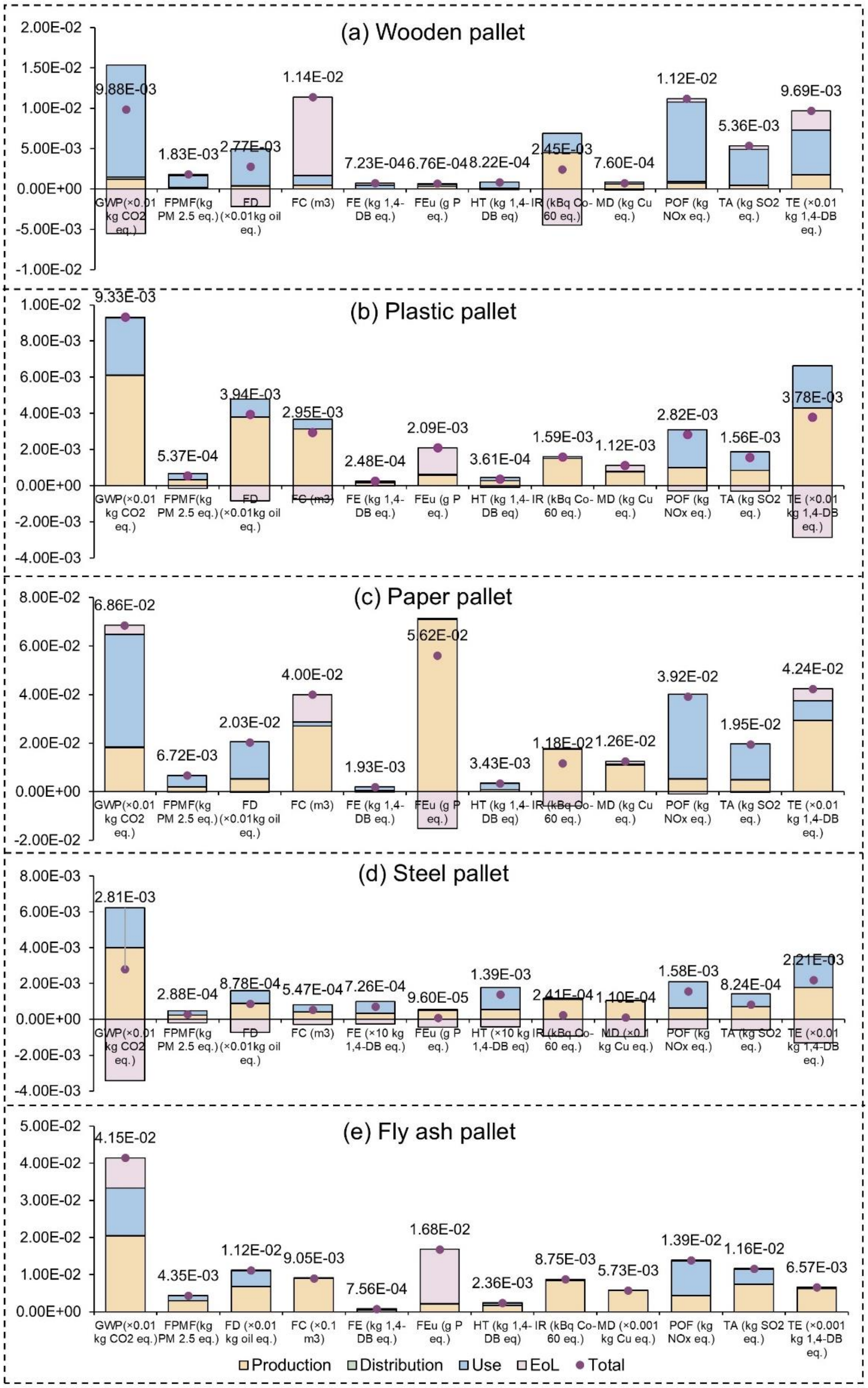

Fig. 26 Environmental impacts of five types of pallets under sharing system scenario. Some of the results have been scaled to fit within certain parameters, and the real values

can be calculated by applying the corresponding multipliers indicated in brackets. (a) wooden pallet; (b) plastic pallet; (c) paper pallet; (d) steel pallet; (e) fly ash pallet.

4.2.1.2.6 Sensitivity and uncertainty analysis under the sharing system scenario

Through changing RSL of wooden pallets from 5 trips to 25 trips, air pollution categories can be reduced from 78% in GWP (Fig. 27 (a)), FPMF, FD to 80% in FE and POF. FEu result has a variance of 79%. The increase in service life (from 40 to 120 trips) has the greatest effect on GWP results, about 64% variance for plastic pallets. The environmental impacts have been reduced through increasing RSL for plastic pallets (Fig. 27 (b)). 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. 27 (c)). 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. 27 (d)). MD is the most sensitive to service life, having 79% output variance. FC and TE are not sensitive to the life times. The increasing service life of fly ash pallets leads to the decreased environmental impacts. GWP has been decreased by 80% through prolonging its service life (Fig. 27 (e)). The findings indicate a negative correlation between the number of RSL and the overall environmental effects, which is consistent with Weththasinghe et al. (2022). Results of sensitivity analysis for all impact categories can be found in Fig. C. 1 and Table C. 3 in Appendix C.

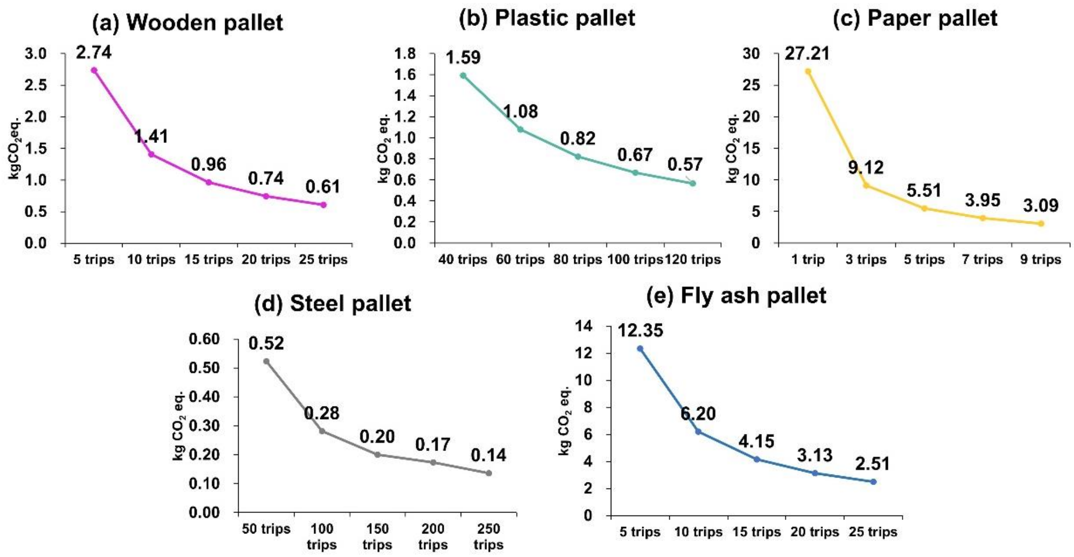

Fig. 27 Sensitivity analysis for each type of pallet. (a) sensitivity analysis for wooden pallets; (b) sensitivity analysis for plastic pallets; (c) sensitivity analysis for paper pallets; (d) sensitivity analysis for steel pallets; (e) sensitivity analysis for fly ash pallets.

Steel pallets display the smallest GWP result (0.28 ± 0.03 kg CO_2 eq.), while paper pallets achieve the value of 6.86 ± 0.09 kg CO_2 eq. (mean ± SD). Wooden pallets, plastic pallets and fly ash pallets have the GWP result of 0.99 ± 0.01, 0.93 ± 0.04 and 4.15 ± 0.08 kg CO_2 eq. respectively (Fig. 28). Regarding FD category, steel pallets have the smallest result of 0.09 ± 0.01 kg oil eq. and paper pallets have the highest result (2.03 ± 0.03 kg oil eq.). Fly ash pallets have 6.57 ± 0.29 and steel pallet has 0.22 ± 0.01 for TE. Results of uncertainty analysis for all impact categories can be found in Table C. 4 in Appendix C.

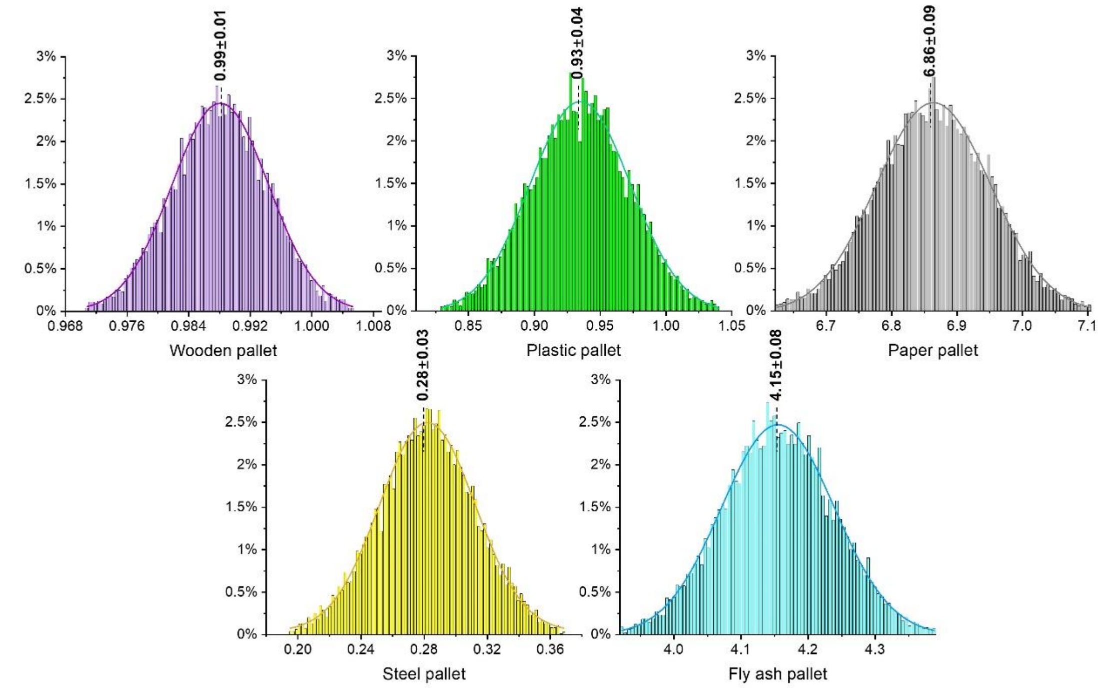

Fig. 28 Uncertainty analysis for five types of pallets under the sharing system scenario (unit: kg CO_2 eq.)

4.2.1.2.7 Comparison of environmental impacts of sharing system scenario

This section analyses the environmental impacts of five types of pallets—wooden, plastic, paper, steel, and fly ash—under a sharing system scenario, where pallets are reused multiple times. It explores the specific environmental effects of each pallet type, examining how different materials and their reuse contribute to overall environmental impacts, while highlighting the advantages and trade-offs associated with each pallet system.

Air pollution. In the sharing system scenario, wooden pallets exhibit relatively low environmental impacts in the air pollution category, with a GWP of 0.99 kg CO_2 eq., which is similar to the plastic pallets (0.93 kg CO_2 eq.). This reduction in global warming potential can be attributed to the reuse of pallets, which reduces the need for new production and, consequently, lowers emissions. However, paper pallets show a much higher GWP (6.86 kg CO_2 eq.), due to the lower reuse efficiency and carrying capacity. Similarly, fly ash pallets exhibit significant emissions (4.15 kg CO_2 eq.) in this category (Fig. 29), stemming from the manufacturing and processing of adjuvants, which requires significant amounts of energy and the relatively low reuse times. Steel pallets, with the lowest GWP (0.28 kg CO_2 eq.), benefit from efficient recyclability and the highest carrying capacity and reuse times.

For FPMF, wooden pallets and steel pallets perform better than others, with values of 0.0018 kg $PM_{2.5}$ eq. and 0.0003 kg $PM_{2.5}$ eq., respectively. The reuse of wooden pallets reduces emissions from forestry and material processing. Plastic pallets perform moderately in this category, showing lower emissions (0.0005 kg $PM_{2.5}$ eq.) than paper pallets due to the relatively higher carrying capacity and reuse times. IR, which accounts for the release of radionuclides into the environment, is particularly relevant for fly ash pallets (0.01 kBq Co-60 eq.), which shows the highest value due to the handling of industrial waste, such as fly ash, which contains radioactive elements. The POF category measures the potential to form ground-level ozone, which can result in smog and respiratory health issues. Paper pallets have the highest impact in this category (0.04 kg NO_x eq.), stemming from the emissions of VOCs and NO_x during the production, including chemical pulping process, and transport of paper pallets.

Water and soil pollution. Paper pallets show the highest FEu potential (0.06 g P eq.), mainly due to the chemical treatments required in paper production. Fly ash pallets also have higher value in this category (0.02 g P eq.), due to the runoff of toxic materials and chemicals from the fly ash, which can contaminate water systems. TA is highest for paper pallets (0.02 kg SO_2 eq.) due to the sulfur emissions involved in paper manufacturing processes, such as pulping and bleaching. Fly ash pallets also show a significant impact in this category (0.01 kg SO_2 eq.), due to the by-products of burning coal and industrial waste, which contribute to acidification. By contrast, wooden pallets and plastic pallets have lower TA impacts, with values of 0.01 kg SO_2 eq. and 0.002 kg SO_2 eq., respectively. The relatively lower emissions from the renewable material of wooden pallets and the relatively higher reuse times of plastic pallets help reduce acidifying emissions. Steel pallets again perform the best in this category (0.001 kg SO_2 eq.), benefiting from the reuse stage and the efficient recycling processes.

Resource and energy consumption. Wooden pallets exhibit a lower FD value (0.28 kg oil eq.), as their material is largely renewable. Similarly, steel pallets have the lowest FD value (0.09 kg oil eq.), as they can be recycled and reused multiple times with minimal additional resource input. Plastic pallets, though also reused, have a higher FD (0.39 kg oil eq.) due to the petroleum-based materials used in production, though they still perform better than paper pallets (2.03 kg oil eq.) and fly ash pallets (1.12 kg oil eq.). The high FD of paper and fly ash pallets can be attributed to their low reuse capacity. Steel pallets show particularly low FC (0.0005 m^3) and MD (0.001 kg Cu eq.) results, largely due to their high load-bearing capacity and extensive reuse potential. Steel pallets have the longest lifespan with the highest number of reuse cycles, which significantly reduces their overall energy and resource consumption per FU. Although the initial production of steel is resource-intensive, the ability to reuse and recycle steel pallets offsets much of their environmental burden over time. In contrast, paper pallets exhibit the highest impacts in both FC (0.04 m^3) and MD (0.01 kg Cu eq.), owing to their lowest carrying capacity and shortest lifespan, which limits their reuse potential. Paper pallets often need to be replaced more frequently, requiring greater raw material input and water for manufacturing, which amplifies their environmental impacts.

Toxicity risks. Results of HT, FE and TE show that paper pallets and fly ash pallets exhibit the highest impacts. Fly ash pallets have the highest TE value (6.57 kg 1,4-DB eq.), stemming from the hazardous substances generated during the production and treatment of fly ash. Paper pallets follow with a TE of 4.24 kg 1,4-DB eq., due to the chemical pulping processes involved. Wooden pallets, plastic pallets, and steel pallets exhibit much lower TE values as the reuse processes reduce the release of toxic substances for new product manufacturing. Paper pallets also show significant HT impacts (0.003 kg 1,4-DB eq.) due to the chemical treatments used in the paper production process.

Overall, paper pallets exhibit the highest environmental impacts across nine of the assessed categories, particularly in air pollution and water pollution categories. This is primarily due to their short RSL of four trips, which results in higher material consumption throughout their life cycle. Additionally, 17.8% of paper pallet waste ends up in landfills, where it contributes to GHG emissions and the release of toxic substances, further exacerbating their environmental impacts. Fly ash pallets have the highest results in three environmental impact categories, due to their low durability and landfill disposal method, which increases their impact. In contrast, steel pallets consistently demonstrate the lowest impacts across 11 categories. The main reason for the superior performance of steel pallets is the highest load carrying capacity (two tonnes) and the longest life span (100 trips), which largely reduces environmental impacts based on the FU, demonstrating that the life span and carrying capacity are negatively related to environmental effects (Weththasinghe et al., 2022). Steel pallets also have a high recycling rate, and materials can be recovered at the EoL stage, which creates environmental benefits that offset some of the impact of the energy-intensive production stage. The production stage however, remains the most impactful for steel pallets due to the energy demands and emissions associated with steel manufacturing.

The LCA results provide useful information for evaluating the environmental performance of pallets in China. The resource and energy consumption in the production stage is high, which has significant impacts on resource depletion and water consumption. To reduce these impacts, it is recommended to use alternative materials with lower environmental impacts, such as recycled materials, and to use renewable energy sources for electricity generation and consumption. Moreover, the toxicity and particulate matter emissions are extensive in the use stage, which are mainly caused by the transportation of goods using trucks that run on diesel fuel. These emissions have significant impacts on air pollution, human health and ecosystem quality. To reduce these impacts, it is recommended to optimise the transportation distance and mode to reduce emissions (Sacchi et al., 2021). Besides, the landfilling of pallets at the EoL stage can cause leaching of pollutants into groundwater and surface water, such as heavy metals, chlorides, sulphates and organic compounds. These pollutants have significant impacts on water pollution, human health and ecosystem quality. To reduce these impacts, it is recommended to implement recycling options for pallets at the EoL stage, such as recovering the materials for new pallet production or other applications, or incinerating for energy recovery. Therefore, establishing sharing system is not adequate, CE strategies are required in the pallet industry.

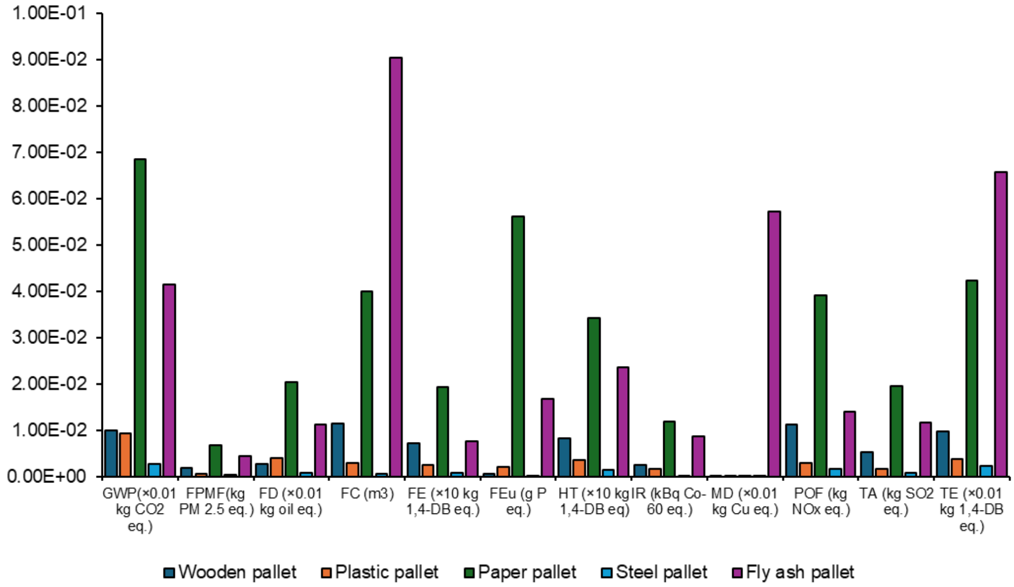

Fig. 29 Environmental impacts comparison for each type of pallet under the sharing system scenario. Some of the results have been scaled to fit within certain parameters, and the real values can be calculated by applying the corresponding multipliers indicated in brackets.

4.2.1.2.8 Summary

This section presents the environmental impact results of five types of pallets—wooden, plastic, paper, steel, and fly ash—under the sharing system scenario, which assumes the pallets are shared among different users and reused over multiple trips. The findings highlight that paper pallets exhibit the highest environmental impacts in most categories, particularly in air and water pollution, due to their shortest RSL and lowest carrying capacity. Steel pallets show the lowest impacts across nearly all categories, primarily because of their high load-carrying capacity and long lifespan, which significantly reduce the environmental burdens per FU. Fly ash pallets also demonstrate notable impacts, especially in toxicity and resource consumption, due to their relatively low durability and EoL disposal practices. Overall, the sharing system amplifies the advantages of more durable pallets with higher reuse potential, particularly steel pallets, while less durable options, such as paper and fly ash perform poorly across multiple impact categories.

4.2.1.3 Environmental impacts under the CE scenario

This section will first explore the environmental impacts of different EoL treatment methods for each type of pallet, including wooden, plastic, paper, steel, and fly ash pallets. By analysing the results from various disposal scenarios such as recycling and incineration, a comprehensive combination of CE strategies will be developed, which will form the basis for building the CE scenario.

4.2.1.3.1 Scenario analysis for waste management methods

4.2.1.3.1.1 Wooden pallet

The LCA results for wooden pallets under three disposal scenarios—base case, incineration, and recycling—reveal distinct environmental impacts across various categories. The incineration scenario shows the lowest GWP, at -10.34 kg CO_2 eq., due to the system credits for wood incineration (Fig. 30 (a)). The recycling scenario shows the GWP of -4.93 kg CO_2 eq. due to credits from avoiding the extraction and processing of virgin wood. For FPMF, the recycling scenario demonstrates the lowest value at 0.0002 kg $PM_{2.5}$ eq., compared to 0.002 kg $PM_{2.5}$ eq. in the base case and 0.004 kg $PM_{2.5}$ eq. in the incineration scenario. The process of making waste wood into biomass fuel and the combustion of wood fuel introduces higher levels of particulate matter, reflecting emissions from the combustion of waste wood, despite the benefits of energy recovery (García-Durañona et al., 2016).

TA also decreases in the recycling scenario, from 0.01 SO_2 eq. in the base case to 0.001 kg SO_2 eq. Recycling avoids emissions of acidifying substances by diverting waste from landfills and combustion facilities, whereas incineration introduces higher levels of these emissions due to the combustion process. FD decreases from -3.24 kg oil eq. in the base case to -4.01 kg oil eq. in incineration scenario, while FC decreases from 0.15 m^3 to 0.08 m^3 in recycling scenario. Recycling minimises nutrient release, because of the avoidance of virgin material which is reflected by the lowest FEu result in recycling scenario. TE is highest in the incineration scenario at 4.83 kg 1,4-DB eq. but decreases to 1.60 kg 1,4-DB eq. in recycling. The higher TE in the incineration scenario can be attributed to the environmental burdens of waste combustion, whereas recycling mitigates toxic emissions by diverting materials away from incineration and landfill.

Overall, recycling scenario has lower impact than incineration scenario across nine categories, driven by the environmental credits from avoiding the use of virgin wood. In contrast, incineration offers lower impacts in categories, including GWP, FD and IR, considering the recovery of energy through energy generation.

4.2.1.3.1.2 Plastic pallet

The environmental impacts of plastic pallets under the incineration for energy recovery and recycling scenarios reveal significant differences across various impact categories. The recycling of plastic pallets has the lowest results in four environmental impact categories (GWP, FD, FE and MD) due to the system credits for plastics recycling. The incineration scenario has the lowest results in eight impact categories. This comparison provides insights into the potential environmental benefits and drawbacks associated with these two treatment methods.

The GWP of the recycling scenario stands at -11.5 kg CO_2 eq., indicating a substantial reduction in carbon emissions due to avoided production of virgin plastics, which outweighs the environmental burdens caused by the process associated with the production of secondary plastic pellets from waste plastic pallets (Fig. 30 (b)). The negative GWP in recycling reflects the benefits of recovering material and avoiding the emissions associated with producing new plastics, while incineration releases GHGs during the combustion process, even though some energy is recovered. The incineration scenario has a positive GWP of 11.3 kg CO_2 eq.. In contrast, FPMF shows a much lower impact in the incineration scenario (-0.017 kg $PM_{2.5}$ eq.) compared to recycling (-0.003kg $PM_{2.5}$ eq.).

For TA, the recycling scenario presents a moderate benefit (-0.01 kg SO_2 eq.), while incineration leads to a significant decrease (-0.03 kg SO_2 eq.), due to the system credits for plastics incineration. Resource and energy consumption, represented by FD, FC and MD, shows significant improvements in the recycling scenario. FD in recycling is -9.85 kg oil eq., which is much lower than incineration (-2.35 kg oil eq.), indicating that recycling avoids the extraction of fossil fuels used in the production of virgin plastics. MD also reflects a clear benefit from recycling (0.02 kg Cu eq.), as it reduces the demand for raw materials, whereas incineration requires additional inputs for combustion process. FC has a different pattern, with incineration resulting in a lower impact (-0.06 m^3) compared to recycling (-0.05 m^3). Incineration scenario has lower environmental impacts in HT and TE than recycling scenario. HT shows a reduction in incineration (-0.008 kg 1,4-DB eq.) compared to base case scenario (-0.006 kg 1,4-DB eq.), indicating lower exposure to toxic chemicals. TE also decreases from -19.98 to -43.08 kg 1,4-DB eq. in incineration.

4.2.1.3.1.3 Paper pallet

The environmental impacts of paper pallets under incineration for energy recovery and recycling show diverse outcomes across different categories.

Incineration scenario has lower environmental impacts than the recycling scenario for five impact categories. Recycling, on the other hand, is more advantageous in terms of reducing impact categories, such as FPMF, FEu, MD, etc., because it avoids the need for virgin materials and reduces the release of harmful pollutants into the environment.

The incineration for energy recovery scenario shows a significant reduction in GWP (-2.09 kg CO_2 eq.), making it more environmentally favourable compared to recycling (0.44 kg CO_2 eq.). This negative GWP in recovery is due to the energy produced during incineration, which offsets the need for energy from fossil fuels, leading to a net reduction in GHG emissions. Recycling, while still better than the base case scenario, does not offer as substantial a GWP reduction because of the energy required to process and reconstitute the paper into new products. Therefore, the improvement of low carbon recycling technologies is vital (Merrild et al., 2008). Recycling shows a lower impact in FPMF (-0.0003 kg $PM_{2.5}$ eq.) than recovery (-0.0001 kg $PM_{2.5}$ eq.). Recycling has a negative impact (-0.14 g P eq.) in FEu, indicating it mitigates eutrophication better than the energy recovery scenario (Fig. 30 (c)). The recycling process reduces nutrient releases into water bodies by avoiding the production of new materials.

Besides, the recycling scenario shows a more positive effect by reducing FE compared to recovery. Recycling reduces chemical releases that harm aquatic life for producing virgin pulp, while energy recovery, due to combustion emissions, may release some harmful substances but is not as severe as the base case. In the incineration scenario, FD is significantly reduced (-0.74 kg oil eq.), due to the replacement of fossil energy with energy generated from burning paper waste. In contrast, recycling shows a positive value (0.11 kg oil eq.), indicating it requires more energy for the reprocessing of materials.

However, the recycling scenario has a lower impact compared to energy recovery in TE and HT. Recycling reduces ecotoxic impacts by avoiding harmful chemicals associated with virgin material production. Recycling offers the environmental benefits, with a significant reduction in POF (-0.009 kg NO_x eq.) compared to the energy recovery scenario (0.002 kg NO_x eq.). This indicates that recycling helps reduce the formation of pollutants that contribute to ground-level ozone and smog, while energy recovery has negative impact in this category. Recycling also performs better (-0.003 kg SO_2 eq.) compared to energy recovery (-0.0003 kg SO_2 eq.) in TA, suggesting that recycling reduces emissions that contribute to acid rain more effectively than incineration.

4.2.1.3.1.4 Steel pallet

Steel pallets have environmental benefits for all impact categories, when they are recycled at the EoL cycle (Fig. 30 (d)). EoL stage brings out environmental benefits, because of the system credits associated with steel recycling (Ayres, 1997). Waste steel pallets are recycled to make steel plates, which avoids the production of primary steel. Recycling steel reduces the need for mining new iron ore, which can have negative impacts on the environment such as deforestation, soil erosion, water pollution, and biodiversity loss (Norgate and Haque, 2010).

4.2.1.3.1.2 Fly ash pallet

In the recycling scenario for fly ash pallets, all environmental impact categories are negative, showing substantial environmental benefits. The results indicate that recycling fly ash pallets performs better than the base case scenario across all environmental impact categories. Negative values across categories demonstrate that recycling not only reduces environmental burdens but also contributes positively by offsetting impact of emissions and resource use. This makes recycling an environmentally superior option for managing fly ash pallets, with benefits spanning across air, water, soil, and resource conservation.

GWP decreases from 12.27 kg CO_2 eq. in the base case to -20.77 kg CO_2 eq. in the recycling scenario (Fig. 30 (e)). This negative value indicates that recycling avoids emissions, providing a significant contribution to mitigating global warming. The formation of fine particulate matter drops from 0.00078 kg $PM_{2.5}$ eq. in the base case to -0.03 kg $PM_{2.5}$ eq., indicating a substantial reduction in air pollutants that contribute to respiratory health issues and degraded air quality. TA is also greatly reduced, with a drop to -0.08 SO_2 eq., meaning that recycling helps mitigate acid rain and its harmful effects on the environment.

Recycling also reduces the potential for nutrient overload in freshwater ecosystems, preventing eutrophication and the resulting negative impacts on water bodies, such as algal blooms and loss of aquatic life. The recycling process also significantly reduces toxicity risks. For instance, TE reduces from 0.47 kg 1,4-DB eq. to -58.63 kg 1,4-DB eq., which indicates fewer harmful chemicals being released into the environment, helping protect terrestrial organisms and ecosystems. Resource and energy consumption categories have also dropped compared to base case scenario. For instance, FD is significantly reduced from 0.27 kg oil eq. in the base case to -7.39 kg oil eq.. This means that recycling fly ash pallets substantially reduces the demand for non-renewable energy sources, helping to preserve fossil fuel reserves. Based on the above results, detailed CE scenarios for each type of pallet are explained in Table 14.

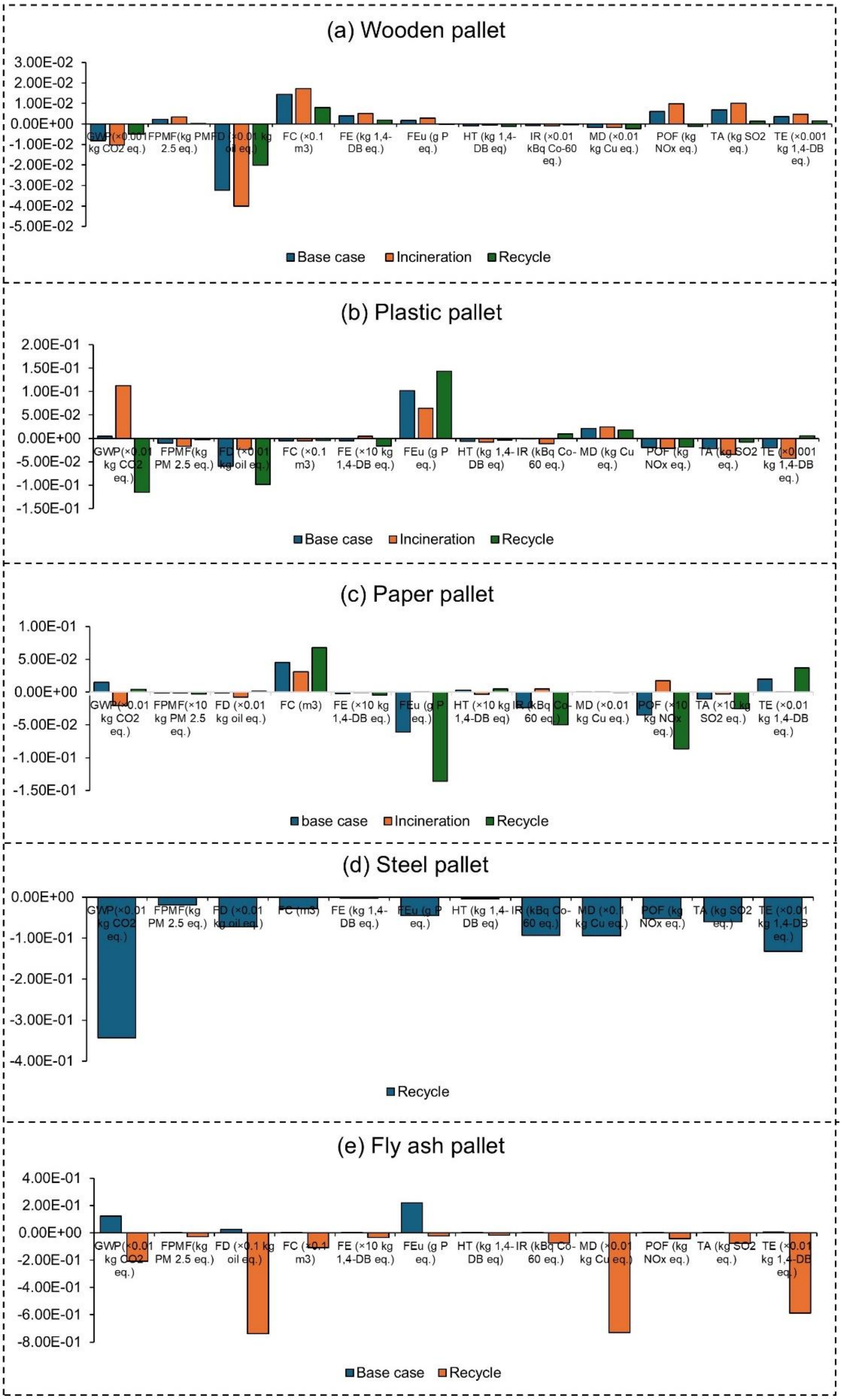

Fig. 30 Environmental impacts for EoL stage of each type of pallet. Some of the results have been scaled to fit within certain parameters, and the real values can be calculated by

applying the corresponding multipliers indicated in brackets. (a) Wooden pallet; (b) Plastic pallet; (c) Paper pallet; (d) Steel pallet; (e) Fly ash pallet.

Table 14

Specifications, scenario settings, and FUs of pallet designs

Pallet material type	Load capacity (tonnes)	Base case scenario	Number of pallets required	Sharing scenario	Number of pallets required	CE scenario	Number of pallets required
Wooden pallet	1.00	Pallet system as in China today, with single use and then disposal of pallets	1.00	Pallets are re-used 15 times	0.07	Remanufacture wooden pallets by using 100% recycled logs Use solar energy for production to reduce the consumption of fossil fuels Reuse for 15 times and repair twice through the entire life by using solar energy 100% incinerate/recycle at the end of life	0.07
Plastic pallet	1.50	Pallet system as in China today, with single use and then disposal of pallets	0.67	Pallets are re-used 70 times	0.01	Remanufacture plastic pallets by using 100% recycled plastic granulates Use solar energy for production to reduce the consumption of fossil fuels Reuse pallets for 70 times by using solar energy	0.01

						100% incinerate/recycle at the end of life using solar energy	
Paper pallet	1.00	Pallet system as in China today, with single use and then disposal of pallets	1.00	Pallets are re-used 4 times	0.25	Remanufacture paper pallets by using 100% recycled pulp Use solar energy for production to reduce the consumption of fossil fuels Reuse for 4 times by using solar energy 100% incinerate/recycle at the end of life	0.25
Steel pallet	2.00	Pallet system as in China today, with single use and then disposal of pallets	0.50	Pallets are re-used 100 times	0.01	Remanufacture steel pallets by using 100% recycled steel Use solar energy for production to reduce the consumption of fossil fuels Reuse for 100 times by using solar energy 100% recycle at the end of life using solar energy	0.01
Fly ash pallet	1.50	Pallet system as in China today, with	0.67	Pallets are re-used 15 times	0.04	Remanufacture fly ash pallets by using 100% recycled rare earth elements and plastic granulates	0.04

	single use and then disposal of pallets		Use solar energy for production to reduce the consumption of fossil fuels Reuse for 15 times by using solar energy 100% recycle at the end of life using solar energy

4.2.1.3.2 Scenario analysis under the CE scenario

4.2.1.3.2.1 Wooden pallet

The LCA results under the CE scenario show that the main environmental effects of the pallets throughout their life cycle are in the use stage (Fig. 31 (a)), because of the resource and energy input required for repairing wooden pallets for providing more services. Wooden pallets need to be repaired twice in order to achieve 15 trips in their whole life cycle (Weththasinghe et al., 2022), which increases the consumption of electricity, i.e., electricity used for repairing pallets and operating forklifts. Steel nails, which are manufactured by a multistep process, contributing to GHG emissions, are used to assemble dismantled or virgin boards to repair damaged pallets. The use stage contributes the most to all the categories, ranging from 96% for MD to 99% for IR because of the resource depletion and anthropogenic emissions of radionuclides generated in the upstream process, e.g., mining, burning of coal (Thinkstep, 2021). The EoL stage has environmental benefits, because of the significant amounts of energy recovered as heat, avoiding the environmental effects from combustion of other fuels, and the credits related to wood recycling (Ng et al., 2014).

4.2.1.3.2.2 Plastic pallet

The LCA results show that the use stage is the most significant source of environmental impacts for most of the categories, ranging from 50% for HT to almost 95% for POF and FE (Fig. 31 (b)). The use stage involves the transportation of goods by trucks that run on diesel fuel. The use stage accounts for more services in the CE system scenario, as each pallet has a longer service life and a higher utilisation rate, which emits more GHGs and other pollutants, such as CO_2, heavy metals and BC (Goldberg, 1985; Wu et al., 2017). These pollutants can lead to global warming, ozone formation and toxic impacts on the environment and human health. The production stage accounts for 73% and 74% in FC and IR respectively. The reason for this is that the production stage involves inputs of colour masterbatch, and additional transportation distance to collect waste pallets. This transportation consumes diesel fuel and emits GHGs and other pollutants. The EoL stage has environmental benefits, because of the systems credits for plastics incineration and recycling, which offsets the environmental effects in the other life cycle stages (Garcia and Robertson, 2017).

4.2.1.3.2.3 Paper pallet

The LCA results show that the use stage is the most significant source of environmental effects for most categories, except water pollution, resource and energy consumption categories, where the production stage is the hotspot. The use stage entails the transportation of goods using trucks that operate on diesel fuel and provides more services in the CE scenario. The use stage contributes to the highest proportion of the impacts on most of the categories, ranging from 72% for HT to 94% for POF (Fig.31 (c)). The main reason for this is the emission of GHGs and other pollutants from diesel combustion. These pollutants can have toxic effects on the environment and human health.

The production stage has the highest environmental impacts in FEu (98%). The main reason for this is the application of pesticides or fertilisers during corn cultivation in the upstream process of starch gum production, and the nutrient load of the water body increases (Zhang et al., 2021). These pesticides or fertilisers can lead to nutrient enrichment and toxic effects on aquatic ecosystems and human health. For example, pesticides can contaminate surface water and groundwater, and affect aquatic organisms and drinking water quality. Fertilisers can increase the concentration of nitrogen and phosphorus in water, and cause algal blooms and oxygen depletion. These conditions can harm aquatic life and human health. The EoL stage has environmental benefits for most of the air pollution categories.

4.2.1.3.2.4 Steel pallet

The main environmental effects of steel pallets throughout their life cycle are in the use stage in the CE scenario. The use stage accounts for the highest proportion of the impacts on most of the selected categories, ranging from 65% for FC to 97% for POF (Fig.31 (d)). The EoL stage has environmental benefits, because of the avoidance of raw material inputs, which offsets the environmental effects in the other life cycle stages. The main rationale for this is that the circularity of the steel pallets can diminish the demand for new pallet production, lowering the resource and energy consumption for the production stage (Price et al., 2002), and the waste and emissions generation during the EoL phase (Tian et al., 2013). However, the recycling process itself has environmental effects, such as water consumption and waste generation, which raises the need to improve the recycling technology.

4.2.1.3.2.5 Fly ash pallet

The LCA results show that the main environmental impacts of the pallets throughout their life cycle are in the use stage. The use stage accounts for the highest proportion of the impacts on most of the categories, ranging from 50% for FEu to almost 96% for POF (Fig. 31 (e)). The reason for this is that the use stage involves transportation emissions for trucks, such as SO_2, NO_x and BC, which can cause acidification and particulate matter formation (Ali et al., 2021; Durga et al., 2014; Soni et al., 2018). The other environmental impacts are mainly in the production stage, which accounts for 84% in MD and 94% in IR. The reason for this is that the production stage involves material inputs such as steel nails, water and additional transportation distance to collect waste pallets. The EoL stage has environmental benefits, because of the avoidance of raw material inputs, which offsets the environmental effects in the other life cycle stages.

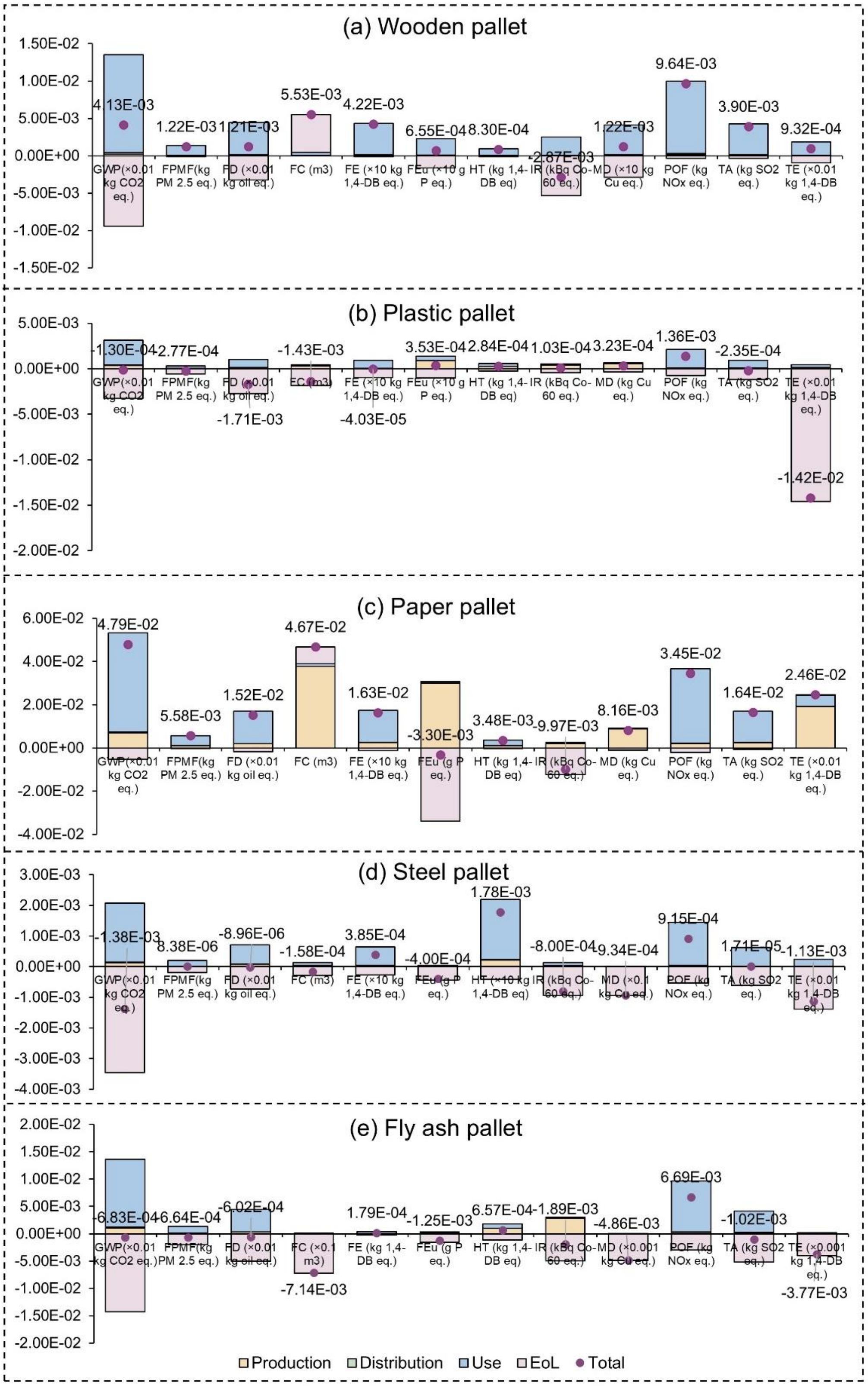

Fig. 31 Environmental impacts of five types of pallets under CE scenario. Some of the results have been scaled to fit within certain parameters, and the real values can be calculated by applying the corresponding multipliers indicated in brackets. (a) wooden pallet; (b) plastic pallet; (c) paper pallet; (d) steel pallet; (e) fly ash pallet.

4.2.1.3.2.6 Uncertainty analysis under the CE scenario

Steel pallets display the smallest GWP result (-0.14 ± 0.001 kg CO_2 eq.), while paper pallets achieve the value of 4.79 ± 0.05 kg CO_2 eq. (mean ± SD). Wooden, plastic and fly ash pallets have the GWP result of 0.41 ± 0.0001, -0.01 ± 0.002 and -0.07 ± 0.01 kg CO_2 eq. respectively (Fig. 32). Regarding FD category, plastic pallets have the smallest result of -0.17 ± 0.006 kg oil eq., followed by fly ash pallets (-0.06 ± 0.002 kg oil eq.), and paper pallets have the highest result (1.52 ± 0.01 kg oil eq.). Fly ash pallets have -3.77 ± 0.002 and paper pallets have 2.46 ± 0.15 for TE. Uncertainty analysis results for all impact categories can be found in Table. C. 4 in Appendix C.

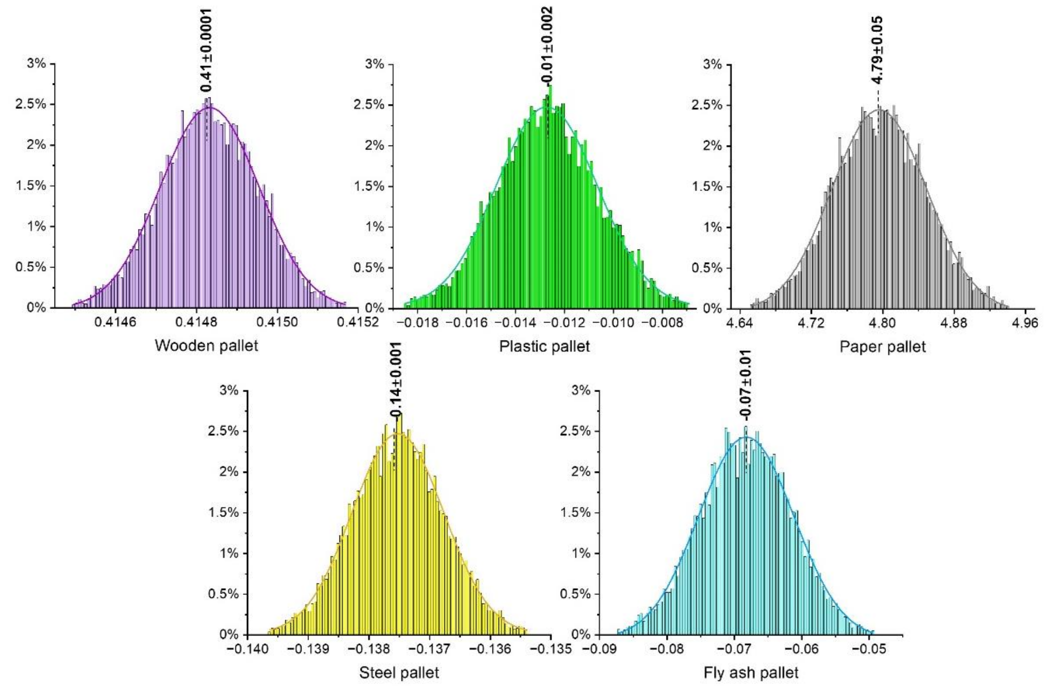

Fig. 32 Uncertainty analysis for five types of pallets under the CE scenario (unit: kg CO_2 eq.)

4.2.1.3.2.7 Comparison of environmental impacts of CE scenario

This analysis investigates the environmental impacts of five types of pallets—wooden, plastic, paper, steel, and fly ash—under the CE scenario. Each pallet undergoes the identified CE strategies, such as using 100% recycled materials, renewable energy utilisation, extended reuse, and sustainable EoL management. The study aims to identify and compare the environmental burdens for each pallet type, providing insights into the effectiveness of CE approaches in reducing the environmental effects of each pallet type.

Air pollution. GWP indicates that paper pallets exhibit the highest impact at 4.79 kg CO_2 eq., which is attributed to the process involved in gum production, as well as emissions generated during its incineration at the end of life. In contrast, steel pallets show a GWP of -0.14 kg CO_2 eq., primarily reflecting the environmental benefits of steel recycling, which offsets the need for virgin steel production and results in a net reduction of GHG emissions (Fig. 33). The reduction is also attributed to the energy-saving effect of using solar energy for the entire lifecycle. The FPMF results show that paper pallets lead with 0.006 kg $PM_{2.5}$ eq., mainly due to particulate emissions from the recycling of paper pallets. Wooden pallets, with 0.001 kg $PM_{2.5}$ eq., contribute less due to their lower frequency of disposal (wooden pallets are reused multiple times before being disposed). POF reveals that paper pallets again have the highest impact, at 0.03 kg NO_x eq.. This is driven by NO_x emissions throughout the life cycle, especially during transportation stages.

Water and soil pollution. Fly ash pallets show a negative FEu value of -0.001 g P eq., largely attributed to the recycling processes that reduce the production of raw materials. TA for paper pallets is significant, contributing 0.02 kg SO_2 eq., which is mainly due to sulfur dioxide emissions generated during the chemical additives used in the gum production processes. On the other hand, fly ash pallets exhibit a negative TA of -0.001 kg SO_2 eq., reflecting influence during the recycling phase.

Resource and energy consumption. FC is highest for paper pallets (0.05 m^3), and wooden pallets rank the second at 0.01 m^3. The significant water usage stems from the processing of pulp for paper pallets, and heat treatment for wooden pallets. In terms of FD, plastic pallets have the largest reduction in fossil fuel reliance, with a value of -0.17 kg oil eq.. This is due to the closed-loop recycling process for plastic granulates and the integration of renewable energy sources, which reduce the need for virgin fossil resources. On the contrary, paper pallets have a significant FD value of 1.52 kg oil eq., reflecting the lowest carrying capacity and RSL. Fly ash pallets, with an FD value of -0.06 kg oil eq., benefit from using recycled materials and renewable energy inputs, further minimising their reliance on fossil fuels. The MD value for fly ash pallets is -4.86 kg Cu eq., which is due to the effective reuse of metals in fly ash through the recycling process. This indicates that fly ash pallets reduce the consumption of metal resources (such as lanthanum and cerium) during production through recycling.

Toxicity risks. HT is highest for paper pallets, with a value of 0.004 kg 1,4-DB eq., primarily driven by the presence of toxic substances used during pulp and gum processing and emissions from incineration. Wooden pallets, by contrast, show a lower HT value of 0.001 kg 1,4-DB eq., as their natural materials result in fewer toxic risks throughout their lifecycle. For TE, fly ash pallets display the lowest potential at -3.77 kg 1,4-DB eq., indicating that the recycling of fly ash pallets reduces the demand for virgin metal extraction, which minimises the overall environmental impact. Steel pallets display lower environmental impacts, which can be attributed to effective recycling processes and the integration of renewable energy sources in their production methods.

Overall, the analysis reveals significant differences among the five pallet types in their environmental impacts under the CE scenario. Paper pallets show the highest impacts across ten categories, largely due to their low durability and the need for a higher number of pallets to transport the same volume of goods, thereby increasing environmental burdens per FU. On the other hand, fly ash pallets demonstrate the lowest impacts across five impact categories, benefiting from their ability to divert waste from landfills and reduce resource consumption through remanufacturing processes. This evaluation emphasises the importance of selecting materials and enhancing both the reusable service life and load-carrying capacity to align with sustainability goals and minimise overall environmental impacts.

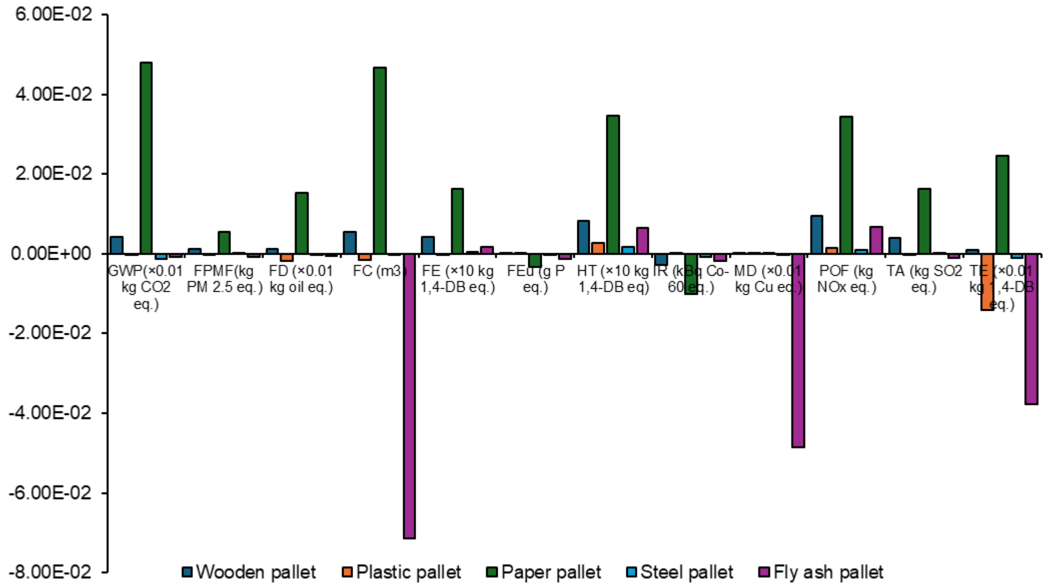

Fig. 33 Environmental impacts comparison for each type of pallet under CE scenario. Some of the results have been scaled to fit within certain parameters, and the real values can be calculated by applying the corresponding multipliers indicated in brackets.

4.2.1.3.2.8 Summary

This section presents the environmental impact results of five types of pallets under CE scenario. The analysis reveals distinct environmental profiles for each pallet type. Paper pallets demonstrate the highest environmental impacts across most categories, primarily due to their low durability, which necessitates frequent replacements. In contrast, fly ash pallets exhibit the lowest impacts across five impact categories, highlighting their effective reuse of materials and reduced resource consumption. Plastic pallets yield the lowest results in two impact categories, largely attributable to their avoidance of petroleum-based materials and the energy-intensive processes required to produce raw materials. Steel pallets also perform well, showing the lowest impacts in three categories due to their high load-carrying capacity and longevity. Overall, the findings demonstrate the critical importance of selecting materials and enhancing CE strategies to optimise environmental performance in pallet management.

4.2.1.4 Environmental impacts comparison of three scenarios at product scale

The CE scenario typically results in the greatest reduction of environmental impacts compared to both the base case and sharing system scenarios for the five pallet types. The sharing system also demonstrates reductions in impacts but generally to a lesser extent than the CE scenario.

Wooden pallet. The environmental impacts of wooden pallets exhibit significant improvements under both the sharing system and CE scenarios. Under the sharing system scenario, reductions range from 88.78% (TE) to 93.11% (FE). Under the CE scenario, reductions span from 92.46% (HT) to 249.56% (IR). For example, GWP under the sharing system decreases by 92.22%, reducing from 12.67 kg CO_2 eq. to 0.99 kg CO_2 eq.. This reduction is even more pronounced under the CE scenario, with a 96.75% decrease, lowering GWP to 0.41 kg CO_2 eq. (Fig. 34). This highlights how CE strategies drastically reduce the carbon emissions associated with wooden pallets. TE shows substantial reductions as well, decreasing by 88.78% under the sharing scenario, from 8.64 kg 1,4-DB eq. to 0.97 kg 1,4-DB eq., and by 98.92% under the CE scenario, with a final value of 0.09 kg 1,4-DB eq.. Improved waste management under CE strategies accounts for these reductions. Similarly, FEu decreases by 92.46% in the sharing scenario, from 0.009 g P eq. to 0.0001 g P eq., and by 99.27% under the CE scenario. FD follows a similar trend, with a 92.26% reduction under the sharing system, from 3.58 kg oil eq. to 0.28 kg oil eq., and a 96.62% reduction in the CE scenario, bringing it down to 0.12 kg oil eq.. FPMF decreases by 92.53% under the sharing system, from 0.02 kg $PM_{2.5}$ eq. to 0.002 kg $PM_{2.5}$ eq., and by 95.02% under the CE scenario, reaching 0.001 kg $PM_{2.5}$ eq., indicating improvements in air quality and reductions in particulate emissions.

Plastic pallet. Plastic pallets demonstrate notable environmental performance under both the sharing system and CE scenarios, with reductions ranging from 96.93% (TE) to 98.56% (FEu) in the sharing scenario. Under the CE scenario, the reductions are even more pronounced, ranging from 98.74% (HT) to 111.54% (TE). GWP is reduced by 98.49% in the sharing scenario, from 61.68 kg CO_2 eq. to 0.93 kg CO_2 eq., and by 100.02% in the CE scenario, resulting in a net negative impact of -0.01 kg CO_2 eq., showing that plastic pallets can offset emissions when managed in a circular system. FD decreases by 98.53% in the sharing scenario, from 26.77 kg oil eq. to 0.39 kg oil eq., and achieves a 100.64% reduction under the CE scenario, reducing fossil fuel use to -0.17 kg oil eq.. This indicates that all virgin fossil resources can be replaced by recycled materials. FEu also shows substantial reductions of 98.56% under the sharing scenario and 99.98% under the CE scenario, mitigating water pollution significantly. FPMF decreases by 98.32%, lowering from 0.03 kg $PM_{2.5}$

eq. to -0.0003 kg $PM_{2.5}$ eq., under the CE scenario, highlighting substantial air quality improvements. Furthermore, POF, which measures ground-level ozone creation, decreases by 98.52% in the sharing scenario and by 99.28% in the CE scenario.

Paper pallet. The environmental benefits of paper pallets are generally less impressive compared to other pallet types, largely due to their lower carrying capacity and RSL. Under the sharing scenario, reductions range from 73.66% (TE) to 75.02% (FEu). Under the CE scenario, the reduction range spans from 70.42% (FC) to 121.31% (IR). GWP decreases by 74.78% in the sharing scenario, from 27.21 kg CO_2 eq. to 6.86 kg CO_2 eq., and by 82.37% under the CE scenario, reducing it to 4.79 kg CO_2 eq.. IR reduces by 74.79% under the sharing scenario and by 121.31% under the CE scenario. FD also decreases significantly, with a 74.88% reduction under the sharing scenario and an 81.16% reduction under the CE scenario. FEu reductions amount to 75.02% under the sharing system and 101.47% under the CE scenario, indicating improvements in nutrient pollution management. TA decreases by 74.81% under the sharing scenario and by 78.83% under the CE scenario.

Steel pallet. Under the sharing scenario, reductions range from 96.80% (TE) to 98.97% (MD). Under the CE scenario, reductions span from 98.40% (HT) to 108.73% (MD). GWP decreases by 98.84% in the sharing scenario, from 24.25 kg CO_2 eq. to 0.28 kg CO_2 eq., and further achieves a 100.57% reduction in the CE scenario, resulting in a net negative impact of -0.14 kg CO_2 eq., demonstrating that recycling steel can lead to negative emissions. MD shows a 108.73% reduction in the CE scenario, indicating that recycled steel decreases the need for virgin metal extraction. FPMF decreases by 98.74% in the sharing scenario and by 99.96% in the CE scenario, reflecting significant reductions in air pollution. FD also sees a major decrease, with a 98.89%

reduction in the sharing scenario and a 100.01% reduction in the CE scenario, indicating the elimination of fossil fuel use through steel recycling. Furthermore, FC sees a 100.84% reduction in the CE scenario compared to the base case, reflecting substantial water savings through CE practices.

Fly ash pallet. Fly ash pallets demonstrate significant potential for environmental benefits under CE strategies. Under the sharing system scenario, reductions range from 93.13% (TE) to 93.33% (MD and FEu). In the CE scenario, reductions span from 96.78% (POF) to 105.66% (MD). GWP decreases by 93.25% in the sharing scenario, from 61.54 kg CO_2 eq. to 4.15 kg CO_2 eq., and achieves a 100.11% reduction in the CE scenario, resulting in a net-negative impact of -0.07 kg CO_2 eq.. FD also sees a significant reduction of 93.25% in the sharing scenario, and a 100.36% reduction in the CE scenario. HT decreases by 93.22% in the sharing scenario, and by 98.11% in the CE scenario. FC shows a 93.30% reduction under the sharing scenario, and a 105.29% reduction under the CE scenario, indicating vast improvements in water efficiency. Finally, TA decreases by 93.26% under the sharing scenario, and by 100.59% under the CE scenario, reflecting considerable reductions in AP.

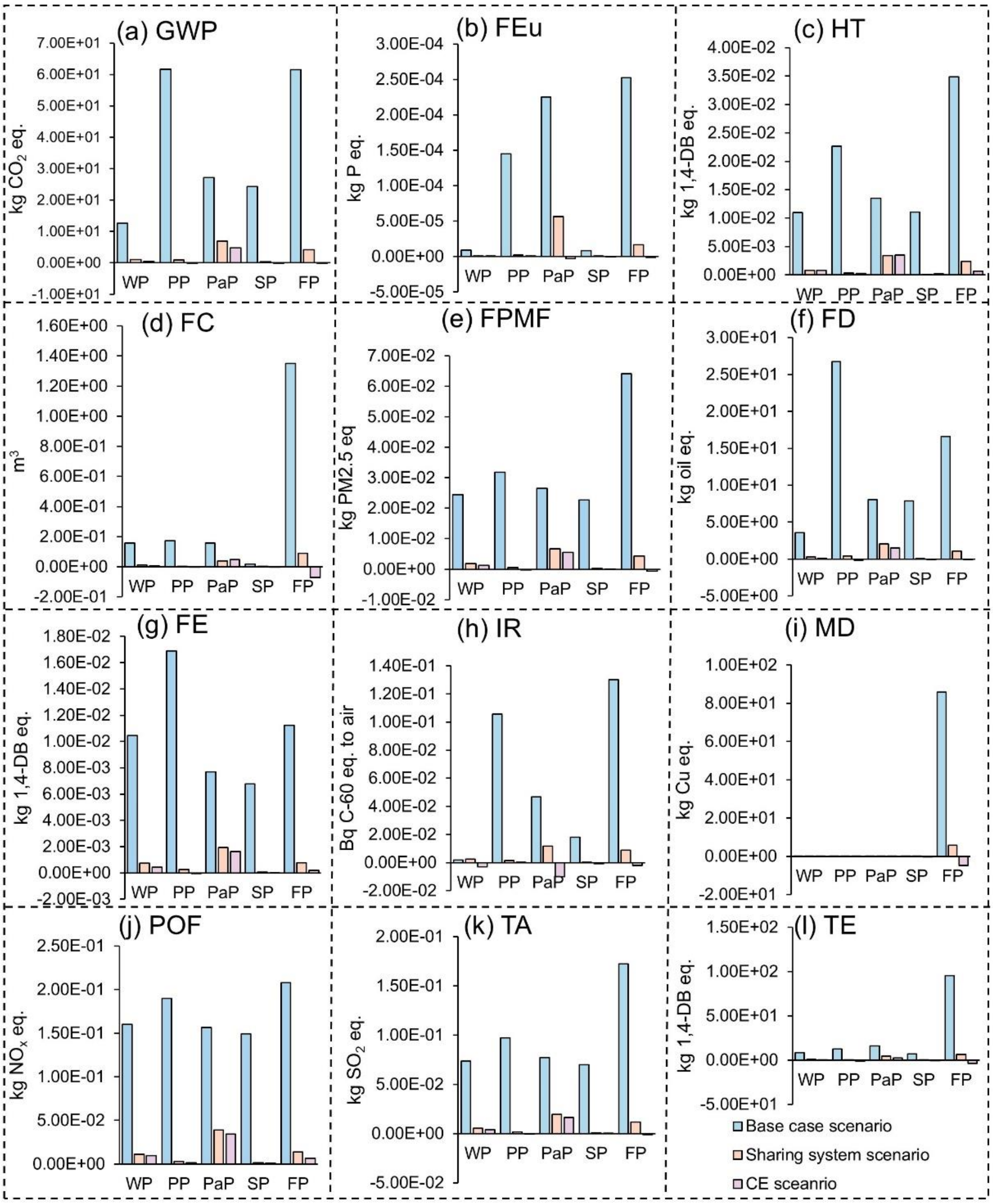

Fig. 34 Environmental impact results for five types of pallets under three scenarios. (a) GWP; (b) FEu; (c) HT; (d) FC; (e) FPMF; (f) FD; (g) FE; (h) IR; (i) MD; (j) POF; (k) TA; (l) TE. (*Abbreviation: Wooden pallet (WP), Plastic pallet (PP), Paper pallet (PaP), Steel pallet (SP), Fly ash pallet (FP).*

4.2.2 Environmental impact results at national scale under three stages

4.2.2.1 Environmental impact results at national scale

Following the product-scale evaluations, which quantify the environmental impacts of five distinct pallet types, this research extends its analysis to provide a broader understanding of the environmental implications associated with the pallet market in China considering the market share of various material compositions. Assessing environmental sustainability at the product level alone is insufficient for capturing the environmental impacts within an entire industry. The green transformation framework developed in this thesis incorporates a national-scale evaluation, providing a more holistic perspective on the environmental performance of the pallet market in China. This analysis leverages market share data, enabling the integration of real-world industry situation and quantifying the environmental impacts associated with three distinct scenarios—base case, sharing system, and CE scenario—within the context of China's pallet logistics sector. At the national scale, the integration of market share data into the evaluation framework allows for a more accurate representation of the environmental consequences of pallet usage across the country. By considering the proportions of different pallet types in circulation and their respective environmental footprints, this analysis presents a realistic estimation of the industry's overall environmental impacts under various scenarios. For instance, the base case scenario reflects the current practices and consumption patterns in the Chinese pallet market, while the sharing system and CE scenarios explore the potential for more sustainable practices through increased reuse, recycling, and other CE strategies.

The results show that adopting the sharing system and CE strategies can significantly reduce the environmental impacts of pallet logistics in China, compared to the base case scenario, as shown in Fig. 35 (a) – (l). The data highlights that these alternative systems can significantly reduce the environmental burdens associated with pallets, spanning across various impact categories. The reduction rates of each impact category under the sharing system are high, ranging from 90% to 96% compared to base case scenario. For instance, the reduction in GWP under the sharing system is 95%, lowering the emissions from 43.23 Mt CO_2 eq. in the base case scenario to 2.14 Mt CO_2 eq.. The ability to reduce the main carbon emissions associated with pallet production, transportation, and disposal is primarily due to the increased reuse of pallets and the more efficient use of materials within a sharing economy framework. Similarly, the results show significant reductions in other key impact categories. FC decreases by 93%, from 284.81 million m^3 to 19.40 million m^3 under the sharing system. This decrease is largely attributable to more pallet reuse that minimises the water required during the manufacturing stage of pallet logistics. TE can be reduced by 90% (from 18.48 Mt 1,4-DB eq. to 1.76 Mt 1,4-DB eq.) under the sharing system. These improvements reflect the lower release of harmful chemicals and pollutants into ecosystems, due to the sharing system, where pallets are managed to be reused.

While the sharing system demonstrates considerable environmental benefits, the CE scenario delivers greater improvements, further optimising resource efficiency and minimising environmental effects. The results of environmental impact categories under CE scenario can be reduced from 94% to 108% compared to base case scenario. Regarding GWP, the CE scenario reduces emissions by 98%, bringing the figure down from 43.23 Mt CO_2 eq. in the base case to 0.82 Mt CO_2 eq.. This indicates that the CE scenario eliminates most of the carbon emissions associated with pallet logistics, largely through the adoption of CE strategies that lower the need for virgin materials and reduce emissions across the entire supply chain, which can contribute to China's climate goals. The reductions in FC are also noteworthy under the CE scenario. FC decreases by 97%, from 284.81 million m^3 to 7.75 million m^3. These reductions demonstrate the CE's capacity to optimise water use throughout the pallet lifecycle. TE experiences a significant reduction as well, declining by 102% under the CE scenario, from 18.48 Mt 1,4-DB eq. to -0.33 Mt 1,4-DB eq.. This reduction in TE suggests that the CE scenario significantly mitigates the release of hazardous substances into the environment, further supporting the ecological sustainability of pallet logistics under a circular framework. Besides, the results of some categories have negative values under the CE scenario, such as IR and MD. For example, IR can be reduced from 49.51 million kBq Co-60 eq. under the base case scenario to -4.17 million kBq Co-60 eq. under the CE scenario, which means that the CE scenario can prevent the release of more harmful radioactive substances than it emits. Such reductions are vital for minimising long-term ecological and human health risks associated with exposure to IR. Similarly, MD can be reduced from 2.02 Mt Cu eq. under the base case scenario to -0.11 Mt Cu eq. under the CE scenario. This outcome suggests that the CE scenario can save more metal resources than it consumes, primarily through the extensive use of recycled materials and the minimisation of virgin resource extraction. This is particularly important for conserving finite metal resources, many of which are critical for manufacturing and infrastructure development.

Overall, the national-scale assessment demonstrates the potential of CE strategies to improve the environmental performance of the pallet market in China, thus contributing to the green transformation of the pallet industry in China. The transition from a base case scenario to a sharing system and, ultimately, to a CE-based system, marks a significant step toward sustainable pallet logistics. The additional reductions achieved in the CE scenario, compared to the sharing system, highlight the importance of adopting more comprehensive CE strategies. Moreover, the national-scale evaluation sheds light on the scalability of sustainable practices, illustrating how material-specific improvements identified at the product level can be magnified when applied across an entire industry. This comprehensive study contributes valuable insights into the environmental sustainability of pallet logistics in China, offering perspectives at both the product and national scales. By linking material-specific impacts to market-wide outcomes, the research presents a robust framework for evaluating and optimising the environmental performance of the pallet industry, thus contributing to the green transformation. This dual-level approach not only highlights the potential for reducing environmental burdens through CE practices but also provides practical implications for guiding the industry's transition towards more sustainable logistics operations.

The implications of these findings offer practical guidance for industry stakeholders and policymakers aiming to reduce the environmental impacts of pallet logistics. The CE scenario, with its ability to improve environmental performance in certain categories, has the potential for not only minimising harm but also contributing to environmental restoration. By adopting these strategies, the Chinese pallet market could play a pivotal role in advancing the country's broader sustainability goals, including those related to carbon neutrality and resource conservation.

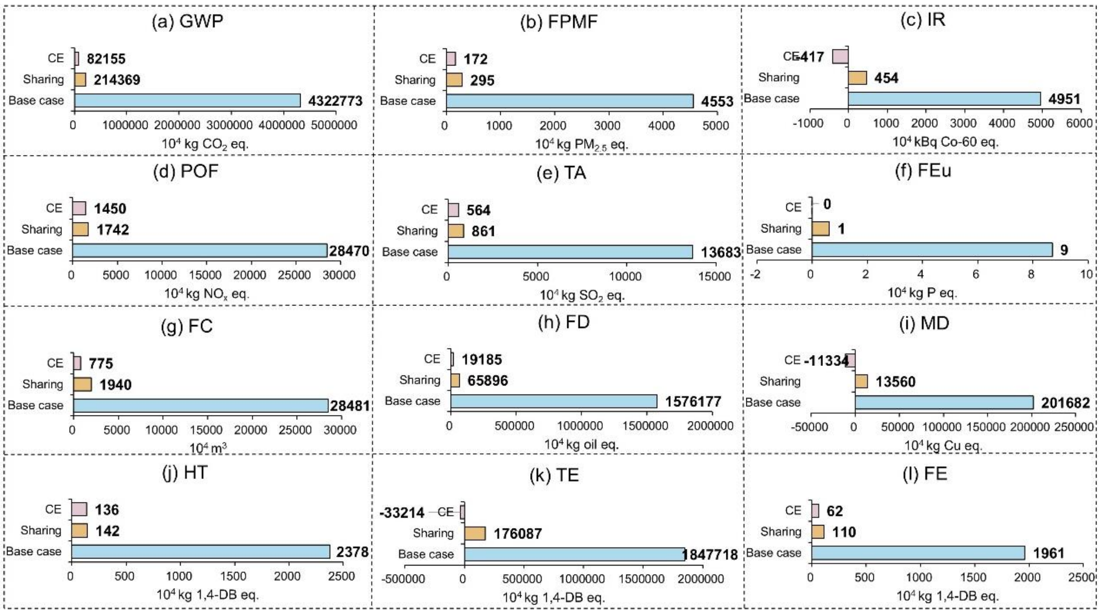

Fig. 35 Environmental impacts comparison of pallet market in China under three scenarios. (a) GWP; (b) FPMF; (c) IR; (d) POF; (e) TA; (f) FEu; (g) FC; (h) FD; (i) MD; (j) HT; (k) TE; (l) FE.

4.2.2.2 Summary

This section provides a comprehensive analysis of the environmental impacts of pallet logistics in China, comparing a base case scenario with two alternative scenarios: a pallet-sharing system and a CE scenario. The findings reveal that both alternative systems significantly reduce environmental burdens, with the sharing system decreasing impacts by 90% to 96% across various categories. The CE scenario demonstrates even greater benefits, achieving reductions from 94% to 108%. Additionally, the CE scenario shows environmental benefits in certain categories, by preventing more harm than it generates. These results highlight the potential of CE strategies to the green transformation of pallet logistics, emphasising the importance of industry-wide adoption of circular practices for resource conservation and environmental impacts mitigation.

4.2.3 Comparison with other studies

The application of LCA in pallet analysis remains a relatively nascent area of research, making direct comparisons between studies challenging. This difficulty is compounded by several factors, including variations in system boundaries, FUs, assumptions, and the choice of LCIA methods across studies. While many LCAs focus on a single type of pallet, most FUs are either trip-based or focused on one pallet piece, without adequately considering the pallet's characteristics, such as load-bearing capacity or RSL. The lack of a consistent FU across studies undermines the comparability of environmental results. In addition, only 34% of studies clearly present their data inventory, and an even smaller percentage (24%) describe the data timeframe, signalling significant gaps in data transparency, which further limits the robustness and comparability of results.

Moreover, the existing literature overwhelmingly focuses on wooden pallets, with 86% of studies addressing only this pallet type, neglecting the environmental impacts of plastic, steel, paper, or fly ash pallets, despite their presence in global and particularly Chinese market. For example, plastic pallets, which have been gaining market share in China and have become a significant competitor to wooden pallets, are underrepresented in the literature, with only 13 studies investigating their environmental impacts. Additionally, around 40% of the existing literature examines the environmental impacts of pallets within the context of the U.S. market, which is geographically limited and fails to capture specific conditions and practices in other regions, such as China, where pallets are predominantly single-use and undergoing a green transformation.

A noteworthy contribution comes from Alanya-Rosenbaum et al. (2021), who proposed a novel FU that incorporates RSL and load-bearing capacity in the assessment of wooden pallets. Their study calculated a GWP of 10.4 kg CO_2 eq. per 45.4 tons of pallet loads delivered, aligning with this study's FU approach. However, differences in LCIA methods restricted the comparability of their results with this study, allowing only limited impact categories—namely GWP, TA, FEu, and FD—to be evaluated. Carrano et al. (2014) and García-Durañona et al. (2016) used a simpler FU of "one piece of wooden pallet" without considering the pallet's functional performance, further highlighting the gap in holistic environmental assessments. Gasol et al. (2008) also overlooked key factors, such as load-bearing capacities, making their findings difficult to compare with more nuanced assessments.

Plastic pallets have generally been studied in comparison to wooden pallets, with 77% of studies focusing on this comparative analysis. For example, Weththasinghe et al. (2022) revealed that plastic pallets had a 1.5 times higher carbon footprint than wooden pallets from a cradle-to-grave perspective in Australia. Similarly, Anil et al. (2020) found plastic pallets to have higher environmental impact across various categories, though the relevance of these findings to China is limited due to outdated data and assumptions, such as the use of now-restricted treatments, such as methyl bromide fumigation. Kočí (2019) also found that wooden pallets have lower environmental impacts than plastic pallets, especially when wood is used for energy recovery at the end of its life cycle, a result that aligns with the findings of this study. In this study, wooden pallets demonstrated lower environmental impacts compared to plastic pallets in most environmental categories under the base case and sharing system scenario, especially in categories such as GWP. The GWP of wooden pallets was calculated to be 12.67 kg CO_2 eq., significantly lower than plastic pallets, which had a GWP of 61.68 kg CO_2 eq.. This finding is consistent with the research by Weththasinghe et al. (2022) and Kočí (2019), who both noted the environmental burden of plastic pallet production, largely due to the reliance on petroleum-based materials. The use stage of wooden pallets in this study was found to be the most dominant in terms of environmental impacts, particularly for categories, such as HT, FE, and TE, due to the additional resources and energy required for pallet repair. In contrast, for plastic pallets, the production stage contributed the most to environmental impacts, particularly in the categories of IR and fossil energy use, owing to the extraction and processing of fossil fuels. Studies that focused on paper pallets (e.g., Bengtsson and Logie, 2015) demonstrated that paper pallets have the highest results in GWP and FD compared with wooden and plastic pallets, though comprehensive comparisons across all pallet types remain scarce.

Regarding CE strategies, the existing literature tends to focus on isolated strategies such as recycling, reuse, and repair. For example, Ng et al. (2014) examined the benefits of using recycled materials for wooden pallets, while Kočí (2019) assessed recycled plastics. These studies illustrate the feasibility of mitigating the environmental impacts by adopting CE strategies. However, the study that evaluates the environmental implications of adopting the combination of the relevant CE strategies (such as reuse, recycling, repair, and remanufacturing) across different pallet types remains lacking. This study attempts to fill this gap by applying a comprehensive green transformation framework, which demonstrates the significant potential for reducing environmental impacts through pallet sharing systems and CE strategies.

In conclusion, although the current LCA research provides valuable insights into the environmental impacts of pallets, the significant variations in FUs, system boundaries, and methodologies make direct comparisons challenging. The current literature is limited in terms of data transparency, geographic focus, and the consideration of diverse pallet types, particularly in regions such as China, where the pallet market is rapidly evolving. This study contributes to closing this gap by presenting a comprehensive cradle-to-grave LCA of five widely used pallet materials, with a well-defined system boundary and FU that incorporates RSL and load-bearing capacity, offering a more accurate reflection of the environmental performance and the impact reduction potential of pallets in China.

Chapter 5 Overall discussion and conclusions

In this section, a critical reflection on the research questions and research objectives is presented, alongside a discussion of the main findings. The structure of this chapter is as follows: Section 5.1.1 offers an in-depth assessment of the primary research questions posed in Section 3.1 and explains how they were addressed throughout the thesis. Section 5.1.2 discusses the broader implications of these findings for management practices, highlighting their relevance to decision-making processes. Section 5.1.3 acknowledges the limitations of the research, examining both methodological and practical constraints. Lastly, Section 5.2 highlights the key findings of this thesis which have been linked back to the objectives set out, and provides recommendations for future research avenues, laying the groundwork for continued exploration in the field.

5.1 Overall discussion of the integrated MFA and LCA

5.1.1 Research questions

- The production and consumption scale of pallets in China continues to grow. Where do the pallets entering the Chinese socio-economic system come from? And where do they go? How to establish a systematic method to quantitatively track the sources, sinks and pathways of pallets?

The first research question focused on understanding the sources, destinations, and pathways of pallets within the Chinese socio-economic system and establishing a systematic approach for tracking these flows. Through the MFA conducted in Section 4.1, this thesis has filled significant data gaps previously noted in the literature review in Section 2.3.7. While previous research on pallets, such as those conducted by Buehlmann et al. (2009), Gerber (2020), and Schweinle et al. (2020), provided limited insights into specific types or regions (e.g., EPAL 1 pallets in Germany), this research comprehensively quantifies the flows and stocks of pallets across different sectors in China.

The MFA results reveal several critical insights. First, the inefficiency in resource use, particularly the 36% pre-consumer waste rate, highlights substantial opportunities for improvement in the pallet manufacturing sector. At the pallet manufacturing stage, the total pre-consumer waste generated is 4.53 Mt, indicating the low efficiency of resource use. Eco-design and design for circularity are two complementary approaches that can enhance the environmental sustainability and circularity of pallets. Additionally, the waste disposal practices in China are far from circular, as shown by the landfill rates, particularly for wooden and plastic pallets. With landfill rates for wooden pallets being five times higher in China compared to the US (Gerber, 2018), this study demonstrates the need for better waste management systems, including effective collection and segregation processes. The significant amount of post-consumer waste landfilled (45.9% for plastic pallets and 2% for wooden pallets) demonstrates the urgency of establishing closed-loop recycling systems. This aligns with global efforts to minimise the environmental impacts associated with landfilling, such as methane emissions, groundwater contamination, and ecosystem disruption (Yadav et al., 2020). 1.6% of plastic 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).

Furthermore, this thesis contributes to the methodological development of pallet MFA by providing a framework for data collection and analysis that can be adapted for the logistic carrier industries in other regions. The approach taken here can help standardise data evaluation, facilitating cross-regional and cross-industry comparisons. The suggestions of the combination of eco-design and design for circularity, show potential for reducing pre-consumer waste and increasing the lifespan of pallets, further supporting the transition towards a circular pallet economy. 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).

- The whole life cycle of pallets will cause environmental impacts. What are the hotspots that cause environmental effects? How to identify and evaluate the environmental impacts of different types of pallets in the whole life cycle?

The second research question investigates the environmental hotspots in the life cycle of pallets and seeks to evaluate and compare the environmental impacts of different pallet types—wooden, plastic, steel, paper, and fly ash. A significant motivation for this research stems from the existing literature, which predominantly focuses on wooden pallets, particularly within the United States, thereby neglecting other materials such as plastic, steel, paper, and fly ash that also constitute a substantial portion of the pallet market. In China, these five materials account for 99% of the market share, yet there is an absence of comprehensive studies addressing their environmental impacts. This research fills this research gap by offering a holistic assessment of the life-cycle impacts across these materials in the Chinese context. In addition, a key limitation identified in the literature review in Section 2.4.11 is the narrow focus on a single environmental indicator—GWP. This singular focus inadequately captures the broad array of environmental burdens associated with pallet production and disposal, including FD, FEu, FC, and HT, among others. By incorporating a wider spectrum of environmental impact categories, the present study provides a more comprehensive understanding of the environmental trade-offs inherent in the use of different pallet materials. Such an approach is crucial for identifying environmental hotspots, as focusing solely on GWP could obscure significant environmental harms that occur in other stages of the life cycle or through other impact pathways.

Furthermore, the existing body of research exhibits notable inconsistencies in system boundaries and the adoption of FUs. The FU, which defines the basis for comparing different products, varies significantly across studies, thereby undermining the comparability of their results. Many studies adopt a mass-based FU, which fails to account for the differing functional characteristics of pallets, such as load-bearing capacity and service life. This omission leads to distorted comparisons and prevents a comprehensive evaluation of environmental performance relative to the utility provided by each pallet type. For instance, a heavier pallet, while potentially having higher production impacts, might offer greater durability and a longer lifespan, thus reducing its overall environmental impact. In addition, the system boundaries adopted in previous studies vary widely, with some focusing exclusively on the production phase while others include the EoL stage. Such discrepancies make it difficult to draw robust conclusions about the environmental performance of pallets, as certain life-cycle stages—such as disposal or recycling—can significantly alter the environmental footprint. For example, steel pallets may exhibit high production impacts but also offer considerable environmental benefits at the EoL stage due to their recyclability.

Given these challenges, this study employs LCA methodology which adopts a cradle-to-grave perspective, incorporating the entire life cycle of each pallet type. This approach ensures that the relevant environmental impacts are captured, and the results can be compared on a consistent basis. By standardising the FU to account for pallets' functional performance and lifespan, and ensuring uniform system boundaries, the research aims to provide a reliable basis for comparing the environmental impacts of the five pallet types in the Chinese context. By filling these methodological and empirical gaps, this study contributes to a more comprehensive understanding of the environmental impacts associated with the primary types of pallets used in China. This knowledge is essential for guiding sustainable logistics practices and advancing the CE in the pallet industry.

The analysis in Chapter 4.2.1 reveals significant differences in the environmental impacts of five types of pallets—wooden, plastic, paper, steel, and fly ash—across multiple impact categories. Based on LCA, fly ash pallets exhibit the highest environmental impacts across nine categories, particularly in terms of air pollution and toxicity risks. These high environmental burdens are primarily attributed to the energy-intensive production processes and the hazardous substances required for fly ash treatment. For example, in terms of GWP, fly ash pallets contribute 61.54 kg CO_2 eq., a value second only to plastic pallets (61.68 kg CO_2 eq.). This finding indicates that although fly ash is a byproduct of coal combustion, its handling and processing demand substantial energy inputs. Additionally, fly ash treatment leads to significant emissions of FPMF (0.06 kg $PM_{2.5}$ eq.) and releases of radioactive substances (0.13 kBq Co-60 eq.), further exacerbating air pollution and health risks.

In comparison, plastic pallets, although showing lower burdens in certain categories, still present considerable environmental impacts due to their reliance on petroleum-based materials. The production of plastic pallets is resource-intensive, particularly in FD, where plastic pallets record an FD value of 26.77 kg oil eq., seven times higher than that of wooden pallets. Furthermore, the low recycling rate (25%) and high landfill rate (45.9%) of plastic pallets significantly increase their overall environmental burdens. Wooden pallets, by contrast, demonstrate the lowest environmental impacts across ten categories. The GWP of wooden pallets is 12.67 kg CO_2 eq., reflecting their renewable material composition and lower resource demands. In addition, wooden pallets benefit from a relatively high recycling rate (44.6%) and energy recovery rate (53.4%), which further mitigate their overall environmental footprint. Steel pallets, while associated with higher energy consumption and emissions during production, offer substantial environmental benefits at the EoL stage due to their high recycling potential. This recycling significantly offsets the production-stage impacts, particularly in terms of MD. The sensitivity analysis highlights that reducing the recycling rate of steel pallets from 100% to 70% significantly elevates environmental impacts across all categories. Maintaining high recycling rates is therefore critical to minimising the environmental footprint of steel pallet disposal. Paper pallets, although showing moderate impacts in some categories, are limited by their lower carrying capacity and reduced energy recovery rate, which increases their environmental burden at the EoL stage.

- How to establish a framework to facilitate the green transformation of the pallet industry?

The analysis presented in Section 2.5.2 highlights a significant research gap in the existing literature concerning the environmental implications of CE strategies for pallets. The literature review highlights a significant gap in the existing research, where the focus has predominantly been on single CE strategy for specific pallet types, primarily wooden pallets. This narrow approach neglects the environmental impacts associated with other pallet types and the comprehensive integration of CE strategies that could benefit the entire pallet industry. This narrow focus neglects the diversity of pallet types, including plastic, paper, steel, and fly ash, and fails to address the comprehensive integration of CE strategies necessary for the green transformation of the entire pallet industry. Moreover, the limited scope of existing research has hindered a holistic understanding of the pallet industry's environmental impacts. Most studies have centred on product-level evaluations, overlooking broader industry structures that influence environmental performance. This oversight is particularly pronounced in the context of China, where a lack of LCI data and analysis regarding the pallet market exacerbates the challenge of identifying effective CE strategies. Given China's unique market conditions, pallet types, and practices, the absence of a comprehensive framework for green transformation is a significant gap that this thesis seeks to address.

In response to these deficiencies, this research proposes a framework that encompasses three distinct scenarios: the base case, the sharing system, and comprehensive CE strategies as presented in Section 3.3. Each scenario serves a specific purpose in understanding the environmental impacts and the reduction potential of the pallet industry. The base case reflects current practices and consumption patterns within the Chinese pallet market, providing a baseline for evaluating environmental implications. The sharing system, on the other hand, explores the possibilities of increased reuse to reduce reliance on disposable pallets. Finally, the comprehensive CE strategies aim to integrate multiple CE practices, promoting the supply chain with low environmental impacts

A negative correlation between the number of RSL and the environmental effects has been confirmed through sensitivity analysis in Section 4.2. The analysis indicates that increasing the reuse frequency of pallets can lead to significant reductions in environmental impacts, ranging from 38% to 80% across various categories. For instance, the GWP impact can be mitigated by 65% to 89% when pallets are reused more extensively. These findings demonstrate the importance of establishing best practices in pallet handling and employee training, as suggested by Carrano et al. (2014), to extend the service life of pallets and enhance their environmental performance. Besides, the comparative analysis of the environmental impacts of different pallet types under the CE scenario reveals environmental benefits. For example, wooden pallets exhibit a GWP reduction of 96.75%, decreasing from 12.67 kg CO_2 eq. to 0.41 kg CO_2 eq. The significant decrease in environmental burdens highlights the effectiveness of CE strategies in mitigating carbon emissions associated with pallet logistics. Similarly, plastic pallets achieve a remarkable reduction in GWP, from 61.68 kg CO_2 eq. to a net negative impact of -0.01 kg CO_2 eq., showing the potential for emissions offsets within a circular system.

The comparative analysis of environmental impacts for different pallet types within the context of the sharing system and comprehensive CE strategies reveals substantial environmental impacts reduction. For wooden pallets, reductions range from 92.46% (HT) to an impressive 249.56% (IR). Plastic pallets show even more pronounced improvements, with reductions spanning from 98.74% (HT) to 111.54% (TE). Paper pallets experience reductions ranging from 70.42% (FC) to 121.31% (IR). However, their lower carrying capacity and shorter service life limit the extent of these benefits, leading to comparatively smaller reductions Steel pallets achieve reductions from 98.40% (HT) to 108.73% (MD), while fly ash pallets demonstrate reductions ranging from 96.78% (POF) to 105.66% (MD). These substantial reductions across all pallet types highlight the effectiveness of CE strategies in minimising environmental burdens. In addition, the environmental performance of pallets varies significantly across different scenarios. In examining the impacts of various pallet types, it is essential to consider the green transformation stages, spanning from base case, the sharing system, to the CE scenario. Under the base case, wooden pallets demonstrate lower impacts across ten impact categories. In the sharing system, steel pallets show the lowest impacts across nearly all categories, primarily due to their high load-carrying capacity and long lifespan, which significantly reduce the environmental burdens per FU. In contrast, fly ash pallets exhibit the lowest impacts across five impact categories under the CE scenario. However, one of the important factors influencing the environmental performance of pallets is the decarbonisation of the Chinese energy system. China has declared its pledge to peak its carbon dioxide emissions before 2030 and to reach carbon neutrality by 2060. This will require a significant shift from coal and other fossil fuels to renewable energy sources, such as wind and solar power. However, this transition will take some decades, and until then, steel pallets will be more GHG-intensive than wooden pallets, as steel production relies heavily on coal and coke. Therefore, the environmental impacts of steel pallets will depend on the pace and scale of the decarbonisation of the Chinese energy system. Another factor that affects the environmental performance of pallets is the availability of fly ash, which is a by-product of coal combustion. Fly ash can be used as a raw material for pallets, which can reduce the amount of fly ash that would otherwise be disposed of in landfills. However, there is also a limitation on the amount of fly ash that can be used for pallets, as it depends on the quality and quantity of fly ash produced by coal-fired power plants. Moreover, the amount of fly ash will decrease with the decarbonisation of energy, as coal consumption will decline. Therefore, the availability and quality of fly ash in the future will have impacts on the environmental performance of fly ash pallets. These findings demonstrate the importance of adopting diverse strategies and selecting appropriate materials to effectively mitigate environmental impacts associated with pallet logistics.

The national-scale LCA assessment further illustrates the framework's applicability. By integrating market share data into the evaluation, the research provides a realistic estimation of the environmental impacts associated with different scenarios within China's pallet logistics sector. The results indicate that transitioning from the base case to the sharing system and, ultimately, to a CE system can lead to substantial reductions in environmental impacts. The results show that adopting the sharing system and CE strategies can significantly reduce the environmental impacts of pallet logistics in China, compared to the base case scenario. The reduction rates of each impact category under the sharing system are high, ranging from 90% to 96%. While the sharing system demonstrates considerable environmental benefits, the CE scenario delivers greater improvements, further minimising the environmental footprint. The results of environmental impact categories under CE scenario can be reduced from 94% to 108% compared to base case scenario. These findings reinforce the necessity of adopting comprehensive CE strategies for the green transformation of the pallet industry in China.

5.1.2 Implications for management

A pallet sharing system can bring benefits to the logistics industry and the society, such as reducing the consumption of resources, saving the costs of purchasing pallets, increasing the utilisation rate of pallets, enhancing the coordination and integration of supply chain partners, and improving the environmental performance of logistics activities (Hariga et al., 2016; Hellström and Johansson, 2010; Rosenau et al., 1996; Zhou et al., 2014). However, establishing pallet sharing system also faces many challenges and barriers in its implementation, especially in China, where the development of sharing system is still in its infancy. 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, it fails to address the challenges that impede the diffusion of pallet circulation and sharing in China and the current rate of pallet circulation and sharing in China is only 1.8%. The main barriers and strategies for promoting the green transformation of the pallet industry have been summarised in Table 15.

Lack of pallet standardisation. Without standardised pallets, the logistics operators have to deal with different sizes and dimensions of pallets, which may not fit well with the loading and unloading equipment, the storage facilities, the transportation vehicles or the packaging materials. This can result in higher costs for handling, sorting, repairing, replacing or disposing of pallets, as well as lower utilisation of space and resources. In addition, non-standardised pallets may not meet the quality and safety requirements of certain industries or markets, such as food, pharmaceuticals, chemicals, etc., which can pose risks for the products, the workers and the environment, as well as damage the reputation and competitiveness of the enterprises. 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, instead of relying solely on pallet producers, who have limited influence or negotiating power, the emphasis should be on involving the top user companies in the supply chain to promote pallet standardisation.

Low awareness and willingness of users to participate in pallet sharing system. Many enterprises in China prefer to use their own customised pallets or disposable pallets, rather than adopt standardised pallets or participate in pallet sharing systems, which is partly due to the lack of trust, transparency and incentives in the pallet market, as well as the perceived costs and risks of changing their existing practices (Ren et al., 2019). Consumers also have low awareness of the benefits of pallet sharing and CE strategies, such as reducing environmental impacts, improving efficiency and saving resources. The success of pallet sharing system in Europe and the US is contingent upon factors such as the availability of pallet collection and recycling services, and environmental awareness of stakeholders (Gerber, 2020). Drawing lessons from them, China could enhance communication or education mechanism that can raise awareness and understanding of the benefits and challenges of the sharing system among different stakeholders, such as consumers and producers (Kirchherr and Piscicelli, 2019).

The loss of tonnage problem. Despite the advantages of sharing pallets, most users in China only use pallets within their own warehouses, rather than sharing them with other suppliers or distributors (Zhang et al., 2023). This reluctance is partly due to the "loss of tonnage" problem associated with using pallets for transportation, wherein pallets occupy space in trucks or railway containers, thereby reducing the amount of goods that can be transported and increasing transportation costs (Kočí, 2019). Therefore, reducing transportation cost by increasing vehicle-to-goods matching efficiency and optimising load factor is an effective way (Duan et al., 2019; Li, 2019). This can reduce empty trips, improve vehicle utilisation rate (Abate and Kveiborg, 2013) as well as reduce tonnage loss and fuel consumption (Kang et al., 2021). By improving vehicle-to-goods matching efficiency and load factor through information technology and data analysis, China can enhance transportation efficiency and reduce transportation cost (Sacchi et al., 2021), thus creating more incentives for enterprises to use and share pallets.

Lack of differentiation in the management strategies. The existing policy lacks differentiation in the management strategies for various types of pallets. Different materials of pallets have different hotspots of environmental effects based on the results in Section 4.2. Among all the factors that cause environmental impacts, the production stage is the hotspot for plastic, steel and fly ash pallets under the current practice. 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). Environmental performance could be improved through reducing the inefficient driving of transport vehicles, deploying clean energy trucks to transport pallets and developing lightweight pallets, in order to reduce environmental impacts of the use stage (Bauer et al., 2015; Wu et al., 2019).

Lack of sufficient and reliable data and platform. There is no comprehensive and transparent database or platform that can facilitate CE decision making and coordination among different actors. For example, there is no effective tracking or tracing system that can monitor the flow and status of pallets and other resources throughout their lifecycle (Li et al., 2018). Specifically, plastic pallets are regarded as a competitor for wooden pallets, 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. Therefore, awareness needs to be raised on the traceability and supervision of plastic raw materials (Mendoza et al., 2022). In addition, the loss or open dump of pallets still exists, which can cause visual pollution, fire hazards, soil erosion, and harm to animals that ingest or get entangled in them (Lehner et al., 2019). Therefore, establishing a comprehensive and transparent tracking system that can monitor the flow and status of pallets and provide information on the availability, location, quality, and price of pallets can be helpful to monitor the quality of pallets and increase collection rates.

Lack of standards and regulations for pallet quality, safety and certification. A deficiency in the Chinese pallet industry pertains to the absence of a unified standard dictating the quality parameters for remanufactured pallets, which poses significant challenges in ensuring consistent quality, safety, and reliability in the utilisation of such pallets, potentially impeding their wider adoption and integration into supply chain operations. Although China has enacted some laws and regulations related to CE, such as the Circular Economy Promotion Law, the Cleaner Production Promotion Law, and the Environmental Protection Law, they are still fragmented, inconsistent, and inadequate to cover all aspects of CE. Especially, these regulations are not enacted for the pallet industry. A certification system for remanufactured or recycled pallets that can ensure their quality and safety and promote their recognition and adoption in the market can be constructed.

The lack of infrastructure and technology for pallet collection, sorting, treatment and recovery. The lack of infrastructure and technology for pallet collection, sorting, treatment and recovery, can result in higher waste generation or lower resource recovery. The construction of the infrastructure and development of technology for pallet collection, sorting and treatment, such as building or upgrading facilities or equipment for repairing or remanufacturing damaged pallets, or for recycling or recovering materials from waste pallets, the increased availability, compatibility or interoperability with different types of pallets or systems can facilitate the achievement of CE scenario (Joensuu et al., 2020).

Table 15

Barriers and strategies for promoting the green transformation of the pallet industry

Barriers	Strategies
Lack of pallet standardisation	Engage top-tier user companies in the supply chain to advocate for standardisation
Low awareness and willingness to participate in pallet sharing systems	Enhance educational mechanisms to raise awareness of the benefits of pallet sharing and CE strategies
The tonnage loss problem	Optimise vehicle-to-goods matching efficiency and load factor to reduce transportation costs and increase vehicle utilisation
Lack of differentiation in management strategies	Develop differentiated management strategies for various pallet materials to address specific environmental impact hotspots
Lack of sufficient and reliable data and platform	Establish a comprehensive and transparent database or platform to facilitate CE decision-making and coordination
Lack of standards and regulations for pallet quality, safety, and certification	Implement unified standards for remanufactured pallets to ensure quality, safety, and reliability
Lack of infrastructure and technology for pallet collection, sorting, treatment, and recovery	Construct and upgrade infrastructure and technology for efficient pallet collection, sorting, treatment, and recovery processes

5.1.3 Research limitations

This study has some limitations that need to be acknowledged and addressed in future research. First, the potential omission of relevant literature in the keyword search and exclusion criteria of Chapter 2 may lead to the disregard of pivotal research outcomes, consequently impacting the recommendations proposed. For instance, the decision to exclude grey literature and non-English publications might raise issues related to publication bias. Similarly, the use of specific keyword combinations and synonyms in titles and abstracts could result in the exclusion of relevant studies that do not employ the chosen terminology. While the systematic literature reviews strive for comprehensiveness and aim to draw general conclusions on the subject, the possible exclusion of certain studies means that the reviews may not be entirely comprehensive, potentially overlooking crucial research that could alter the analysis's conclusions.

Second, the MFA and LCA analysis have adopted some assumptions and simplifications, which may affect the accuracy and validity of the results. For example, the MFA analysis assumed that the material input and output of each pallet type are constant and homogeneous, and that the material losses during use stage are negligible. However, in reality, the material input and output may vary depending on the quality, design, and usage of each pallet type, and the material losses and wastes may be significant due to damage, or improper handling. The LCA analysis also used generic data from existing databases, which may not be representative or specific for the Chinese context.

Third, the green transformation pathway evaluation of this study only constructs two alternative scenarios: sharing system and CE, which may not cover all possible scenarios or strategies for reducing the environmental impacts of pallets. Besides, these CE strategies may not be exhaustive or definitive, and they may face some challenges or limitations in their application or effectiveness. The scenario evaluation also relied on some hypothetical parameters and estimates, such as the reuse times and the recycling rates, which may vary depending on different conditions and contexts. Therefore, the scenario evaluation may not reflect the actual or potential environmental benefits or challenges of implementing these scenarios or strategies in practice, and may miss some other feasible or effective scenarios or strategies for reducing the environmental impacts of pallets. Future research could explore other scenarios, such as green procurement, eco-innovation, etc., and compare their effectiveness and feasibility with sharing system and CE strategies. In addition, this thesis does not account for the environmental impacts associated with pallets produced from other alternative materials. This oversight presents an opportunity for future research to explore the environmental implications of various pallet materials, such as biodegradable options. By incorporating these materials into the analysis, subsequent studies could provide a more comprehensive understanding of the environmental performance of pallets made from innovative materials and contribute to the development of more sustainable practices within the logistics.

Fourth, the assessment dimensions ignore other important aspects, such as social and cost aspects, which may influence the decision making and behaviour of pallet stakeholders. Therefore, the assessment dimensions may not capture all the relevant criteria for promoting the green transformation of the pallet industry in China, and may neglect some potential benefits or costs associated with different types of pallets. Future research could include more assessment dimensions to provide a more holistic evaluation of the green transformation of the pallet industry in China, and could also use multi-criteria decision analysis methods to integrate different assessment dimensions into a comprehensive framework.

5.2 Conclusions and future work

5.2.1 Conclusions

This thesis has provided implications to green the booming pallet sector by examining the pallet flows along the entire supply chain and the waste structure of different pallet categories in different sectors, and establishing a comprehensive green transformation framework which adopts sharing system and CE strategies. The environmental effects and the reduction potential covering the whole life cycle stage have been systematically evaluated. Further, the main challenges and strategies for the green transformation of the pallet logistics have also been discussed. Besides, this research has provided implications by integrating MFA and LCA methods: 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 at two scales. 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 and the reduction potential in three scenarios at two levels across various categories, providing a comprehensive view of each pallet type's environmental performance. 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.

The overall aim of this thesis is to investigate the circularity and establish a framework for the green transformation pathway of the pallet industry. The objectives outlined in Chapter 1 and described below, have been achieved:

- To develop and apply an MFA framework for pallets at the national scale in China, and to quantify the sources, sinks and pathways of pallet products in the Chinese socio-economic system in 2020.
- To provide a comprehensive framework to identify the green transformation pathway of the pallet industry in China and examine the

potential for the environmental impacts reduction brought by the scenarios established in the framework.

- To provide guidance for the stakeholders along the entire supply chain on the barriers and strategies that facilitate the green transformation of the logistics carrier industry in China.

Firstly, the development and application of a MFA framework for pallets at the national scale in China allowed for a comprehensive quantification of the sources, sinks, and pathways of pallet products within the socio-economic system in 2020. This analysis revealed critical gaps in the current management practices and emphasised the opportunities to increase circularity. Secondly, the establishment of a comprehensive framework to identify the green transformation pathway of the pallet industry in China demonstrated the potential for substantial environmental impact reductions through various scenarios. The findings indicated that adopting a pallet sharing system could significantly enhance the environmental performance of logistics activities. This was particularly evident in the comparative analysis of environmental impacts across different pallet types, which highlighted the effectiveness of CE strategies in mitigating environmental burdens. Lastly, the thesis provides practical guidance for stakeholders throughout the supply chain, identifying barriers and strategies that can facilitate the green transformation of the logistics carrier industry in China. By addressing issues such as the low awareness and willingness of users to participate in pallet sharing systems, the "loss of tonnage" problem, and the lack of infrastructure and technology for pallet recovery, this research aims to foster greater collaboration among supply chain partners and promote a sustainable transition within the industry.

The following points summarise the key findings of this thesis:

- This thesis significantly fills existing data gaps and comprehensively analyse pallet flows and stocks across various sectors in China using MFA, surpassing previous studies that were often limited in scope. The MFA research identifies the areas for increasing the resource efficiency and promoting circularity. A 36% pre-consumer waste rate highlights substantial improvement opportunities in the pallet manufacturing sector, generating 4.53 Mt of waste. Current waste management practices in China are not circular, as evidenced by relatively high landfill rates for wooden and plastic pallets. There is an urgent need for improved collection and segregation systems.

- The existing literature predominantly emphasise the carbon footprint of wooden pallets, particularly in the U.S., neglecting other materials that constitute a substantial portion of the pallet market in China. This study addresses this gap by establishing a green transformation framework which offers comprehensive assessments of the lifecycle environmental impacts across five pallet types under three scenarios at product scale and national scale. A framework on identifying the green transformation stages of pallet logistics in China is established, transforming from the baseline scenario with single-use pallets and the current waste disposal methods, establishing a pallet sharing system to adopt comprehensive CE strategies. The study emphasises the applicability of the proposed framework, indicating that transitioning from the base case to a sharing system and ultimately to a CE system can lead to significant environmental impact reductions, with rates as high as 90% to 96% under the sharing system and 94% to 108% under CE strategies. The results suggest that green transformation in the pallet market can also contribute to the efforts to achieve carbon neutrality in China.

- The research also identifies the main barriers and proposes some strategies for achieving the green transformation of the pallet industry in China. 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.

This research uses pallets as an example to provide some enlightenment for stakeholders, in China and beyond, who are facing challenges and opportunities of green transformation in logistics carrier systems. By facilitating the green transformation of Chinese pallet industry which accounts for 25% of the global pallet market, the study can contribute to SDG12 targets and efforts to achieve China's pledge to achieve carbon neutrality by 2060.

5.2.2 Avenues for future research

This study has provided a comprehensive analysis of the green transformation of the pallet logistics in China. Based on the limitations and findings of this study, some avenues for future research are suggested as follows:

- Future studies could further examine the socio-cultural norms that influence the consumer behaviour regarding pallets, especially how to bridge the gap between consumer awareness and consumer actions in terms of purchasing and disposing of pallets. This could help to understand the motivations and barriers for consumers to adopt more sustainable and circular practices, such as sharing or recycling pallets, and to design effective interventions and incentives to encourage such practices.

- Future research could also explore other scenarios or strategies, such as green procurement, eco-innovation, etc., and compare their effectiveness and feasibility. This could help to discover more opportunities and challenges for improving the environmental performance of pallets, and to evaluate the optimal combination of strategies for different types of pallets.
- This thesis does not address the environmental impacts of pallets made from other alternative materials, such as biodegradable options. Future research could fill this gap by examining these materials, offering a more comprehensive understanding of pallets' environmental performance and aiding in the development of sustainable practices within the logistics sector.
- Future research could also include more assessment dimensions, such as social and cost aspects, to provide a more holistic evaluation of the sustainability of the pallet industry in China. This could help to understand the social and economic implications of pallets, such as job creation, customer satisfaction, social equity, profitability, competitiveness, etc., and to balance the environmental, social, and economic goals of sustainability.

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Appendices

Appendix A Literature review

Table A. 1: Keyword search and search results for LCA of pallets in China

Search strings	Search results	Relevance to topic	
		Included	Excluded
“life cycle assessment” AND ““pallet” AND “China”	6	0	6
“environmental impact” AND “pallet” AND “China”	11	0	11
“life cycle assessment” AND “pallet”	53	22	31
“environmental impact” AND “pallet”	120	29	91

Table A. 2: Overview of the functional units, material type, system boundary and life cycle inventory of pallet LCA literature review

Reference	Country	Material type	Goal and scope definition	Functional unit	System boundary	LCA software	Database	Foreground LCI data	Multifunctionality	Impact assessment method	Impact category /other category	Normalisation	Weighting	Uncertainty analysis

Bilbao, A.M., Carrano, A.L., Hewitt, M., Thorn, B.K., 2011. On the environmental impacts of pallet management operations. Management Research Review.	Not specified	Wooden and plastic pallets	To calculate the environmental impacts related to pallet management	Not defined	Cradle-to-grave	Excluded	Not specified	Not specified	Not specified	Not performed	Not specified	Not performed	Not performed	Not performed
Bilbao, M.A., Carrano, A., Thorn, B., Hewitt, M., 2010. Environmental impact analysis of pallets management, IIE Annual Conference. Proceedings. Institute of Industrial and Systems Engineers (IISE), p. 1.	the US	Wooden pallets	To determine the most effective pallet management system to minimize carbon dioxide emissions	Not defined	From pallet manufacturers to the consumer product manufacturers	Excluded	Not specified	Not specified	Not specified	Not performed	Not performed	Not specified	Not performed	Not performed

Alanya-Rosenbaum, S., Bergman, R., Gething, B., 2021. Assessing the life cycle environmental impacts of the wood pallet sector in the United States. Journal of Cleaner Production 320, 128726.	the US	Wooden pallets	To quantify the environmental impacts of wooden pallets and identify key environmental hotspots within the supply chain for potential system improvements	45.4 t of pallet loads of product delivered using wood pallets	Cradle-to-grave	SimaPro v9	Ecoinvent and DATASMART (US EI 2.2) databases	Primary and secondary data	Allocation by weight	TRACI method	GWP, AP, EP, OD, PS, FD and CED	Not performed	Not performed	Sensitivity analysis
Alanya-Rosenbaum, S., Bergman, R., Gething, B., Mousavi-Avval, S.H., 2022. Life cycle assessment of the wood pallet repair and remanufacturing	the US	Wooden pallets	To quantify environmental impacts of wooden pallet repair/ remanufacturing	One repaired/remanufactured pallet output	Gate-to-gate (covering raw material supply, raw material transportation and pallet	SimaPro v9.1	Ecoinvent v3.524 and DATASMART (US EI 2.2)	Primary and secondary data	Allocation by weight	TRACI 2.1	GWP, AP, EP, OD, PS, FD and CED	Not performed	Not performed	Sensitivity analysis

sector in the United States. Biofuels, Bioproducts and Biorefining 16, 1342-1352.					repair/remanufacturing)									
Kočí, V., 2019. Comparisons of environmental impacts between wood and plastic transport pallets. Science of the Total Environment 686, 514-528.	Not specified	Wooden and plastic pallets	To compare the environment impacts of wooden and plastic pallets	The transport of 1000 kg of cargo	Cradle-to-grave	GaBi 8s	Not specified	Primary and secondary data	Avoided	ReCiPe 2016 v1.1Midpoint(H)	GWP, FPMF, FD, FC, FE, FEu, HT, IR, LU, ME, MEu, MD, POF, SOD, TA and TE	Not performed	Not performed	Sensitivity analysis

Khan, M.M.H., Deviatkin, I., Havukainen, J., Horttanainen, M., 2021. Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. The International Journal of Life Cycle Assessment 26, 1607-1622.	Finland	Wooden, plastic, and woo d-polymer composit e pallets	To assess the environment al impacts of manufacturin g, utilising, and disposal of pallets made of different materials	1000 trips	Cradle-to-grave	GaBi	GaBi thinkstep	Primary and secondary data	Avoided	CML 2001–Jan. 2016	ADP, AP, EP, GWP, and OD	Performe d	Not perfor med	Sensitivit y analysis
Carrano, A.L., Pazour, J.A., Roy, D., Thorn, B.K., 2015. Selection of pallet management strategies based on carbon emissions impact. International Journal of	the US	Wooden pallets	To compare carbon footprint of three pallet management strategies	100,000 pallet-trips	Cradle-to-grave	SimaPro	Ecoinvent and the U.S. Life Cycle Inventory	Primary and secondary data	Not specified	Not specified	GWP	Not performe d	Not perfor med	Not performe d

Production Economics 164, 258-270.														
Carrano, A.L., Thorn, B.K., Woltag, H., 2014. Characterizing the carbon footprint of wood pallet logistics. Forest Products Journal 64, 232-241.	the US	Wooden pallets	To compare carbon footprint of three types of wooden pallets	One piece of wooden pallet	Cradle-to-grave	SimaPro	Ecoinvent	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Not performed
Tornese, F., Carrano, A.L., Thorn, B.K., Pazour, J.A., Roy, D., 2016. Carbon footprint analysis of pallet remanufacturing. Journal of Cleaner Production 126,	the US	Wooden pallets	To assess carbon footprint of the remanufacturing of wooden pallets	One piece of wooden pallet	Gate to gate	Excluded	Ecoinvent	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Not performed

630-642.															
Tornese, F., Pazour, J.A., Thorn, B.K., Roy, D., Carrano, A.L., 2018. Investigating the environmental and economic impact of loading conditions and repositioning strategies for pallet pooling providers. Journal of Cleaner Production 172, 155-168.	Not specified	Wooden pallets	To assess carbon footprint of collecting, remanufacturing, and repositioning pallets	One piece of wooden pallet	From pallet collecting, remanufacturing, to repositioning	Excluded	From literature or estimated through direct observations	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Not performed	

Weththasinghe, K., Akash, A., Harding, T., Subhani, M., Wijayasundara, M., 2022. Carbon footprint of wood and plastic as packaging materials–An Australian case of pallets. Journal of Cleaner Production 363, 132446.	Australia	Wooden and plastic pallets	To compare carbon footprint of wooden and plastic pallets	Completing 100 trips using pallets, carrying the same load.	cradle-to-grave	Excluded	The Department of the Environment and Energy's National Greenhouse Accounts (NGA) Factors 2020	Primary and secondary data	the proportion of products manufactured at the plant.	GHG Protocol	GWP	Not performed	Not performed	Sensitivity analysis
Bengtsson, J., Logie, J., 2015. Life cycle assessment of one-way and pooled pallet alternatives. Procedia CIRP 29, 414-419.	China or Australia	Wooden, plastic pallets and cardboard pallets	To calculate the environmental impact of wooden, and plastic pallets compared to their key market alternatives: simple/one-	1,000 customer trips, carrying the same load.	Cradle-to-grave	SimaPro (v8.03)	Ecoinvent	Primary and secondary data	Not performed	ReCiPe (v1.10)	GWP, TA, FEu, MEu, HT, PO, FPMF. FE, ME, IR, ULO, ALO, MD, TE, OD, WD and FD	ReCiPe	ReCiPe	Sensitivity analysis

			way pallets of softwood or cardboard											
Anil, S.K., Ma, J., Kremer, G.E., Ray, C.D., Shahidi, S.M., 2020. Life cycle assessment comparison of wooden and plastic pallets in the grocery industry. Journal of Industrial Ecology 24, 871-886.	the US	Wooden and plastic pallets	To compare environmental impacts of wooden and plastic pallets	1 pallet trip and 100,000 pallet trips	Cradle-to-grave	SimaPro software	Ecoinvent	Primary and secondary data	Not specified	CML2002,Eco-Indicator 99,and Impact2002+	Carcinogens, AE, TE, LU, NE, OD, EP, AP, ME, GWP and TA	Not performed	Not performed	Monte Carlo analysis

García-Durañona, L., Farreny, R., Navarro, P., Boschmonart-Rives, J., 2016. Life Cycle Assessment of a coniferous wood supply chain for pallet production in Catalonia, Spain. Journal of Cleaner Production 137, 178 188.	Spain	Wooden pallets	To assess the environmental impact of the production of wooden pallets	1 unit of EUR-pallet (22.35 kg)	Cradle-to-gate (from the extraction of wood in the forest to the final products ready for distribution)	SimaPro 8.0.3.14	Ecoinvent 3.1	Primary and secondary data	Mass and economic value	ReCiPe Midpoint (H) v1.10	GWP, OD, TA, FEu, HT; ALO, WD and CED	Not performed	Not performed	Not performed
Gasol, C.M., Farreny, R., Gabarrell, X., Rieradevall, J., 2008. Life cycle assessment comparison among different reuse intensities for industrial wooden containers. The International Journal	Spain	Wooden pallets	To develop a LCI analysis and compare the environmental impacts of pallets with low use and high use	Transport 1,000 t by road with wooden pallets	Cradle-to-grave	SimaPro 7.0	Ecoinvent	Primary and secondary data	Not specified	CML Leiden 2000	ADP, GWP, OD, HT, AP, EP and CED	Not performed	Not performed	Not performed

of Life Cycle Assessment 13, 421-431														
Anil, S.K., 2010. Environmental analysis of pallets using life cycle analysis and multi-objective dynamic programming.	the US	Wooden and plastic pallets	To compare environmental impacts of wooden and plastic pallets	1 pallet trip and 100,000 pallet trips	Cradle-to-grave	SimaPro software	Ecoinvent	Primary and secondary data	Not specified	CML2002,Eco-Indicator 99,and Impact2002+	Carcinogens, AE, TE, LU, NE, OD, EP, AP, ME, GWP and TA	Not performed	Not performed	Monte Carlo analysis
Ng, R., Shi, C.W.P., Tan, H.X., Song, B., 2014. Avoided impact quantification from recycling of wood waste in Singapore: an assessment of pallet made from	Singapore	Wooden pallets	To compare the carbon emissions of pallets from technical wood and virgin wood	Pallet system of standard size	Cradle-to-grave	Excluded	Excluded	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Sensitivity analysis

technical wood versus virgin softwood. Journal of Cleaner Production 65, 447-457.															
Park, J., Horvath, L., Bush, R.J., 2018. Life Cycle Inventory Analysis of the Wood Pallet Repair Process in the United States. Journal of Industrial Ecology 22, 1117-1126.	the US	Wooden pallets	To quantify the carbon footprint of the repair process of wooden pallets	A repaired 48 by 40 inch (1,219 by 1,016 mm) stringer-class wood pallet	Gate-to-gate (including only pallet-repair–related activities)	SimaPro (Version 7.3.3)	Ecoinvent and U.S. Life Cycle Inventory	Primary and secondary data	Volume-based weighting factors	Not specified	GWP	Not performed	Not performed	Pedigree matrix	

Shao, F., Cui, Q., 2023. Comparison of life cycle assessment for wooden pallet and different plastic pallets based on SimaPro. Pigment & Resin Technology.	Not specified	Wooden and plastic pallets	To compare the environmental impact of wooden and plastic pallets	A 1 * 1.2mpallet	Cradle-to-grave	SimaPro	Ecoinvent 3.0 and ELCD	Primary and secondary data	Not specified	CML2001	ADP, GWP, OD, HT, FE, ME, TE, PO AP, EP and WD	Not performed	Not performed	Not performed
Kim, S., Horvath, L., Russell, J.D., Park, J., 2023. Sustainable and Secure Transport: Achieving Environmental Impact Reductions by Optimizing Pallet-Package Strength Interactions during Transport. Sustainability 15, 12687.	the US	Wooden pallets	To examine the environmental impact of optimising a unit load by decreasing the board grade of the pallets' corrugated boxes and stiffening the top deck boards of the pallets	A double-stacked unit loads with the same maximum safe load capacity under floor stacking conditions	Cradle-to-grave	SimaPro 9.0	Ecoinvent v.3	Secondary data	Not specified	TRACI2.1	OD, GWP, smog, AP, EP, carcinogens, non-carcinogens, RE, ecotoxicity and FD	Not performed	Not performed	Sensitivity analysis

Tornese, F., Pazour, J.A., Thorn, B.K., Carrano, A.L., 2019. Environmental and economic impacts of preemptive remanufacturing policies for block and stringer pallets. Journal of Cleaner Production 235, 1327-1337.	Not specified	Wooden pallets	To evaluate the impact of preemptive remanufacturing policies on the economic and environmental performance of wooden pallet logistics	48- by 40-inch stringer and block pallets	Gate-to-gate	Excluded	Excluded	Secondary data	Not specified	Excluded	GWP	Not performed	Not performed	Not performed
Choi, B., Yoo, S., Lee, K.-D., Park, S.-i., 2020. An environmental impact comparison of disposable wood pallets and reusable steel cradles: A case study on rolled steel coils in container shipping in South	South Korea	Wooden pallets	To compare environmental impacts of disposable wood pallets and reusable steel cradles	1,000 RSCs	Cradle-to-grave	SimaPro 8.2.0	Ecoinvent and Agrifootprint	Secondary data	Not specified	IMPACT 2002+	Carcinogens, non-carcinogens, RI, IR OD, RO, AE, TE, TA, LU, AA, AEu, GWP, NE and ME	Not performed	Not performed	Not performed

Korea. International Journal of Sustainable Transportation 14, 335-342.														
Zacchei, E., Tadeu, A., Almeida, J., Esteves, M., Santos, M.I., Silva, S., 2022. Design of new modular metal pallets: Experimental validation and life cycle analysis. Materials & Design 214, 110425.	Portugal	Wooden, plastic and aluminium, steel pallets	To compare the environmental performance of pallets made of steel, wood, plastic or aluminium	A pallet with a lifespan of 20 years	Cradle-to-grave	SimaPro	Ecoinvent v3.6	Primary and secondary data	Not specified	CML–IAmethod - version4.7	ADP, GWP, OD, PO, AP and EP	Not performed	Not performed	Not performed

Niero, M., Di Felice, F., Ren, J., Manzardo, A., Scipioni, A., 2014. How can a life cycle inventory parametric model streamline life cycle assessment in the wooden pallet sector? The International Journal of Life Cycle Assessment 19, 901-918.	Italy	Wooden pallets	To develop a LCI parametric model of wooden pallets	One unit of finished pallet ready to be transported	Cradle-to-grave	Not specified	Ecoinvent, US Life Cycle Inventory, ELCD	Primary and secondary data	Not specified	ReCiPe 2008	GWP, FD, HT, FPMF and ALO	Not performed	Not performed	Not performed
Korol, J., Burchart-Korol, D., Pichlak, M., 2016. Expansion of environmental impact assessment for eco-efficiency evaluation of biocomposites for industrial application. Journal of Cleaner	Not specified	Plastic pallet produced from biocomposites and composites based on PP, GF and	To compare the environmental impacts of different materials	One heavy-duty plastic pallet made by an injection molding process	Cradle-to-gate (from raw material extraction to plastic pallet production)	SimaPro 8	Ecoinvent database 3.1	Secondary data	Not specified	ReCiPe 2008	GWP, OD, HT PO, FPMF, IR, TA, FEu, MEu, TE, FE, ME, ALO, ULO, NLT, WD,	ReCiPe	ReCiPe	Not performed

Production 113, 144-152.		CF, JF, and KF									MD and FD			
Korol, J., Hejna, A., Burchart-Korol, D., Chmielnicki, B., Wypiór, K., 2019. Water footprint assessment of selected polymers, polymer blends, composites, and biocomposites for industrial application. Polymers 11, 1791.	Not specified	PP, as well as its blends with bio-based polymers (poly(lactic acid) and thermoplasticstarch) and composites with CF, JF and KF	To evaluate the water footprint of selected polymer blends and composites	One standard EUR-pallet	Cradle-to-gate	Not specified	Ecoinvent database v 3.1; National Residential Efficiency Measures Database; Natural Institute of Research on Jute and Allied Fibre Technology	Secondary data	Not specified	Excluded	Water footprint	Not performed	Not performed	Not performed

Korol, J., Hejna, A., Burchart-Korol, D., Wachowicz, J., 2020. Comparative analysis of carbon, ecological, and water footprints of polypropylene-based composites filled with cotton, jute and kenaf fibers. Materials 13, 3541.	Not specified	PP-based composites filled with CF, JF and KF	To assess the environmental footprints of polypropylene-based composites filled with natural fibers	One standard European pallet (EUR-pallet)	Cradle-to-gate	Not specified	Ecoinvent database v 3.1	Primary and secondary data	Not specified	Excluded	Carbon, ecological, and water footprints	Not performed	Not performed	Not performed
Lee, S., Xu, X., 2004. A simplified life cycle assessment of re-usable and single-use bulk transit packaging. Packaging Technology and Science: An International Journal 17, 67-83.	New Zealand	Plastic and wooden pallets	To evaluate and contrast the environmental performance of the reusable Enviropak© T760 packaging system	A unit of the Enviropak© T760 and the wooden pallet.	Cradle-to-grave	Not specified	Simapro 5.1, the Association of Plastic Manufacturers in Europe (APME) and the Life Cycle Assessment	Secondary data	Not specified	Environmental Priority Strategy (EPS) 2000 Default Method	Environmental load units	EPS 2000 Default Method	Environmental Priority Strategy (EPS) 2000 Default Meth	Monte Carlo analysis

			against that of the disposable wooden pallet packaging system				Data Inventory of the Centre for Design at RMIT University, Melbourne, Australia						od	
Khan, M.M.H., Havukainen, J., Niini, A., Leminen, V., Horttanainen, M., 2023. Consequential life-cycle assessment of treatment options for repulping reject from liquid packaging board waste treatment. Waste Management 155, 348-356.	Finland	EoL treatment methods	To compare the environmental impact of recycling rejected materials from the treatment of liquid packaging board waste	The treatment of one tonne of repulping reject	Cradle-to-grave	Gabi 10.5.0.78	Sphera database version 10.5.0.78	Primary and secondary data	System expansion	ReCiPe 2016 v1.1	GWP, FD, FEu, HT, PO, TA, FPMF, FC, FE, IR, LU, ME, MD, SOD and TE	Not performed	Not performed	Sensitivity analysis

Notes: GWP (climate change); FPMF (fine particulate matter formation); FD (fossil depletion); FC (freshwater consumption); FE (freshwater ecotoxicity);

FEu (freshwater eutrophication); HT (human toxicity); IR (ionizing radiation); LU (land use); ME (marine ecotoxicity); MEu (marine eutrophication); MD (metal depletion); POF (photochemical ozone formation); SOD (stratospheric ozone depletion); TA (terrestrial acidification); TE (terrestrial ecotoxicity); CED (cumulative energy demand); OD (ozone depletion); PS (photochemical smog); ADP (Abiotic depletion potential); AP (acidification potential); EP (eutrophication potential); AE (aquatic eco-toxicity); NE (non-renewable energy); ME (mineral extraction); WD (water depletion); PO (photochemical oxidation); RE (respiratory effects); RO (respiratory organics); AA (aquatic acidification); AEu (aquatic eutrophication); RI (respiratory inorganics); ALO (agricultural land occupation); ULO (urban land occupation); NLT (natural land transformation).

Table A. 3: Overview of the material type, system boundary, CE strategy and life cycle inventory of pallet CE literature review

Reference	**Country**	**Material type**	**Goal and scope definition**	**CE strategy**	**Functional unit**	**System boundary**	**LCA software**	**Database**	**Foreground LCI data**	**Multifunction ality**	**Impact assessment method**	**Impact category/ other category**	**Normal isation**	**Weig hting**	**Uncertainty analysis**

Alanya-Rosenbaum, S., Bergman, R., Gething, B., 2021. Assessing the life cycle environmental impacts of the wood pallet sector in the United States. Journal of Cleaner Production 320, 128726.	the US	Wooden pallets	To quantify the environmental impacts of wooden pallets and identify key environmental hotspots within the supply chain for potential system improvements	Repair	45.4 t of pallet loads of product delivered using wood pallets	Cradle-to-grave	SimaPro v9	Ecoinvent and DATASMART (US EI 2.2) databases	Primary and secondary data	Allocation by weight	TRACI method	GWP, AP, EP, OD, PS, FD and CED	Not performed	Not performed	Sensitivity analysis

Alanya-Rosenbaum, S., Bergman, R., Gething, B., Mousavi-Avval, S.H., 2022. Life cycle assessment of the wood pallet repair and remanufacturing sector in the United States. Biofuels, Bioproducts and Biorefining 16, 1342-1352.	the US	Wooden pallets	To quantify environmental impacts of wooden pallet repair / remanufacturing	Repair & remanufacture	One repaired/remanufactured pallet output	Gate-to-gate (covering raw material supply, raw material transportation and pallet repair/remanufacturing)	SimaPro v9.1	Ecoinvent v3.524 and DATASMART (US EI 2.2)	Primary and secondary data	Allocation by weight	TRACI 2.1	GWP, AP, EP, OD, PS, FD and CED	Not performed	Not performed	Sensitivity analysis

Kočí, V., 2019. Comparisons of environmental impacts between wood and plastic transport pallets. Science of the Total Environment 686, 514-528.	Not specified	Wooden and plastic pallets	To compare the environment impacts of wooden and plastic pallets	Recycle	The transport of 1000 kg of cargo	Cradle-to-grave	GaBi 8s	Not specified	Primary and secondary data	Avoided	ReCiPe 2016 v1.1 Midpoint(H)	GWP, FPMF, FD, FC, FE, FEu, HT, IR, LU, ME, MEu, MD, POF, SOD, TA and TE	Not performed	Not performed	Sensitivity analysis

Khan, M.M.H., Deviatkin, I., Havukainen, J., Horttanainen, M., 2021. Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. The International Journal of Life Cycle Assessment 26, 1607-1622.	Finland	Wooden, plastic, and woo d-polymer composit e pallets	To assess the environme ntal impacts of manufactur ing, utilising, and disposal of pallets made of different materials	Recycle	1000 trips	Cradle-to-grave	GaBi	GaBi thinkstep	Pri ma ry an d se co nd ary dat a	Avoi ded	CML 2001– Jan. 2016	ADP, AP, EP, GWP , and OD	Perfor med	Not perfor med	Sensitivit y analysis

Carrano, A.L., Pazour, J.A., Roy, D., Thorn, B.K., 2015. Selection of pallet management strategies based on carbon emissions impact. International Journal of Production Economics 164, 258-270.	the US	Wooden pallets	To compare carbon footprint of three pallet manageme nt strategies	Reuse	100,000 pallet-trips	Cradle-to-grave	SimaPro	Ecoinvent and the U.S. Life Cycle Inventory	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Not performed

Carrano, A.L., Thorn, B.K., Woltag, H., 2014. Characterizing the carbon footprint of wood pallet logistics. Forest Products Journal 64, 232-241.	the US	Wooden pallets	To compare carbon footprint of three types of wooden pallets	Repair & Recycle & Recover	One piece of wooden pallet	Cradle-to-grave	SimaPro	Ecoinvent	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Not performed
Tornese, F., Carrano, A.L., Thorn, B.K., Pazour, J.A., Roy, D., 2016. Carbon footprint analysis of pallet remanufacturing. Journal of Cleaner Production 126, 630-642.	the US	Wooden pallets	To assess carbon footprint of the remanufacturing of wooden pallets	Remanufacture	One piece of wooden pallet	Gate to gate	Excluded	Ecoinvent	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Not performed

Weththasinghe, K., Akash, A., Harding, T., Subhani, M., Wijayasundara, M., 2022. Carbon footprint of wood and plastic as packaging materials–An Australian case of pallets. Journal of Cleaner Production 363, 132446.	Australia	Wooden and plastic pallets	To compare carbon footprint of wooden and plastic pallets	recycle	Completing 100 trips using pallets, carrying the same load.	cradle-to-grave	Excluded	The Department of the Environment and Energy's National Greenhouse Accounts (NGA) Factors 2020	Primary and secondary data	the proportion of products manufactured at the plant.	GHG Protocol	GWP	Not performed	Not performed	Sensitivity analysis

Bengtsson, J., Logie, J., 2015. Life cycle assessment of one-way and pooled pallet alternatives. Procedia CIRP 29, 414-419.	China or Australia	Wooden, plastic pallets and cardboard pallets	To calculate the environmental impact of wooden, and plastic pallets compared to their key market alternatives: simple/one-way pallets of softwood or cardboard	Reuse	1,000 customer trips, carrying the same load.	Cradle-to-grave	SimaPro (v8.03)	Ecoinvent	Primary and secondary data	Not performed	ReCiPe (v1.10)	GWP, TA, FEu, MEu, HT, PO, FPMF. FE, ME, IR, ULO, ALO, MD, TE, OD, WD and FD	ReCiPe	ReCiPe	Sensitivity analysis

Gasol, C.M., Farreny, R., Gabarrell, X., Rieradevall, J., 2008. Life cycle assessment comparison among different reuse intensities for industrial wooden containers. The International Journal of Life Cycle Assessment 13, 421-431	Spain	Wooden pallets	To develop a LCI analysis and compare the environmental impacts of pallets with low use and high use	Reuse	Transport 1,000 t by road with wooden pallets	Cradle-to-grave	SimaPro 7.0	Ecoinvent	Primary and secondary data	Not specified	CML Leiden 2000	ADP, GWP, OD, HT, AP, EP and CED	Not performed	Not performed	Not performed

Ng, R., Shi, C.W.P., Tan, H.X., Song, B., 2014. Avoided impact quantification from recycling of wood waste in Singapore: an assessment of pallet made from technical wood versus virgin softwood. Journal of Cleaner Production 65, 447-457.	Singapore	Wooden pallets	To compare the carbon emissions of pallets from technical wood and virgin wood	Recycle	Pallet system of standard size	Cradle-to-grave	Excluded	Excluded	Primary and secondary data	Not specified	Not specified	GWP	Not performed	Not performed	Sensitivity analysis

Park, J., Horvath, L., Bush, R.J., 2018. Life Cycle Inventory Analysis of the Wood Pallet Repair Process in the United States. Journal of Industrial Ecology 22, 1117-1126.	the US	Wooden pallets	To quantify the carbon footprint of the repair process of wooden pallets	Repair	A repaired 48 by 40 inch (1,219 by 1,016 mm) stringer-class wood pallet	Gate-to-gate (including only pallet-repair–related activities)	SimaPro (Version 7.3.3)	Ecoinvent and U.S. Life Cycle Inventory	Primary and secondary data	Volume-based weighting factors	Not specified	GWP	Not performed	Not performed	Pedigree matrix

Kim, S., Horvath, L., Russell, J.D., Park, J., 2023. Sustainable and Secure Transport: Achieving Environmental Impact Reductions by Optimizing Pallet-Package Strength Interactions during Transport. Sustainability 15, 12687.	the US	Wooden pallets	To examine the environmental impact of optimising a unit load by decreasing the board grade of the pallets' corrugated boxes and stiffening the top deck boards of the pallets	Rethink	A double-stacked unit loads with the same maximum safe load capacity under floor stacking conditions	Cradle-to-grave	SimaPro 9.0	Ecoinvent v.3	Secondary data	Not specified	TRACI 2.1	OD, GWP, smog, AP, EP, carcinogens, non-carcinogens, RE, ecotoxicity and FD	Not performed	Not performed	Sensitivity analysis

Tornese, F., Pazour, J.A., Thorn, B.K., Carrano, A.L., 2019. Environmental and economic impacts of preemptive remanufacturing policies for block and stringer pallets. Journal of Cleaner Production 235, 1327-1337.	Not specified	Wooden pallets	To evaluate the impact of preemptive remanufacturing policies on the economic and environmental performance of wooden pallet logistics	Remanufacture	48- by 40-inch stringer and block pallets	Gate-to-gate	Excluded	Excluded	Secondary data	Not specified	Excluded	GWP	Not performed	Not performed	Not performed

Choi, B., Yoo, S., Lee, K.-D., Park, S.-i., 2020. An environmental impact comparison of disposable wood pallets and reusable steel cradles: A case study on rolled steel coils in container shipping in South Korea. International Journal of Sustainable Transportation 14, 335-342.	South Korea	Wooden pallets	To compare environmental impacts of disposable wood pallets and reusable steel cradles	Reuse	1,000 RSCs	Cradle-to-grave	SimaPro 8.2.0	Ecoinvent and Agrifootprint	Secondary data	Not specified	IMPACT 2002+	Carcinogens, non-carcinogens, RI, IR OD, RO, AE, TE, TA, LU, AA, AEu, GWP, NE and ME	Not performed	Not performed	Not performed

Korol, J., Burchart-Korol, D., Pichlak, M., 2016. Expansion of environmental impact assessment for eco-efficiency evaluation of biocomposites for industrial application. Journal of Cleaner Production 113, 144-152.	Not specified	Plastic pallet produced from biocomposites and composites based on PP, GF and CF, JF, and KF	To compare the environmental impacts of different materials	Rethink	One heavy-duty plastic pallet made by an injection molding process	Cradle-to-gate (from raw material extraction to plastic pallet production)	SimaPro 8	Ecoinvent database 3.1	Secondary data	Not specified	ReCiPe 2008	GWP, OD, HTPO, FPMF, IR, TA, FEu, MEu, TE, FE, ME, ALO, ULO, NLT, WD, MD and FD	ReCiPe	ReCiPe	Not performed

Korol, J., Hejna, A., Burchart-Korol, D., Chmielnicki, B., Wypiór, K., 2019. Water footprint assessment of selected polymers, polymer blends, composites, and biocomposites for industrial application. Polymers 11, 1791.	Not specified	PP, as well as its blends with bio-based polymers (poly(lactic acid) and thermoplasticstarch) and composites with CF, JF and KF	To evaluate the water footprint of selected polymer blends and composites	Rethink	One standard EUR-pallet	Cradle-to-gate	Not specified	Ecoinvent database v 3.1; National Residential Efficiency Measures Database; Natural Institute of Research on Jute and Allied Fibre Technology	Secondary data	Not specified	Excluded	Water footprint	Not performed	Not performed	Not performed

Korol, J., Hejna, A., Burchart-Korol, D., Wachowicz, J., 2020. Comparative analysis of carbon, ecological, and water footprints of polypropylene-based composites filled with cotton, jute and kenaf fibers. Materials 13, 3541.	Not specified	PP-based composites filled with CF, JF and KF	To assess the environmental footprints of polypropylene-based composites filled with natural fibers	Rethink	One standard European pallet (EUR-pallet)	Cradle-to-gate	Not specified	Ecoinvent database v 3.1	Primary and secondary data	Not specified	Excluded	Carbon, ecological, and water footprints	Not performed	Not performed	Not performed

Lee, S., Xu, X., 2004. A simplified life cycle assessment of re-usable and single-use bulk transit packaging. Packaging Technology and Science: An International Journal 17, 67-83.	New Zealand	Plastic and wooden pallets	To evaluate and contrast the environmental performance of the reusable Enviropak © T760 packaging system against that of the disposable wooden pallet packaging system	reuse	A unit of the Enviropak © T760 and the wooden pallet.	Cradle-to-grave	Not specified	Simapro 5.1, the Association of Plastic Manufacturers in Europe (APME) and the Life Cycle Assessment Data Inventory of the Centre for Design at RMIT University, Melbourne, Australia	Secondary data	Not specified	Environmental Priority Strategy (EPS) 2000 Default Method	Environmental load units	EPS 2000 Default Method	Environmental Priority Strategy (EPS) 2000 Default Method	Monte Carlo analysis

Khan, M.M.H., Havukainen, J., Niini, A., Leminen, V., Horttanainen, M., 2023. Consequential life-cycle assessment of treatment options for repulping reject from liquid packaging board waste treatment. Waste Management 155, 348-356.	Finland	EoL treatment methods	To compare the environmental impact of recycling rejected materials from the treatment of liquid packaging board waste	Recycle & Recover	The treatment of one tonne of repulping reject	Cradle-to-grave	Gabi 10.5.0.78	Sphera database version 10.5.0.78	Primary and secondary data	System expansion	ReCiPe 2016 v1.1	GWP, FD, FEu, HT, PO, TA, FPMF, FC, FE, IR, LU, ME, MD, SOD and TE	Not performed	Not performed	Sensitivity analysis

Notes: GWP (climate change); FPMF (fine particulate matter formation); FD (fossil depletion); FC (freshwater consumption); FE (freshwater ecotoxicity); FEu (freshwater eutrophication); HT (human toxicity); IR (ionizing radiation); LU (land use); ME (marine ecotoxicity); MEu (marine eutrophication); MD (metal depletion); POF (photochemical ozone formation); SOD (stratospheric ozone depletion); TA (terrestrial acidification); TE (terrestrial ecotoxicity); CED (cumulative energy demand); OD (ozone depletion); PS (photochemical smog); ADP (Abiotic depletion potential); AP (acidification potential); EP (eutrophication potential); AE (aquatic eco-toxicity); NE (non-renewable energy); ME (mineral extraction); WD (water depletion); PO (photochemical oxidation); RE (respiratory effects); RO (respiratory organics); AA (aquatic acidification); AEu (aquatic eutrophication); RI (respiratory inorganics); ALO (agricultural land occupation); ULO (urban land occupation); NLT (natural land transformation).

Appendix B List of datasets for LCA

The data inventory and their correspondence with the databases for LCA study are shown in Table B.1.

Table B.1 Data inventory of input and output of pallets from cradle to grave under three scenarios

Wooden pallet[4]	**Base case scenario**							
	Production	Input			Datasets	Output		
		Electricity	MJ	1.72E+00	[1][5]	Wooden pallet	kg	2.50E+01
		Logs	kg	4.25E+01	[2]	Wooden residue	kg	1.76E+01
		Steel nails	kg	1.62E-01	[3]	Dust	kg	7.01E-02
		Steam	MJ	8.25E-04	[4]			

[4] Source: Wuxi Qiancheng Packaging Engineering Co., Ltd. Reference: Data is collected during visits to Wuxi Qiancheng Packaging Engineering Co., Ltd., based on warehouse daily reports from January 2020 to December 2020. The primary data related to the product manufacturing process are checked by the author on site in the factory and reviewed by the enterprise's engineers. Electricity data are collected from direct measurement of the equipment's power rating and operating time in the factory and subsequently reviewed by engineers. The emission data during the pallet manufacturing process are collected from Qiancheng's EIA report in 2020. Industry ranges are established during visits to other relevant companies, including Taicang Panjing Packaging Co., Ltd., Huaian Jinlida Packaging Co., Ltd., Xinchuang (Tianjin) Packaging Industrial Technology Co., Ltd., Luchen Wood Co., Ltd., CHEP Logistics Equipment (China) Co., Ltd., Loscam International Holdings Co., Ltd., Renqiu Xiangrui Packaging Products Co., Ltd. and CFLP.

[5] Note: correspondence refers to dataset in Table B.2: Database correspondence for the background processes in LCA.

Distribution	Transportation distance: 250 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 25 kg						
Use	Electricity	MJ	3.30E-01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1025 kg						
EoL[6]	33.3% of waste wooden pallets are dismantled to repair or remanufacture other pallets, 53.4% are used as biomass fuel, 11.3% are recycled to produce wood shavings, and 2.0% are landfilled			[1][2][3][4][6][7][8][9]			
Sharing system scenario							
Use	Logs	kg	1.39E+00	[2]			
	Electricity	MJ	6.08E+00	[1]			
	Steel nails	kg	8.00E-02	[3]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Repair distance: 170 km			[5]			
CE scenario							
Production	Input				Output		
	Electricity	MJ	4.49E-01	[32]	Wooden pallet	kg	2.50E+01
	Recycled logs	kg	2.50E+01	[31]			

[6] Source: Wooden pallet recycling centre.

		Recycled steel nails	kg	1.62E-01	[31]
		Steam	MJ	8.25E-04	[33]
		Transportation distance: 170 km			[5]
	Distribution	Transportation distance: 250 km			[5]
		Euro 4, 34–40 t gross weight with 27 t payload capacity			
		Weight: 25 kg			
	Use	Recycled logs	kg	1.39E+00	[31]
		Recycled steel nails	kg	8.00E-02	[31]
		Electricity	MJ	6.08E+00	[32]
		Transportation distance: 300 km			[5]
		Euro 4, 34–40 t gross weight with 27 t payload capacity			
		Weight: 1025 kg			
		Repair distance: 170 km			[5]
	EoL	Incineration for energy recovery or recycling			[2][3[4][6][9][32]
Plastic pallet[7]	**Base case scenario**				
	Production	Input			Output

[7] Source: Shanghai Leju Technology Co., Ltd. Reference: Data is collected during visits to Shanghai Leju Technology Co., Ltd., based on warehouse daily reports from January 2020 to December 2020. The primary data related to the product manufacturing process are checked by the author on site in the factory and reviewed by the enterprise's engineers. Electricity data are collected from direct measurement of the equipment's power rating and operating time in the factory and subsequently reviewed by engineers. Water and oil consumption data are calculated based on production volume and corresponding usage for the year 2020. The emission data during the pallet manufacturing process are collected from Leju's EIA report in 2020. Although Leju is not the largest plastic pallet producer in China, its production process adheres to standardised practices within the country. Industry ranges are established during visits to other relevant companies, including Shanghai Qinghao Plastic Pallet Manufacturing Co., Ltd., Shanghai Lika Pallet Manufacturing Co., Ltd. (the industry's largest plastic pallet manufacturing company), Chongqing Liting Logistics Equipment Co., Ltd., Suzhou Chenan Plastic Co., Ltd. and CFLP.

	Colour masterbatch	kg	3.74E-01	[10]	Plastic pallet	kg	2.00E+01
	Electricity	MJ	4.59E+01	[1]	NMHC	kg	6.89E-03
	Fresh water	kg	1.32E+01	[8]	Plastic residue	kg	2.40E-02
	HDPE granulate	kg	1.95E+00	[11]	Waste hydraulic oil	kg	7.29E-04
	Hydraulic oil	kg	7.29E-04	[12]			
	PP granulate	kg	1.77E+01	[13]			
Distribution	Transportation distance: 250 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 20 kg						
Use	Electricity	MJ	3.30E-01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1520 kg						
EoL	25% of plastic pallets are recycled, 27.5% are incinerated for energy recovery, 45.9% are landfilled, and 1.6% are open dumped[8]			[1][13][14][15][16][17]			
Sharing system scenario							
Use	Electricity	MJ	2.33E+01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1520 kg						
CE scenario							

[8] Source: Jiang et al. (2020)

	Production	Input				Output		
		Colour masterbatch	kg	3.74E-01	[10]	Plastic pallet	kg	2.00E+01
		Electricity	MJ	4.59E+01	[32]	NMHC	kg	6.89E-03
		Fresh water	kg	1.32E+01	[8]	Waste hydraulic oil	kg	7.29E-04
		Recycled HDPE granulate	kg	1.95E+00	[31]			
		Hydraulic oil	kg	7.29E-04	[12]			
		Recycled PP granulate	kg	1.77E+01	[31]			
		Transportation distance: 170 km			[5]			
	Distribution	Transportation distance: 250 km			[5]			
		Euro 4, 34–40 t gross weight with 27 t payload capacity						
		Weight: 20 kg						
	Use	Electricity	MJ	2.33E+01	[32]			
		Transportation distance: 300 km			[5]			
		Euro 4, 34–40 t gross weight with 27 t payload capacity						
		Weight: 1520 kg						
	EoL	Incineration for energy recovery or recycling			[1][13][14][16]			
Paper pallet[9]	**Base case scenario**							
	Production	Input				Output		

[9] Source: Jiangyin Fullway Packaging Co., Ltd. Reference: Data is collected during visits to Jiangyin Fullway Packaging Co., Ltd., based on warehouse daily reports from January 2020 to December 2020. The primary data related to the product manufacturing process are checked by the author on site in the factory and reviewed by the enterprise's engineers. Electricity data are collected from direct measurement of the equipment's power rating and operating time in the factory and subsequently reviewed by engineers. The emission data during the pallet manufacturing process are collected from company's EIA report in 2020. Industry ranges are established during visits to other relevant companies, including Zonse Co., Ltd, Wuxi Keyi Packaging Co., Ltd. and CFLP.

	Cornstarch gum	kg	2.24E+00	[1][8][19][20][21][22]	Paper pallet	kg	7.50E+00
	Electricity	MJ	3.16E+00	[1]	Paper residue	kg	6.71E-03
	Steam	kg	9.39E+00	[4]			
	Kraft paper	kg	6.71E+00	[18]			
Distribution	Transportation distance: 250 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 7.5kg						
Use	Electricity	MJ	3.30E-01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1007.5 kg						
EoL	51.3% of waste paper pallets are recycled, 29.3% are incinerated as fuel, 17.8% are landfilled, and 1.6% are leaked into the environment[10]			[1][4][8][18][19][20][21][22][23][24][25]			
Sharing system scenario							
Use	Electricity	MJ	1.30E+00	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1007.5 kg						
CE scenario							
Production	Input				Output		

[10] Source: Liu et al (2020)

		Cornstarch gum	kg	2.24E+00	[8][19][20][21][22] [32]	Paper pallet	kg	7.50E+00
		Electricity	MJ	3.16E+00	[32]	Paper residue	kg	6.71E-03
		Steam	kg	9.39E+00	[33]			
		Recycled kraft paper	kg	6.70E+00	[31]			
		Transportation distance: 170 km			[5]			
	Distribution	Transportation distance: 250 km			[5]			
		Euro 4, 34–40 t gross weight with 27 t payload capacity						
		Weight: 7.5kg						
	Use	Electricity	MJ	1.30E+00	[32]			
		Transportation distance: 300 km			[5]			
		Euro 4, 34–40 t gross weight with 27 t payload capacity						
		Weight: 1007.5 kg						
	EoL	Incineration for energy recovery or recycling			[4][8][18][19][20][21][22][23][32][33]			
Steel pallet[11]	**Base case scenario**							
	Production	Input				Output		
		Electricity	MJ	5.40E+00	[1]	Steel pallet	kg	3.00E+01
		Polyethylene	kg	7.50E-01	[11]	Dust	kg	7.38E-01
		Steel screws	kg	1.79E-02	[3]	SO_2	kg	4.32E-05

[11] Source: Tianjin CIMC Logistics Equipment Co., Ltd. Reference: Data is collected during visits to Tianjin CIMC Logistics Equipment Co., Ltd., based on warehouse daily reports from January 2020 to December 2020. The primary data related to the product manufacturing process are checked by the author on site in the factory and reviewed by the enterprise's engineers. Electricity data are collected from direct measurement of the equipment’s power rating and operating time in the factory and subsequently reviewed by engineers. The emission data during the pallet manufacturing process are sourced from CIMC’s EIA report in 2020. Industry ranges are established during visits to other relevant companies, including APT Co., Ltd, Ouyeel Co., Ltd. and CFLP.

	Steel plate	kg	3.33E+01	[26]	NO_X	kg	4.23E-04
					VOCs	kg	7.50E-03
					Steel residue	kg	3.33E+00
Distribution	Transportation distance: 250 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 30 kg						
Use	Electricity	MJ	3.30E-01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 2030 kg						
EoL	100% of steel pallets are recycled			[1][8][26]			
Sharing system scenario							
Use	Electricity	MJ	3.33E+01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 2030 kg						
CE scenario							
Production	Input				Output		
	Electricity	MJ	5.40E+00	[32]	Steel pallet	kg	3.00E+01
	Polyethylene	kg	7.50E-01	[11]	Dust	kg	7.38E-01
	Recycled steel screws	kg	1.79E-02	[31]	SO_2	kg	4.32E-05
	Recycled steel plate	kg	3.00E+01	[31]	NO_X	kg	4.23E-04
					VOCs	kg	7.50E-03
	Transportation distance: 170 km			[5]			

	Distribution	Transportation distance: 250 km			[5]				
		Euro 4, 34–40 t gross weight with 27 t payload capacity							
		Weight: 30 kg							
	Use	Electricity	MJ	3.33E+01	[32]				
		Transportation distance: 300 km			[5]				
		Euro 4, 34–40 t gross weight with 27 t payload capacity							
		Weight: 2030 kg							
	EoL	100% of steel pallets are recycled			[8][26][32]				
Fly ash pallet[12]	**Base case scenario**								
	Production	Input				Output			
		Cerium	kg	9.95E-01	[28]	Fly ash pallet	kg	2.00E+01	
		Electricity	MJ	3.63E+01	[1]	Dust	kg	4.34E-05	
		Lanthanum	kg	9.95E-01	[29]	NMHC	kg	2.09E-03	
		PVC granulate	kg	5.97E+00	[27]	Residue	kg	7.96E-03	
		Steel nails	kg	1.08E-01	[3]				
		Fly ash	kg	3.98E+00	[31]				
		Fresh water	kg	1.50E+00	[8]				
		Recycled PVC	kg	7.96E+00	[31]				

[12] Source: Inner Mongolia Joyant Intelligent Environmental Protection New Material Co., Ltd. Reference: Data is collected during visits to Inner Mongolia Joyant Intelligent Environmental Protection New Material Co., Ltd., based on warehouse daily reports from January 2020 to December 2020. The primary data related to the product manufacturing process is checked by the author on site in the factory and reviewed by the enterprise's engineers. Electricity data are collected from direct measurement of the equipment's power rating and operating time in the factory and subsequently reviewed by engineers. Water consumption data is calculated based on production volume and corresponding water usage for the year 2020. The emission data during the pallet manufacturing process are sourced from the company's EIA report in 2020. Inner Mongolia Joyant Intelligent Environmental Protection New Material Co., Ltd. is the only producer of fly ash pallets in China.

Distribution	Transportation distance: 250 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 20 kg						
Use	Electricity	MJ	3.30E-01	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1520 kg						
EoL	100% of fly ash pallets are landfilled			[30]			
Sharing system scenario							
Use	Electricity	MJ	4.95E+00	[1]			
	Transportation distance: 300 km			[5]			
	Euro 4, 34–40 t gross weight with 27 t payload capacity						
	Weight: 1520 kg						
CE scenario							
Production	Input				Output		
	Recycled cerium	kg	9.95E-01	[31]	Fly ash pallet	kg	2.00E+01
	Electricity	MJ	3.63E+01	[32]	Dust	kg	4.34E-05
	Recycled lanthanum	kg	9.95E-01	[31]	NMHC	kg	2.09E-03
	Recycled PVC granulate	kg	5.97E+00	[31]			
	Recycled steel nails	kg	1.08E-01	[31]			
	Fly ash	kg	3.98E+00	[31]			
	Fresh water	kg	1.50E+00	[8]			
	Recycled PVC	kg	7.96E+00	[31]			
	Transportation distance: 170 km			[5]			

	Distribution	Transportation distance: 250 km			[5]
		Euro 4, 34–40 t gross weight with 27 t payload capacity			
		Weight: 20 kg			
	Use	Electricity	MJ	4.95E+00	[32]
		Transportation distance: 300 km			[5]
		Euro 4, 34–40 t gross weight with 27 t payload capacity			
		Weight: 1520 kg			
	EoL	100% of fly ash pallets are recycled			[8][27][28][29][32]

Table B.2 presents the correspondence for all processes that serve as background activities throughout the LCA.

Table B.2: Database correspondence for the background processes in LCA[13]

Code process		Gabi 9.1 datasets
[1]	Electricity	CN: Electricity grid mix ts
[2]	Logs	DE: Spruce log with bark (44% H2O content) ts
[3]	Steel nails	DE: Steel screw - EJOT (A1-A3) ts-EPD
[4]	Steam	CN: Process steam from natural gas 95% ts
[5]	Transportation	GLO: Truck-trailer, Euro 4, 34 - 40t gross weight / 27t payload capacity ts <u-so>
[6]	Wood incineration	EU-28: Wood (natural) in municipal waste incineration plant ts <p-agg>
[7]	Wood landfill	EU-28: Untreated wood on landfill ts <p-agg>
[8]	Water	EU-28: Process water ts
[9]	Sawdust	US: Sawdust, from dried lumber, at planer mill, US PNW USLCI/ts
[10]	Colour masterbatch	EU-28: Titanium dioxide pigment (chloride process) ts

[13] In cases where specific data for China were insufficient, EU-28 averages were used as a priority replacement in the LCA study.

[11]	HDPE granulate	US: Polyethylene High Density Granulate (HDPE/PE-HD) ts
[12]	Hydraulic oil	CN: Crude oil mix ts
[13]	PP granulate	US: Polypropylene granulate (PP) ts
[14]	Plastic incineration	EU-28: Polypropylene (PP) in waste incineration plant ts <p-agg>
[15]	Plastic landfill	EU-28: Plastic waste on landfill ts
[16]	Plastic recycling	US: Recycling of polypropylene (PP) plastic ts <p-agg>
[17]	Plastic open dump	Ecoinvent 3.9.1 GLO: treatment of waste polyethylene, open dump
[18]	Kraft paper	EU-28: Kraft paper (EN15804 A1-A3) ts
[19]	Starch	US: Dried starch (corn wet mill) ts
[20]	Polyvinyl alcohol granulate	DE: Polyvinyl alcohol granulate (PVAL) ts
[21]	Kaolin fine	EU-27: Kaolin fine, granular or powder, moisture content 0 to 30%, expressed in dry mass KPC
[22]	Borax pentahydrate	US: Borax pentahydrate ts
[23]	Paper incineration	EU-28: Paper / Cardboard in waste incineration plant ts <p-agg>
[24]	Paper landfill	EU-28: Paper waste on landfill ts <p-agg>
[25]	Paper open dump	Ecoinvent 3.9.1 GLO: treatment of waste paperboard, open dump
[26]	Steel plate	EU: Steel plate
[27]	Polyvinyl chloride granulate	DE: Polyvinyl chloride granulate (Suspension, S-PVC) ts
[28]	Cerium	CN: Cerium ts
[29]	Lanthanum	CN: Lanthanum ts
[30]	Fly ash landfill	EU-28: Municipal solid waste on landfill ts <p-agg>
[31]	Recycled materials	No environmental impacts are allocated
[32]	Solar energy	EU-28: Electricity from solar thermal
[33]	Steam from biomass	CN: Process steam from biomass (solid) 85%
[34]	Steel landfill	EU-28: Inert matter (Steel) on landfill

Table B.3 presents a sample of the warehouse daily report from Shanghai Leju Technology Co., Ltd. for November 2020. Due to confidentiality concerns, only one month's report is shown to illustrate the data collection process, which served as a representative snapshot of the overall process. The data collection methods applied for other pallet companies in the study followed the same approach. The primary data for raw material inputs in the manufacturing process were gathered from warehouse daily reports for the entire year of 2020. To calculate total material consumption, the author checked the calculations in the reports, and subtracted the stock quantity at the beginning of the year from the stock quantity at the end of the year. This provided the total consumption of each material, which was then divided by the total production volume of plastic pallets in 2020 to derive the material usage per pallet. After the calculation, the results are checked by the author on site in the factory and reviewed by the enterprise's engineers. Electricity data are collected from direct measurement of the equipment's power rating and operating time in the factory and subsequently reviewed by engineers. Water and oil consumption data are calculated based on production volume and corresponding usage for the year 2020. Emission data for the pallet manufacturing process were sourced from Leju's 2020 EIA Report. Additionally, industry ranges are established during visits to other relevant companies.

Table B. 3 Sample of warehouse daily report from Leju (November 2020)

Colour masterbatch (unit: kg)			
Date	Inbound quantity	Outbound quantity	Stock
2020.10.15	2000.00		2000.00
2020.11.17		177.89	1822.11
2020.11.18		41.85	1780.26
2020.11.19	6000.00	193.18	7587.08
2020.11.20		263.34	7323.74
2020.11.21		260.10	7063.64
2020.11.22		202.75	6860.89
2020.11.23		223.88	6637.00
2020.11.24		262.58	6374.42
2020.11.25		295.61	6078.81
2020.11.26		129.35	5949.46
2020.11.27		115.24	2987.63
2020.11.28		243.61	5590.61
2020.11.29		264.33	5326.28
2020.11.30		220.77	5105.51
HDPE (unit: kg)			
Date	Inbound quantity	Outbound quantity	Stock
2020.10.15	9000.00		18000.00
2020.11.17		988.30	17011.70
2020.11.18		232.50	16779.20
2020.11.19		1073.20	15706.00
2020.11.20		1463.00	14243.00
2020.11.21		1445.00	12798.00
2020.11.22		1126.40	11671.60
2020.11.23		1243.80	10427.80
2020.11.24		1458.80	8969.00
2020.11.25		1642.30	7326.70
2020.11.26		718.60	6608.10
2020.11.27		640.20	5967.90
2020.11.28		1353.40	4614.50
2020.11.29		1468.50	3146.00
2020.11.30		1226.50	1919.50
PP (unit: kg)			
Date	Inbound quantity	Outbound quantity	Stock
2020.10.12	30000.00		30000.00
2020.11.4	20000.00		50000.00

2020.11.6	30000.00		80000.00
2020.11.11	30000.00		110000.00
2020.11.12	30000.00		140000.00
2020.11.17		8716.81	131283.19
2020.11.18		2050.65	129232.54
2020.11.19		9465.62	119766.92
2020.11.20		12903.66	106863.26
2020.11.21		12744.90	94118.36
2020.11.22		9934.85	84183.51
2020.11.23		10970.32	73213.20
2020.11.24		12866.62	60346.58
2020.11.25		14485.09	45861.49
2020.11.26		6338.05	39523.44
2020.11.27	30000.00		69523.44
2020.11.27	30000.00	5646.56	93876.88
2020.11.28		11936.99	81939.89
2020.11.29		12952.17	68987.72
2020.11.30		10817.73	58169.99

The following content presents technical data verification interview used to review data from engineers to build LCI.

Technical Data Verification Interview

Purpose of the Interview:

The purpose of this interview is to review and validate the technical data collected during site visits to your company. This data includes raw materials inputs and outputs, energy and water consumption per pallet, and emissions data, all of which are necessary for assessing the environmental impact of pallet production. The focus of this interview is strictly on technical data verification, and no personal or sensitive information will be collected.

Interview Questions for Technical Data Verification:

1. **Manufacturing Process Review:**
    - During my visits, I documented the key stages of the pallet manufacturing process. Could you please review these records to ensure they align with your facility's standard operational procedures?

- Are there any operational variations in the manufacturing process, (e.g., changes in raw material inputs or outputs based on production volume)?

2. **LCI Data Review:**
   - During my visits, I collected LCI data from your company's warehouse daily reports, specifically regarding raw material inputs and outputs. Could you please review these records and provide any feedback?
   - Based on the on-site visit in your company's factories, I calculated the energy and water consumption per pallet. Could you please review these calculations and verify if they align with your company's standard figures?
   - According to the EIA report for 2020, emissions data were provided for the pallet production process. Could you please review and confirm the data?
   - Are there any variations in emissions based on production scale or other operational factors?
3. **Cross-Company Comparisons:**
   - Are there any industry-wide benchmarks or typical ranges for LCI data that your company follows?
4. **Is there anything you would like to add?**
   - Are there any additional technical details or clarifications regarding the data that should be considered for the verification?

Conclusion:

This interview is conducted to validate the technical data gathered. The data will be used solely for environmental impact assessments and analysis in the research context, focusing on reviewing pre-existing, verifiable information. No personal or sensitive data will be collected, and the interview strictly pertains to technical data verification.

Appendix C LCIA results under three scenarios

Table C. 1 Results of LCIA under three scenarios

	Base case scenario					**Sharing system scenario**					**CE scenario**				
	Wooden pallet					Wooden pallet					Wooden pallet				
	Production	Distribution	Use	EoL	Total	Production	Distribution	Use	EoL	Total	Production	Distribution	Use	EoL	Total
GWP	1.86E+00	3.78E-01	1.87E+01	-8.25E+00	1.27E+01	1.24E-01	2.52E-02	1.39E+00	-5.50E-01	9.88E-01	1.76E-02	2.52E-02	1.31E+00	-9.40E-01	4.13E-01
FPMF	2.82E-03	3.85E-04	1.90E-02	2.29E-03	2.45E-02	1.88E-04	2.57E-05	1.46E-03	1.53E-04	1.83E-03	1.74E-05	2.57E-05	1.32E-03	-1.42E-04	1.22E-03
FD	5.36E-01	1.25E-01	6.16E+00	-3.24E+00	3.58E+00	3.58E-02	8.33E-03	4.49E-01	-2.16E-01	2.77E-01	5.73E-03	8.33E-03	4.32E-01	-3.25E-01	1.21E-01
FC	6.78E-03	8.08E-05	4.70E-03	1.45E-01	1.57E-01	4.52E-04	5.39E-06	1.23E-03	9.68E-03	1.14E-02	1.18E-05	5.39E-06	4.46E-04	5.07E-03	5.53E-03
FE	3.08E-04	1.23E-04	6.08E-03	3.95E-03	1.05E-02	2.05E-05	8.20E-06	4.31E-04	2.63E-04	7.23E-04	5.40E-06	8.20E-06	4.21E-04	-1.24E-05	4.22E-04
FEu	4.99E-06	4.50E-08	2.23E-06	1.70E-06	8.97E-06	3.33E-07	3.00E-09	2.27E-07	1.13E-07	6.76E-07	4.14E-09	3.00E-09	2.23E-07	-1.65E-07	6.55E-08

HT	1.94E-03	1.95E-04	9.68E-03	-8.50E-04	1.10E-02	1.29E-04	1.30E-05	7.37E-04	-5.67E-05	8.22E-04	2.59E-05	1.30E-05	9.15E-04	-1.24E-04	8.30E-04
IR	6.78E-02	2.00E-05	1.11E-03	-6.71E-02	1.92E-03	4.52E-03	1.33E-06	2.39E-03	-4.47E-03	2.45E-03	1.71E-05	1.33E-06	2.47E-03	-5.36E-03	-2.87E-03
MD	9.16E-03	1.83E-05	9.44E-04	-1.66E-03	8.46E-03	6.10E-04	1.22E-06	2.59E-04	-1.10E-04	7.60E-04	1.46E-05	1.22E-06	3.95E-04	-2.89E-04	1.22E-04
POF	1.12E-02	2.85E-03	1.40E-01	6.06E-03	1.60E-01	7.44E-04	1.90E-04	9.83E-03	4.04E-04	1.12E-02	1.25E-04	1.90E-04	9.65E-03	-3.27E-04	9.64E-03
TA	6.10E-03	1.20E-03	5.95E-02	6.95E-03	7.37E-02	4.07E-04	8.00E-05	4.41E-03	4.63E-04	5.36E-03	5.44E-05	8.00E-05	4.13E-03	-3.64E-04	3.90E-03
TE	2.65E+00	4.17E-02	2.36E+00	3.59E+00	8.64E+00	1.76E-01	2.78E-03	5.50E-01	2.40E-01	9.69E-01	2.26E-03	2.78E-03	1.80E-01	-9.18E-02	9.32E-02
Plastic pallet						Plastic pallet							Plastic pallet		
GWP	4.26E+01	2.01E-01	1.85E+01	4.28E-01	6.17E+01	6.09E-01	2.88E-03	3.15E-01	6.11E-03	9.33E-01	3.71E-02	2.88E-03	2.74E-01	-3.27E-01	-1.30E-02
FPMF	2.30E-02	2.05E-04	1.88E-02	-1.01E-02	3.19E-02	3.29E-04	2.93E-06	3.50E-04	-1.45E-04	5.37E-04	2.42E-05	2.93E-06	2.74E-04	-5.78E-04	-2.77E-04
FD	2.65E+01	6.66E-02	6.09E+00	-5.92E+00	2.68E+01	3.79E-01	9.51E-04	9.90E-02	-8.46E-02	3.94E-01	1.06E-02	9.51E-04	8.98E-02	-2.72E-01	-1.71E-01

FC	2.20E-01	4.31E-05	4.41E-03	-5.19E-02	1.73E-01	3.14E-03	6.15E-07	5.44E-04	-7.41E-04	2.95E-03	3.22E-04	6.15E-07	1.18E-04	-1.87E-03	-1.43E-03
FE	1.13E-02	6.58E-05	6.01E-03	-5.31E-04	1.69E-02	1.62E-04	9.40E-07	9.24E-05	-7.58E-06	2.48E-04	4.03E-06	9.40E-07	8.67E-05	-9.57E-05	-4.03E-06
FEu	4.09E-05	2.40E-08	2.20E-06	1.02E-04	1.45E-04	5.85E-07	3.43E-10	4.63E-08	1.46E-06	2.09E-06	8.65E-08	3.43E-10	4.81E-08	-9.96E-08	3.53E-08
HT	1.87E-02	1.04E-04	9.57E-03	-5.80E-03	2.26E-02	2.68E-04	1.49E-06	1.74E-04	-8.28E-05	3.61E-04	2.78E-04	1.49E-06	2.74E-04	-2.69E-04	2.84E-04
IR	1.06E-01	1.07E-05	1.05E-03	-1.44E-03	1.06E-01	1.51E-03	1.52E-07	9.59E-05	-2.05E-05	1.59E-03	4.05E-04	1.52E-07	1.41E-04	-4.43E-04	1.03E-04
MD	5.40E-02	9.80E-06	9.21E-04	2.13E-02	7.63E-02	7.71E-04	1.40E-07	4.08E-05	3.05E-04	1.12E-03	5.37E-04	1.40E-07	1.21E-04	-3.35E-04	3.23E-04
POF	6.93E-02	1.52E-03	1.39E-01	-1.98E-02	1.90E-01	9.90E-04	2.17E-05	2.09E-03	-2.83E-04	2.82E-03	8.26E-05	2.17E-05	2.00E-03	-7.42E-04	1.36E-03
TA	5.96E-02	6.41E-04	5.86E-02	-2.18E-02	9.71E-02	8.51E-04	9.16E-06	1.01E-03	-3.11E-04	1.56E-03	7.90E-05	9.16E-06	8.58E-04	-1.18E-03	-2.35E-04
TE	3.00E+01	2.22E-02	2.23E+00	-2.00E+01	1.23E+01	4.29E-01	3.17E-04	2.35E-01	-2.85E-01	3.78E-01	1.08E-02	3.17E-04	3.27E-02	-1.46E+00	-1.42E+00

Paper pallet						Paper pallet					Paper pallet				
GWP	7.24E+00	1.13E-01	1.84E+01	1.48E+00	2.72E+01	1.81E+00	2.83E-02	4.65E+00	3.70E-01	6.86E+00	6.98E-01	2.83E-02	4.59E+00	-5.22E-01	4.79E+00
FPMF	7.77E-03	1.15E-04	1.87E-02	-8.48E-05	2.65E-02	1.94E-03	2.88E-05	4.77E-03	-2.12E-05	6.72E-03	9.70E-04	2.88E-05	4.66E-03	-7.58E-05	5.58E-03
FD	2.11E+00	3.75E-02	6.06E+00	-1.25E-01	8.08E+00	5.27E-01	9.38E-03	1.53E+00	-3.13E-02	2.03E+00	1.87E-01	9.38E-03	1.51E+00	-1.84E-01	1.52E+00
FC	1.08E-01	2.42E-05	4.64E-03	4.50E-02	1.58E-01	2.70E-02	6.05E-06	1.70E-03	1.13E-02	4.00E-02	3.79E-02	6.05E-06	1.07E-03	7.76E-03	4.67E-02
FE	1.92E-03	3.70E-05	5.98E-03	-2.38E-04	7.70E-03	4.80E-04	9.25E-06	1.50E-03	-5.94E-05	1.93E-03	2.48E-04	9.25E-06	1.49E-03	-1.19E-04	1.63E-03
FEu	2.83E-04	1.35E-08	2.20E-06	-6.08E-05	2.25E-04	7.09E-05	3.38E-09	5.67E-07	-1.52E-05	5.62E-05	3.01E-05	3.38E-09	5.70E-07	-3.40E-05	-3.30E-06
HT	3.68E-03	5.86E-05	9.51E-03	2.92E-04	1.35E-02	9.21E-04	1.47E-05	2.42E-03	7.31E-05	3.43E-03	9.71E-04	1.47E-05	2.57E-03	-7.99E-05	3.48E-03
IR	6.94E-02	6.00E-06	1.09E-03	-2.37E-02	4.68E-02	1.74E-02	1.50E-06	3.64E-04	-5.94E-03	1.18E-02	2.02E-03	1.50E-06	4.31E-04	-1.24E-02	-9.97E-03
MD	4.42E-02	5.50E-06	9.28E-04	5.15E-03	5.03E-02	1.10E-02	1.38E-06	2.63E-04	1.29E-03	1.26E-02	8.85E-03	1.38E-06	3.83E-04	-1.07E-03	8.16E-03

POF	2.08E-02	8.54E-04	1.38E-01	-3.49E-03	1.56E-01	5.19E-03	2.14E-04	3.47E-02	-8.72E-04	3.92E-02	1.91E-03	2.14E-04	3.45E-02	-2.16E-03	3.45E-02
TA	1.96E-02	3.61E-04	5.85E-02	-1.08E-03	7.74E-02	4.91E-03	9.03E-05	1.48E-02	-2.70E-04	1.95E-02	2.33E-03	9.03E-05	1.46E-02	-6.32E-04	1.64E-02
TE	1.17E+01	1.25E-02	2.33E+00	1.98E+00	1.61E+01	2.94E+00	3.13E-03	8.11E-01	4.95E-01	4.24E+00	1.93E+00	3.13E-03	5.11E-01	1.58E-02	2.46E+00
Steel pallet						Steel pallet					Steel pallet				
GWP	3.99E+01	2.27E-01	1.84E+01	-3.43E+01	2.42E+01	3.99E-01	2.27E-03	2.23E-01	-3.43E-01	2.81E-01	1.22E-02	2.27E-03	1.93E-01	-3.45E-01	-1.38E-01
FPMF	2.27E-02	2.31E-04	1.88E-02	-1.90E-02	2.28E-02	2.27E-04	2.31E-06	2.49E-04	-1.90E-04	2.88E-04	5.47E-06	2.31E-06	1.93E-04	-1.92E-04	8.38E-06
FD	8.93E+00	7.50E-02	6.11E+00	-7.24E+00	7.88E+00	8.93E-02	7.50E-04	7.01E-02	-7.24E-02	8.78E-02	7.82E-03	7.50E-04	6.33E-02	-7.27E-02	-8.96E-04
FC	4.20E-02	4.85E-05	4.30E-03	-2.76E-02	1.88E-02	4.20E-04	4.85E-07	4.02E-04	-2.76E-04	5.47E-04	4.57E-05	4.85E-07	8.52E-05	-2.89E-04	-1.58E-04
FE	3.33E-03	7.40E-05	6.00E-03	-2.64E-03	6.77E-03	3.33E-05	7.40E-07	6.50E-05	-2.64E-05	7.26E-05	3.55E-06	7.40E-07	6.07E-05	-2.65E-05	3.85E-05

FEu	5.09E-05	2.70E-08	2.21E-06	-4.47E-05	8.49E-06	5.09E-07	2.70E-10	3.32E-08	-4.47E-07	9.60E-08	1.22E-08	2.70E-10	3.45E-08	-4.47E-07	-4.00E-07
HT	5.47E-03	1.18E-04	9.53E-03	-4.06E-03	1.11E-02	5.47E-05	1.18E-06	1.23E-04	-4.06E-05	1.39E-04	2.11E-05	1.18E-06	1.97E-04	-4.17E-05	1.78E-04
IR	1.11E-01	1.20E-05	1.04E-03	-9.35E-02	1.81E-02	1.11E-03	1.20E-07	7.07E-05	-9.35E-04	2.41E-04	3.32E-05	1.20E-07	1.04E-04	-9.37E-04	-8.00E-04
MD	1.05E+00	1.10E-05	9.16E-04	-9.45E-01	1.07E-01	1.05E-02	1.10E-07	2.98E-05	-9.45E-03	1.10E-03	2.10E-05	1.10E-07	8.96E-05	-9.45E-03	-9.34E-03
POF	6.20E-02	1.71E-03	1.39E-01	-5.28E-02	1.50E-01	6.20E-04	1.71E-05	1.47E-03	-5.28E-04	1.58E-03	2.86E-05	1.71E-05	1.40E-03	-5.31E-04	9.15E-04
TA	7.08E-02	7.20E-04	5.86E-02	-6.04E-02	6.97E-02	7.08E-04	7.20E-06	7.13E-04	-6.04E-04	8.24E-04	1.66E-05	7.20E-06	6.02E-04	-6.09E-04	1.71E-05
TE	1.79E+01	2.50E-02	2.18E+00	-1.32E+01	6.91E+00	1.79E-01	2.50E-04	1.73E-01	-1.32E-01	2.21E-01	9.80E-04	2.50E-04	2.31E-02	-1.38E-01	-1.13E-01
Fly ash pallet						Fly ash pallet					Fly ash pallet				
GWP	3.06E+01	2.01E-01	1.85E+01	1.23E+01	6.15E+01	2.04E+00	1.34E-02	1.28E+00	8.18E-01	4.15E+00	1.08E-01	1.34E-02	1.24E+00	-1.43E+00	-6.83E-02

FPMF	4.43E-02	2.05E-04	1.88E-02	7.80E-04	6.41E-02	2.96E-03	1.37E-05	1.33E-03	5.20E-05	4.35E-03	6.74E-05	1.37E-05	1.26E-03	-2.00E-03	-6.64E-04
FD	1.02E+01	6.66E-02	6.09E+00	2.65E-01	1.66E+01	6.79E-01	4.44E-03	4.17E-01	1.77E-02	1.12E+00	3.00E-02	4.44E-03	4.08E-01	-5.03E-01	-6.02E-02
FC	1.34E+00	4.31E-05	4.41E-03	1.52E-03	1.35E+00	8.97E-02	2.87E-06	7.46E-04	1.01E-04	9.05E-02	5.72E-04	2.87E-06	3.23E-04	-7.23E-02	-7.14E-02
FE	4.98E-03	6.58E-05	6.01E-03	1.99E-04	1.13E-02	3.32E-04	4.39E-06	4.07E-04	1.32E-05	7.56E-04	1.27E-05	4.39E-06	4.01E-04	-2.39E-04	1.79E-04
FEu	3.07E-05	2.40E-08	2.20E-06	2.19E-04	2.52E-04	2.05E-06	1.60E-09	1.61E-07	1.46E-05	1.68E-05	1.63E-07	1.60E-09	1.62E-07	-1.57E-06	-1.25E-06
HT	2.49E-02	1.04E-04	9.57E-03	3.11E-04	3.48E-02	1.66E-03	6.93E-06	6.73E-04	2.07E-05	2.36E-03	1.01E-03	6.93E-06	7.72E-04	-1.13E-03	6.57E-04
IR	1.26E-01	1.07E-05	1.05E-03	3.17E-03	1.30E-01	8.39E-03	7.11E-07	1.46E-04	2.12E-04	8.75E-03	2.85E-03	7.11E-07	1.91E-04	-4.93E-03	-1.89E-03
MD	8.59E+01	9.80E-06	9.21E-04	4.96E-02	8.59E+01	5.73E+00	6.53E-07	8.74E-05	3.31E-03	5.73E+00	9.09E-04	6.53E-07	1.67E-04	-4.86E+00	-4.86E+00
POF	6.40E-02	1.52E-03	1.39E-01	3.33E-03	2.08E-01	4.26E-03	1.01E-04	9.35E-03	2.22E-04	1.39E-02	2.64E-04	1.01E-04	9.26E-03	-2.94E-03	6.69E-03

TA	1.11E-01	6.41E-04	5.86E-02	2.28E-03	1.72E-01	7.37E-03	4.28E-05	4.07E-03	1.52E-04	1.16E-02	2.22E-04	4.28E-05	3.92E-03	-5.20E-03	-1.02E-03
TE	9.29E+01	2.22E-02	2.23E+00	4.71E-01	9.56E+01	6.19E+00	1.48E-03	3.39E-01	3.14E-02	6.57E+00	5.80E-02	1.48E-03	1.39E-01	-3.97E+00	-3.77E+00

Table C. 2 Results of sensitivity analysis of the recycling rate assumption of steel pallets

	100% recycle	90% recycle	80% recycle	70% recycle
GWP	2.43E+01	2.77E+01	3.12E+01	3.46E+01
FPMF	2.00E-02	2.00E-02	3.00E-02	3.00E-02
FD	7.88E+00	8.61E+00	9.34E+00	1.01E+01
FC	2.00E-02	2.00E-02	2.00E-02	3.00E-02
FE	1.00E-02	1.00E-02	1.00E-02	1.00E-02
FEu	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HT	1.00E-02	1.00E-02	1.00E-02	1.00E-02
IR	2.00E-02	3.00E-02	4.00E-02	5.00E-02
MD	1.10E-01	2.10E-01	3.10E-01	4.10E-01
POF	1.50E-01	1.50E-01	1.60E-01	1.70E-01
TA	7.00E-02	8.00E-02	8.00E-02	9.00E-02
TE	6.91E+00	8.27E+00	9.63E+00	1.10E+01

Table C. 3 Results of sensitivity analysis of RSL of five types of pallets

Wooden pallet					
	5 trips	10 trips	15 trips	20 trips	25 trips
GWP	2.74E+00	1.41E+00	9.64E-01	7.43E-01	6.10E-01
FPMF	5.18E-03	2.65E-03	1.81E-03	1.39E-03	1.13E-03
FD	7.73E-01	3.96E-01	2.70E-01	2.07E-01	1.69E-01
FC	3.26E-02	1.67E-02	1.14E-02	8.71E-03	7.11E-03
FE	2.13E-03	1.07E-03	7.16E-04	5.39E-04	4.34E-04
FEu	1.98E-06	1.00E-06	6.75E-07	5.12E-07	4.14E-07
HT	2.32E-03	1.19E-03	8.11E-04	6.22E-04	5.09E-04
IR	7.09E-03	3.61E-03	2.44E-03	1.86E-03	1.52E-03
MD	2.20E-03	1.12E-03	7.60E-04	5.80E-04	4.73E-04
POF	3.27E-02	1.64E-02	1.10E-02	8.29E-03	6.66E-03
TA	1.54E-02	7.81E-03	5.29E-03	4.03E-03	3.28E-03
TE	2.29E+00	1.30E+00	9.68E-01	8.02E-01	7.03E-01
Plastic pallet					

	40 trips	60 trips	80 trips	100 trips	120 trips
GWP	1.59E+00	1.08E+00	8.23E-01	6.68E-01	5.66E-01
FPMF	8.77E-04	6.12E-04	4.79E-04	4.00E-04	3.47E-04
FD	6.81E-01	4.58E-01	3.47E-01	2.80E-01	2.35E-01
FC	4.79E-03	3.35E-03	2.63E-03	2.20E-03	1.92E-03
FE	4.28E-04	2.88E-04	2.17E-04	1.75E-04	1.47E-04
FEu	3.64E-06	2.43E-06	1.83E-06	1.47E-06	1.22E-06
HT	6.02E-04	4.14E-04	3.20E-04	2.64E-04	2.26E-04
IR	2.72E-03	1.84E-03	1.40E-03	1.14E-03	9.61E-04
MD	1.93E-03	1.30E-03	9.81E-04	7.90E-04	6.63E-04
POF	4.85E-03	3.27E-03	2.48E-03	2.01E-03	1.69E-03
TA	2.59E-03	1.79E-03	1.38E-03	1.14E-03	9.79E-04
TE	5.06E-01	4.05E-01	3.55E-01	3.25E-01	3.05E-01
Steel pallet					
	50 trips	100 trips	150 trips	200 trips	250 trips
GWP	5.23E-01	2.81E-01	2.01E-01	1.73E-01	1.36E-01
FPMF	5.14E-04	2.88E-04	2.12E-04	1.95E-04	1.52E-04
FD	1.65E-01	8.73E-02	6.12E-02	5.12E-02	4.04E-02
FC	7.31E-04	5.47E-04	4.86E-04	5.76E-04	4.37E-04
FE	1.40E-04	7.26E-05	5.01E-05	4.04E-05	3.20E-05
FEu	1.81E-07	9.60E-08	6.78E-08	5.74E-08	4.51E-08
HT	2.49E-04	1.39E-04	1.02E-04	9.29E-05	7.25E-05
IR	4.21E-04	2.41E-04	1.81E-04	1.71E-04	1.33E-04
MD	2.17E-03	1.09E-03	7.37E-04	5.65E-04	4.50E-04
POF	3.07E-03	1.57E-03	1.08E-03	8.55E-04	6.79E-04
TA	1.52E-03	8.23E-04	5.92E-04	5.19E-04	4.06E-04
TE	2.88E-01	2.21E-01	1.98E-01	2.38E-01	1.80E-01
Paper pallet					
	1 trip	3 trips	5 trips	7 trips	9 trips
GWP	2.72E+01	9.12E+00	5.51E+00	3.95E+00	3.09E+00
FPMF	2.65E-02	8.92E-03	5.40E-03	3.89E-03	3.06E-03
FD	8.08E+00	2.70E+00	1.63E+00	1.17E+00	9.14E-01
FC	1.58E-01	5.31E-02	3.21E-02	2.32E-02	1.82E-02
FE	7.70E-03	2.57E-03	1.55E-03	1.11E-03	8.64E-04
FEu	2.25E-04	7.50E-05	4.50E-05	3.21E-05	2.50E-05
HT	1.35E-02	4.55E-03	2.75E-03	1.98E-03	1.56E-03
IR	4.68E-02	1.57E-02	9.45E-03	6.78E-03	5.30E-03
MD	5.03E-02	1.68E-02	1.01E-02	7.22E-03	5.62E-03
POF	1.56E-01	5.22E-02	3.14E-02	2.25E-02	1.75E-02
TA	7.74E-02	2.60E-02	1.57E-02	1.13E-02	8.82E-03

TE	1.61E+01	5.56E+00	3.46E+00	2.56E+00	2.06E+00
Fly ash pallet					
	5 trips	10 trips	15 trips	20 trips	25 trips
GWP	1.24E+01	6.20E+00	4.15E+00	3.13E+00	2.51E+00
FPMF	1.29E-02	6.49E-03	4.35E-03	3.28E-03	2.64E-03
FD	3.33E+00	1.67E+00	1.12E+00	8.42E-01	6.76E-01
FC	2.71E-01	1.36E-01	9.05E-02	6.80E-02	5.45E-02
FE	2.26E-03	1.13E-03	7.56E-04	5.69E-04	4.56E-04
FEu	5.05E-05	2.52E-05	1.68E-05	1.26E-05	1.01E-05
HT	7.00E-03	3.52E-03	2.36E-03	1.78E-03	1.43E-03
IR	2.61E-02	1.31E-02	8.75E-03	6.58E-03	5.28E-03
MD	1.72E+01	8.59E+00	5.73E+00	4.30E+00	3.44E+00
POF	4.16E-02	2.09E-02	1.39E-02	1.05E-02	8.41E-03
TA	3.46E-02	1.74E-02	1.16E-02	8.77E-03	7.05E-03
TE	1.93E+01	9.75E+00	6.57E+00	4.98E+00	4.02E+00

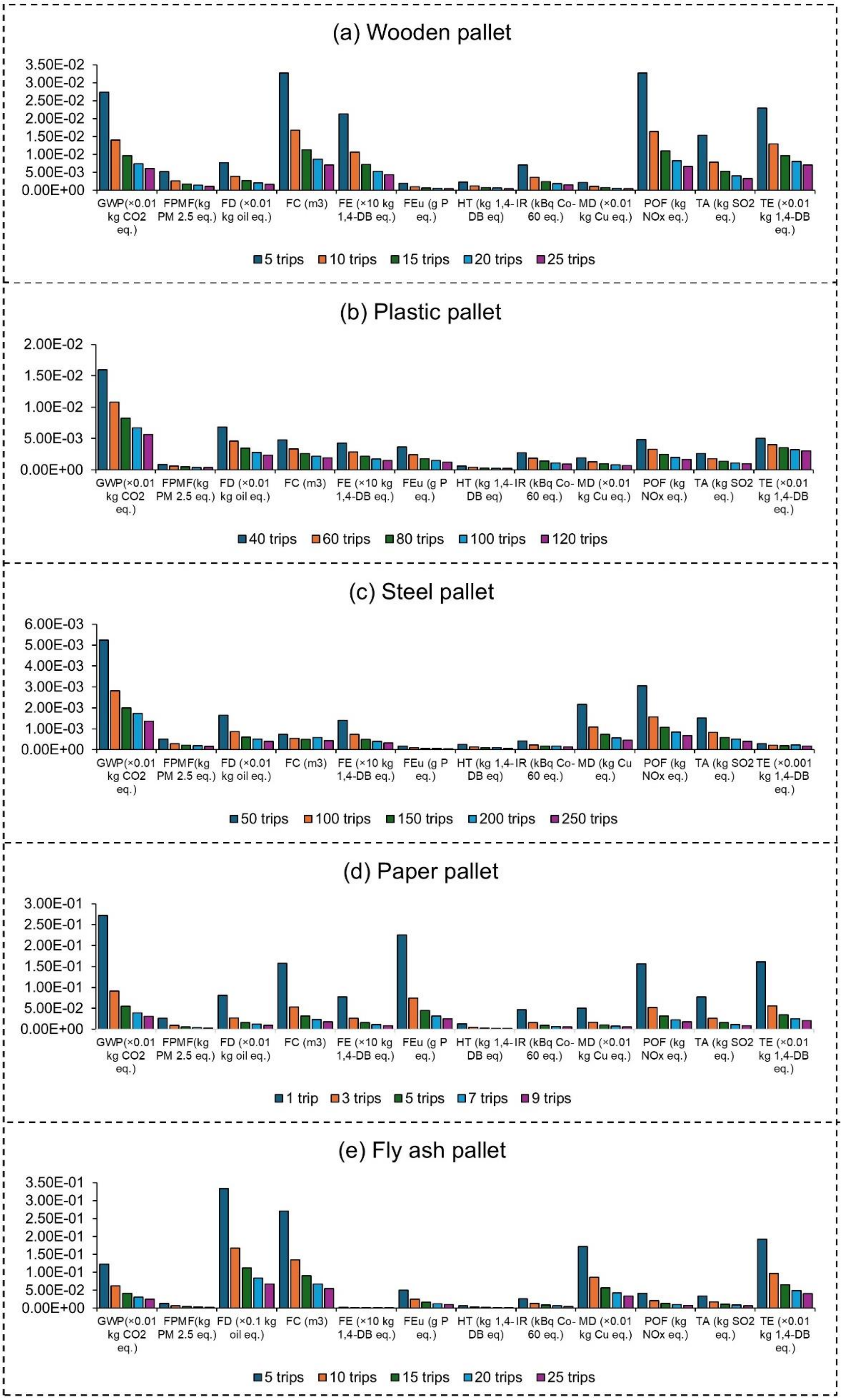

Fig. C.1 Results of sensitivity analysis of RSL of five types of pallets. Some of the results have been scaled to fit within certain parameters, and the real values can be calculated by applying the corresponding multipliers indicated in brackets.

Table C. 4 Results of uncertainty analysis under three scenarios

Base case scenario	Wooden pallet		Plastic pallet		Paper pallet		Steel pallet		Fly ash pallet	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
FC	1.57E-01	3.52E-04	1.73E-01	1.16E-02	1.58E-01	6.13E-03	1.88E-02	2.71E-03	1.35E+00	7.31E-02
FD	3.58E+00	2.68E-02	2.68E+01	1.83E+00	8.08E+00	1.01E-01	7.88E+00	6.66E-01	1.66E+01	4.68E-01
FE	1.05E-02	1.56E-05	1.69E-02	7.65E-04	7.70E-03	1.04E-04	6.77E-03	2.44E-04	1.13E-02	2.09E-04
FEu	8.97E-06	3.06E-07	1.45E-04	2.63E-06	2.25E-04	1.66E-05	8.49E-06	4.08E-06	2.52E-04	1.73E-06
FPMF	2.45E-02	1.61E-04	3.19E-02	1.23E-03	2.65E-02	3.78E-04	2.28E-02	1.75E-03	6.41E-02	2.04E-03
GWP	1.27E+01	9.19E-02	6.17E+01	2.63E+00	2.72E+01	3.42E-01	2.42E+01	3.15E+00	6.15E+01	1.27E+00
HT	1.10E-02	1.23E-04	2.26E-02	1.05E-03	1.35E-02	1.81E-04	1.11E-02	3.84E-04	3.48E-02	1.06E-03
IR	1.92E-03	5.28E-03	1.06E-01	6.50E-03	4.68E-02	5.06E-03	1.81E-02	8.55E-03	1.30E-01	5.88E-03
MD	8.46E-03	5.03E-04	7.63E-02	2.78E-03	5.03E-02	2.82E-03	1.07E-01	8.61E-02	8.59E+01	4.98E+00
POF	1.60E-01	7.75E-04	1.90E-01	3.93E-03	1.56E-01	1.20E-03	1.50E-01	4.84E-03	2.08E-01	2.66E-03
TA	7.37E-02	3.37E-04	9.71E-02	3.17E-03	7.74E-02	9.76E-04	6.97E-02	5.55E-03	1.72E-01	5.11E-03
TE	8.64E+00	1.52E-01	1.23E+01	2.32E+00	1.61E+01	6.63E-01	6.91E+00	1.27E+00	9.56E+01	4.42E+00
Sharing scenario										
FC	1.14E-02	2.36E-05	2.95E-03	1.66E-04	4.00E-02	1.53E-03	5.47E-04	2.69E-05	9.05E-02	4.85E-03

FD	2.77E-01	1.82E-03	3.94E-01	2.58E-02	2.03E+00	2.54E-02	8.78E-02	6.62E-03	1.12E+00	3.11E-02
FE	7.23E-04	1.06E-06	2.48E-04	1.08E-05	1.93E-03	2.63E-05	7.26E-05	2.42E-06	7.56E-04	1.39E-05
FEu	6.76E-07	2.08E-08	2.09E-06	3.72E-08	5.62E-05	4.21E-06	9.60E-08	4.05E-08	1.68E-05	1.15E-07
FPMF	1.83E-03	1.09E-05	5.37E-04	1.78E-05	6.72E-03	9.55E-05	2.88E-04	1.74E-05	4.35E-03	1.36E-04
GWP	9.88E-01	6.23E-03	9.33E-01	3.73E-02	6.86E+00	8.62E-02	2.81E-01	3.13E-02	4.15E+00	8.40E-02
HT	8.22E-04	8.35E-06	3.61E-04	1.50E-05	3.43E-03	4.54E-05	1.39E-04	3.81E-06	2.36E-03	7.01E-05
IR	2.45E-03	3.50E-04	1.59E-03	9.20E-05	1.18E-02	1.28E-03	2.41E-04	8.51E-05	8.75E-03	3.93E-04
MD	7.60E-04	3.41E-05	1.12E-03	3.95E-05	1.26E-02	7.03E-04	1.10E-03	8.57E-04	5.73E+00	3.30E-01
POF	1.12E-02	5.26E-05	2.82E-03	5.60E-05	3.92E-02	3.03E-04	1.58E-03	4.82E-05	1.39E-02	1.76E-04
TA	5.36E-03	2.29E-05	1.56E-03	4.56E-05	1.95E-02	2.47E-04	8.24E-04	5.52E-05	1.16E-02	3.39E-04
TE	9.69E-01	1.02E-02	3.78E-01	3.34E-02	4.24E+00	1.65E-01	2.21E-01	1.27E-02	6.57E+00	2.94E-01
CE scenario										
FC	5.53E-03	6.41E-07	-1.43E-03	1.55E-05	4.67E-02	2.21E-03	-1.58E-04	3.13E-06	-7.14E-02	3.63E-05
FD	1.21E-01	3.17E-05	-1.71E-01	5.84E-04	1.52E+00	1.39E-02	-8.96E-04	5.63E-04	-6.02E-02	1.80E-03
FE	4.22E-04	1.02E-08	-4.03E-06	1.93E-07	1.63E-03	1.84E-05	3.85E-05	2.37E-07	1.79E-04	5.79E-07
FEu	6.55E-08	1.75E-10	3.53E-08	4.72E-09	-3.30E-06	2.23E-06	-4.00E-07	8.27E-10	-1.25E-06	9.93E-09
FPMF	1.22E-03	7.09E-08	-2.77E-04	1.31E-06	5.63E-03	6.77E-05	8.38E-06	2.58E-07	-6.64E-04	4.03E-06

GWP	4.13E-01	1.20E-04	-1.30E-02	2.11E-03	4.79E+00	5.24E-02	-1.38E-01	7.63E-04	-6.83E-02	6.81E-03
HT	8.30E-04	1.42E-06	2.84E-04	2.23E-05	3.48E-03	5.46E-05	1.78E-04	1.40E-06	6.57E-04	8.09E-05
IR	-2.87E-03	1.32E-06	1.03E-04	2.39E-05	-9.97E-03	1.32E-04	-8.00E-04	1.92E-06	-1.89E-03	7.50E-05
MD	1.22E-04	1.13E-06	3.23E-04	3.17E-05	8.16E-03	6.80E-04	-9.34E-03	1.25E-06	-4.86E+00	6.39E-05
POF	9.64E-03	2.13E-07	1.36E-03	3.98E-06	3.45E-02	1.12E-04	9.15E-04	1.19E-06	6.69E-03	1.21E-05
TA	3.90E-03	2.39E-07	-2.35E-04	4.33E-06	1.64E-02	1.50E-04	1.71E-05	7.60E-07	-1.02E-03	1.36E-05
TE	9.32E-02	3.93E-05	-1.42E+00	6.63E-04	2.46E+00	1.54E-01	-1.13E-01	4.72E-05	-3.77E+00	2.24E-03

Appendix D List of publications

Publications based on this PhD

Peer-reviewed papers

- **Zhang, T**., Wen, Z., Fei, F., Kosajan, V., Tan, Y., Xu, M., Ekins, P., 2023. Green transformation strategy of pallet logistics in China based on the life cycle analysis. *Science of The Total Environment*, 903, 166436.
- **Zhang, T**., Wen, Z., Tan, Y., Ekins, P., 2024. Circular economy strategies for the booming industrial pallet use in China. *Sustainable Production and Consumption,* 46, 244-255.
- **Zhang, T**., Wen, Z., Tan, Y., Shi, S., Sun, Y., Ekins, P., 2024. Advancing circular economy of pallets: a comprehensive evaluation framework. *Resources, Conservation and Recycling*, 211, 107874.

Book

- Wen, Z., Li, H., Ke, S., Cheng, M., Tang, Y., Chen, J., **Zhang, T.**, Green production and consumption: mechanisms, methods and practices. Beijing: China Environment Publishing Group, 2023.

Reports

- Sun, X., Zhang, J., **Zhang, T.**, Li, X., Wang, R., Xu, M., Hu, Z., Wang, Y., 2021 Report on Sustainable Development of the Pallet Industry in China. CFLP.
- Wen, Z., **Zhang, T.**, Xu, M., Hu, Z., 2022. Research on accounting for greenhouse gas emissions from shared pallets. Beijing: School of Environment, Tsinghua University.

Publications related to other work

Peer-reviewed papers

- Tan, Y., Wen, Z., Hu, Y., Zeng, X., Kosajan, V., Yin, G., **Zhang, T.**, 2023. Single-use plastic bag alternatives result in higher environmental impacts: Multi-regional analysis in country with uneven waste management. *Waste Management*, 171, 281.
- Chen, C., Wen, Z., Wang, Y., Zhang, W., **Zhang, T.**, 2022. Multi-objective optimization of technology solutions in municipal solid waste treatment system coupled with pollutants cross-media metabolism issues. *Science of The Total Environment*, 807, 150664.
- Zhang, Y., Wen, Z., Hu, Y., **Zhang, T.**, 2022. Waste flow of wet wipes and decision-making mechanism for consumers' discarding behaviors. *Journal of Cleaner Production*, 364, 132684.
- Zhang, Y., Wen, Z., Lin, W., Hu, Y., Kosajan, V., **Zhang, T.**, 2021. Life-cycle environmental impact assessment and plastic pollution prevention measures of wet wipes. *Resources, Conservation and Recycling*, 174, 105803.