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LCA comparison of the single-use takeaway packaging using PP, paper, and PLA materials

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Abstract

The waste of resources and environmental pollution caused by the expanding scale of the take-out market has received widespread attention. In this paper, through the whole life cycle evaluation of typical take-out packaging with different materials of individual plastic lunch boxes and plastic bags, it was found that the carbon emissions of PP, paper, and PLA take-out packaging were mainly from the disposal stage, the assembly, and transportation stage, and the production stage, which were 0.034, 0.026, and 0.044 kg CO_2 eq. respectively. In addition, for paper and PLA take-out packaging, the biological carbon sequestration process in production showed a significant emission reduction effect. On this basis, the annual carbon emissions of take-out packaging in China were estimated to be about 230 million kgCO_2, and if replaced with PLA lunch boxes and paper bag take-out packaging, the CO_2 emissions could be reduced by about 74%. At the same time, the carbon emissions of paper take-out packaging were significantly reduced when a more environmentally friendly disposal method was chosen, and the carbon emissions of PLA and PP take-out packaging can be reduced accordingly. The results show that replacing biomass packaging materials with more environmentally friendly ones, improving the efficiency of biomass packaging production processes, and choosing more environmentally friendly disposal methods are effective ways to reduce carbon emissions from take-out packaging.

Keywords: LCA, food delivery, plastic, PLA, paper

Introduction

In recent years, with the rapid development of China's urbanization and the Internet service industry, the scale of the take-out market has been expanding. 2019 China's food and beverage take-out industry reached 653.6 billion yuan, up 39.3% year-on-year, and by the end of 2019, China had about 460 million take-out consumers, up 12.7% year-on-year, or about 53.9 percent of the urban resident population%[1]. It is conservatively estimated that the three major take-out platforms in China consume about 60 million plastic products a day[2].2019 total take-out orders have reached 3.5 billion, and the total weight of PP meal boxes used is estimated at 540,000 tons based on the average use of two 20g meal boxes for a single take-out[3].

The majority of take-out packaging uses plastic products. However, the production, use, and disposal of plastic take-out packaging have serious problems such as waste of resources and environmental pollution.

Take plastic take-out containers as an example, the microplastics leaked into the environment during industrial production will directly enter the soil, sea and other natural environments, destroying the soil structure, and the plasticizers contained in microplastics will be released into living organisms and eventually enter the bodies of animals and plants through the food chain, endangering human life and health[4-6]. Large pieces of plastic waste, such as plastic bags, can be eaten by animals and pose a greater threat to the survival of organisms and affect the diversity of species[7-9]. In addition, plastic is a non-inert material, easy to be eroded by the soup when serving food, thus forming cross-infection inside and outside the food [10].

In the process of use, to maximize the convenience of customers and save costs, most take-out packaging are used in a single-use manner, it is estimated that daily take-out orders generated by plastic bags can cover 420,000 m^3, about 59 soccer fields, resulting in a serious waste of resources [11], It does not meet the requirement of sustainable development of society.

In the disposal stage, most of the take-out packaging using polyethylene, polypropylene, and other plastic products, but consumer groups have not yet developed good waste separation habits, resulting in take-out waste contains a lot of oil and dirt is difficult to recycle. The recycling price of plastic bags is too low if the recycling will be completely unable to recover the cost of recycling [12]. Therefore, most of the take-out waste is disposed of in landfills or incinerators along with municipal waste, and the leachate and dioxin-based harmful gases that result from the treatment process have a serious impact on the living environment of present and future generations.

To address the dilemma of resource waste and environmental pollution, China has introduced a series of policy measures. In terms of direct impact, China has actively tried to promote the application of more environmentally friendly alternative packaging. in January 2020 China's National Development and Reform Commission and the Ministry of Ecology and Environment issued the Opinions on Further Strengthening Plastic Pollution Control, promoting the use of biodegradable packaging materials in the food and beverage takeaway sector, and setting clear requirements for banning and restricting the use of non-biodegradable plastic packaging products [13]. Actively promote the exploration of new materials for takeaway packaging, such as biodegradable plastic polylactic acid (PLA). PLA has good biodegradability and biocompatibility, and can be disposed of by composting, natural degradation, or burning after use, with the final degradation products being water and carbon dioxide, which will not bring pollution to the environment [14].In terms of indirect impact, China is actively promoting legislation on food waste and the separation of household waste.2021 On April 29, the 28th meeting of the Standing Committee of the 13th National People's Congress voted on April 29 to adopt an anti-food waste law, which means that, from now on, practicing conservation and opposing waste is no longer just advocacy and a call to action, but has become a legal text in force [15]. The Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution, which was amended and passed for the second time in April 2020, proposed to set up a domestic waste separation system and has made progress in stages, with China's current coverage rate of domestic waste separation in residential areas reaching 86.6% and the food waste separation rate in Beijing reaching 21.78%[16].

Currently, most of the research related to take-out packaging is focused on the material comparison. Joan Manuel F. compared three different take-out packaging materials - aluminum, polystyrene (EPS), and polypropylene (PP) - and found that disposable polypropylene plastic containers have the highest environmental impact among seven indicators, including global warming potential (GWP) [17]. Jingnan Zhao Study Finds PLA Reduces Carbon Emissions by 61.25% Compared to Polyethylene (PE) Packaging in Tianjin [18]. Bulim Choi's analysis shows that the current carbon emissions from landfill disposal of PLA in Korea are less than those from incineration[19]. Chen Sha analyzed and calculated the whole life cycle carbon emissions of paper products in China, and obtained the conclusion that the life cycle greenhouse gas emissions of paper products in China were 20.3Mt CO_2-eq in 2015 [20]. Wen Zongguo evaluated the environmental impact of take-out in Beijing based on the whole industry chain of take-out, and concluded that the production and waste disposal segments are the main sources of the environmental impact of take-out[21].

However, there are few studies on the quantitative comparison of carbon emissions for the whole life cycle of different take-out packaging materials in China. Therefore, this paper compares and analyzes the carbon emissions at each stage by conducting a whole life cycle evaluation of take-out packaging made of PLA, paper, and PP plastic, and identifies the production links to be improved in the whole life cycle, to provide data for research related to the emission reduction of take-out packaging in China.

2 Methods

Product life cycle assessment refers to the entire process from raw material acquisition to production, packaging, use, and disposal. Based on the working framework of ISO 14040-2006 environmental management system of the International Society of Environmental Toxicology and Chemistry (SETAC), the life cycle assessment of take-out packaging studied in this paper includes four steps: determination of objectives and scope, inventory analysis, impact assessment and interpretation of results [22].

2.1 Determination of objectives and scope

2.1.1 Research Objectives

Collected data to compare and analyze the carbon emissions of the three types of take-out packaging from the "cradle to grave" stage, and to determine the main steps of the life-cycle impact of the three raw materials on carbon emissions, to provide data for China's take-out packaging emission reduction related research.

2.1.2 Research Scope

According to ISO 14040 standard, the functional unit (function unit) in this study is defined as a single typical take-out package consisting of one 650ml container and one 20*33cm bag, Combine them into one figure, as shown in the following figure.

Figure 1. Research objectives (from left to right, paper, PP, PLA take-out packaging)

The scope of LCA evaluation includes the raw material processing stage, take-away packaging and transportation stage, use stage and disposal stage. Accordingly, find the paper to determine the system boundary of the research objectives, including the main processes in the four stages of the product life cycle, system boundary as shown in the figure.

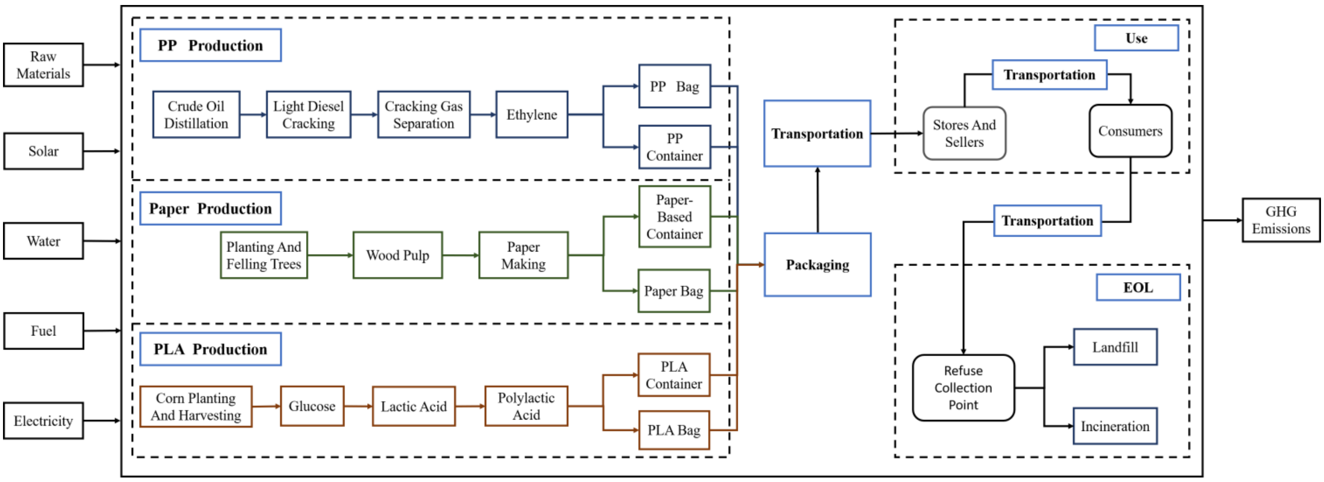

Fig 2. System boundary of PP, paper, and LCA containers and bags

Collected and recorded data on single regular meal take-out packaging in Gulou District, Nanjing, Jiangsu Province, and organized the weight list summarized as follows.

Table 1. three different materials packaging boxes, plastic bags weight list

Container (kg)			**Bag (kg)**		
PP container	Paper-based Container	PLA Container	PP bag	Paper Bag	PLA Bag
0.013	0.022	0.019	0.043	0.016	0.0090

The weight data of PP bag, PP container, and Paper-Based Container were collected from visiting to typical take-out stores in Gulou District, Nanjing, Jiangsu Province, after recording the weight data of PP lunch boxes with a volume specification of 650mL and the corresponding take-out plastic bags,while the weight data of PLA Bag, PLA Container, and Paper bag were collected from Taobao stores. When the above data were selected, the data of 650ml size containers and corresponding size bags were selected and recorded. Considering the complexity of the system, the following descriptions and assumptions are made about the system boundaries. In the use phase, the carbon emissions from the consumer use phase are neglected in this paper due to their small size.

(1) In the transportation stage, the carbon emissions from transportation of raw materials to processing plants were neglected because specific data on transportation distances were not available due to the wide range of sources of raw materials, while the transportation distances from processing plants to merchants, and from merchants to consumers and from consumers to waste disposal were equal for all three materials.

(2) In the feedstock production phase, the amount of biological carbon fixed by PLA and by growing corn and round wood during paper feedstock production was considered, since plants can fix atmospheric CO_2 through photosynthesis.

(3) In the disposal phase, the reduction of total carbon emissions from the incineration of packaging materials for electrical reuse was considered.

(4) In the packaging phase, since the take-out packaging is lighter, the maximum number of boxes that can withstand the packaging process is calculated based on the volume.

2.2 LCA Data

2.2.1 Production

The weight data in the table includes take-out boxes and bags, and the collected data are summarized in the following table.

Table 2. Carbon emission inventory of production of different material takeaway packaging

Package Material	Process	Weight (kg)	Emission factor of sub-product(kg CO_2e/kg)	Emission factor of final product (kg CO_2e)
PP	Crude Oil Distillation	0.017	/	2.0[23]
	Light Diesel Cracking			
	Cracking Gas Separation			
	Ethylene Post processing			
Paper-Based	Planting and Felling Trees	0.038	-1.69[20]	-0.9
	Wood Pulp		0.67[24]	
	Paper Making		0.092[20]	
PLA	Corn Planting and Harvesting	0.028	-2.8[25]	1.6
	Glucose		0.56[25]	
	Lactic Acid		2.1[25]	
	Polylactic Acid		1.3[25]	
	Polylactic Acid Post processing		0.50[25]	

The weight data of PP bag, PP container, and Paper-Based Container were obtained by visiting take-out stores in Gulou District, Nanjing and finding the average value; while the weight data of PLA Bag, PLA Container, and Paper bag were collected from Taobao stores. All the above data are for 650mL size containers and corresponding size bags. The carbon emission data of the production process steps were collected from the paper data. In addition, the amount of biocarbon fixed during the production of planted corn and round wood was considered in the raw material production process.

2.2.2 Packaging and Transportation

Takeaway boxes and bags are generally transported in corrugated carton containers, selected container carton volume of 60cm * 30cm * 40cm, the weight of 1.3kg, can be loaded meal boxes and plastic bags subject to carton volume and tolerable weight control, calculated and summarized as follows.

Table 3. Carbon emission inventory of containerized packaging

Package Material	**Process**	**Weight (kg)**	**Emission factor (kg CO_2e/kg)**
Container	Packaging weight assigned to each container	0.013	0.75[26]
Bag	Packaging weight assigned to each bag	0.00013	

Because of the wide range of raw material sources and the variability of transportation distances, the transportation carbon emissions from the raw material to the processing plant process are ignored. For the other transportation processes, where the transportation distance from the factory to the take-out store is 42.7km, and the take-out store to the customer is 2km is selected from the Beijing take-out transportation distance data[21], the type of energy consumed by the vehicle is diesel, the carbon emission data per unit mass 0.0044 (kg*km) is selected from the carbon footprint assessment study of cooked rice[23], and the transportation distance data from the customer to the disposal site is selected from the Nanchang [27]. The average distance of sanitary landfill transportation of domestic waste, about 15km, that is, the round trip distance is 30km, the type of energy consumed by the vehicle is electric energy, and the carbon emission data per unit mass is 0.00016(kg*km).

Table 4. Carbon emission inventory of transportation process

Package Material	**Process**	**Distance（km）**	**Emission factor (kg*km)**	**GHG emission (kg CO_2e/kg)**
PP	From factory to store	43[21]	0.0044[28]	5.6E-03
	From store to consumer	2[21]	0.0044[28]	1.5E-04
	From consumer to waste management cite	30[27]	0.00016[27]	8.2E-05
Paper-Based	From factory to store	43[21]	0.0044[28]	9.6E-03
	From store to consumer	2[21]	0.0044[28]	3.3E-04
	From consumer to waste management cite	30[27]	0.00016[27]	1.8E-04
PLA	From factory to store	43[21]	0.0044[28]	7.7E-03
	From store to consumer	2[21]	0.0044[28]	2.7E-04
	From consumer to waste management cite	30[27]	0.00015[27]	1.3E-04

2.2.3 EOL

Since there are few studies on carbon emissions from disposal of different materials in China, carbon emissions data for three materials are selected from US EPA data [29], The percentages of landfill and incineration disposal are taken from China's National Bureau of Statistics 2019 China's domestic waste disposal methods [30]. Therefore, scenario analysis of the disposal process (EOL) percentages is considered. The first scenario is the disposal percentage of domestic waste in China in 2019, with 53% for landfill and 47% for incineration, while the second scenario uses the most desirable disposal method for all materials, with PP and paper recycling and PLA landfill disposal.

Table 4. Carbon emission inventory of disposal process

Package Material	**Process**	**Present Disposal Percentage（%）**	**Optimal Disposal Percentage（%）**	**Emission factor (kg)**
PP	Landfilling ratio	53%	-	0.02
	Incineration ratio	47%	-	1.29
	Recycling	-	100%	-0.79
Paper-Based	Landfilling ratio	53%	-	0.18
	Incineration ratio	47%	-	-0.49
	Recycling	-	100%	-3.14
PLA	Landfilling ratio	53%	100%	-1.65
	Incineration ratio	47%	-	-0.63
	composting	-	-	-0.09

2.2.4 Scenario analysis

Due to national policy support and technological developments, the disposal of take-out packaging will evolve towards low environmental impact. In the second scenario of EOL, all PP and paper take-out packaging is recycled and all PLA take-out packaging is composted to explore the potential for carbon emission reduction for the three materials relative to current disposal methods.

3 Results

3.1 Carbon emission inventory of different materials of takeaway packaging

Carbon emissions are calculated separately for the whole life cycle process of meal boxes and bags of different materials, and summarized as follows.

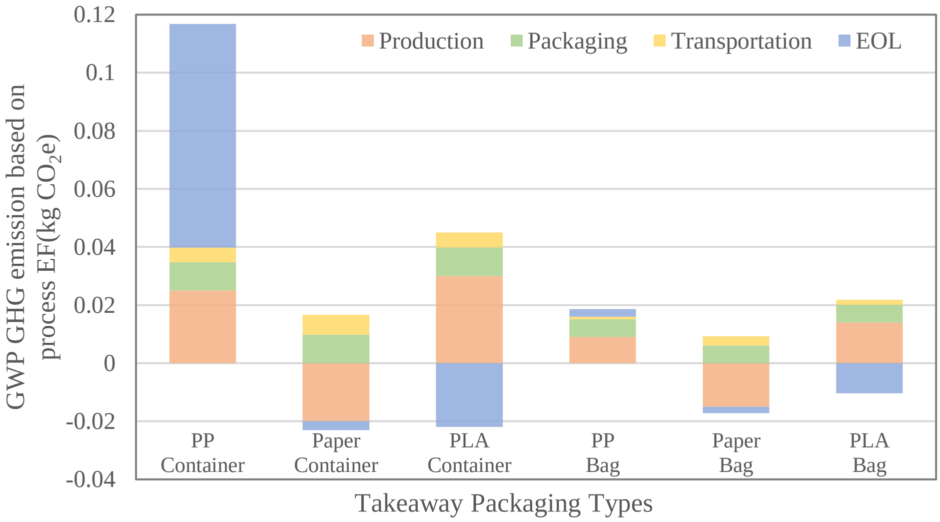

Fig 3. Carbon emissions based on the whole life cycle assessment of PP, paper, PLA takeaway packaging (including biogenic carbon)

Table 5. Carbon emission inventory for the whole life cycle assessment of takeaway packaging (including biogenic carbon)

GHG emission based on product EF (kg CO_2e)						
Process	**PP Container**	**Paper Container**	**PLA Container**	**PP Bag**	**Paper Bag**	**PLA Bag**
Production	0.025	-0.020	0.030	0.0088	-0.015	0.014
Packaging	0.0098	0.0098	0.0098	0.0061	0.0061	0.0061
Transportation	0.0050	0.0069	0.0052	0.0009	0.0032	0.0018
EOL	0.077	-0.0030	-0.0219	0.0026	-0.0022	-0.010
Sum	0.048	-0.0067	0.024	0.018	-0.0077	0.012

As can be seen from the chart, when considering only the impact of carbon emissions on the environment, take-out meal boxes and bags made of PP have the greatest impact on the environment, followed by PLA, and paper has the least impact.

1) PLA take-out packaging mainly comes from the production process. Although the raw material of takeaway packaging made of PLA can absorb CO_2 in the air during the production process of planting, the energy consumption of the existing PLA production process is large, resulting in the highest carbon emission of 0.03kgCO_2 and 121% of carbon emission from PLA production process.

2) The carbon emission of PP material takeaway packaging mainly comes from the disposal process, incineration releases CO_2 that originally does not belong to the atmosphere, which increases the amount of CO_2 in the atmosphere. 0.077kgCO_2 can be released per unit mass of the PP lunch box, accounting for 40% of the total carbon emission of the PP lunch box.

3) The carbon emission of paper take-out packaging mainly comes from the carbon emission in the collection and transportation stages, both of which are similar, with a total average share of 92%. The production process of take-out packaging made of paper material is negative because plant photosynthesis can absorb CO_2 from the air. While paper take-out packaging is heavier, so the transportation phase has a higher

share of carbon emissions than other materials. The disposal process of PLA lunch boxes has a greater potential to reduce carbon emissions, with 0.0219 kg of CO_2 emissions per unit mass of PLA lunch boxes.

3.2 Analysis of carbon emission results per takeaway order

Two-by-two summation of different materials of meal boxes and bags with and without bio-carbon is carried out, and the case without bio-carbon does not take into account the reduction of carbon emissions in the planting part of the production, resulting in the full life-cycle results of the take-out packaging portfolio as follows.

Table 6. Full life cycle carbon emission inventory of takeaway packaging portfolio

GHG emission based on product EF(kg CO_2e)				
Whether included biogenic carbon or not	Package type	Package type		
		PP Container	Paper Container	PLA Container
With biogenic carbon	PP Bag	0.066	0.011	0.043
	Paper Bag	0.040	-0.014	0.017
	PLA Bag	0.059	0.005	0.036
Without biogenic carbon	PP Bag	0.066	0.048	0.095
	Paper Bag	0.067	0.050	0.096
	PLA Bag	0.085	0.067	0.114

As can be seen from the table, when considering the biological carbon sequestration in the production process, the take-out packaging combined with the smallest carbon emissions is paper lunch boxes and paper bags, with each take-out packaging emitting -0.014kgCO_2, and the take-out packaging combined with the largest carbon emissions is plastic lunch boxes and plastic bags, with each take-out packaging emitting 0.066kgCO_2. The carbon emissions of PLA material compared with plastic take-out packaging show a good ability to reduce emissions, but there is more room for improvement compared with paper material.

When the bio-fixation process is not considered, the smallest combination of take-out packaging is a paper lunch box and a plastic bag, which emits 0.048 kg CO_2 per take-out package, and the largest combination of take-out packaging is a PLA lunch box and a PLA bag, which emits 0.114 kg CO_2 per take-out package. For paper and PLA take-out packaging, the bio-solidification process showed good emission reduction.

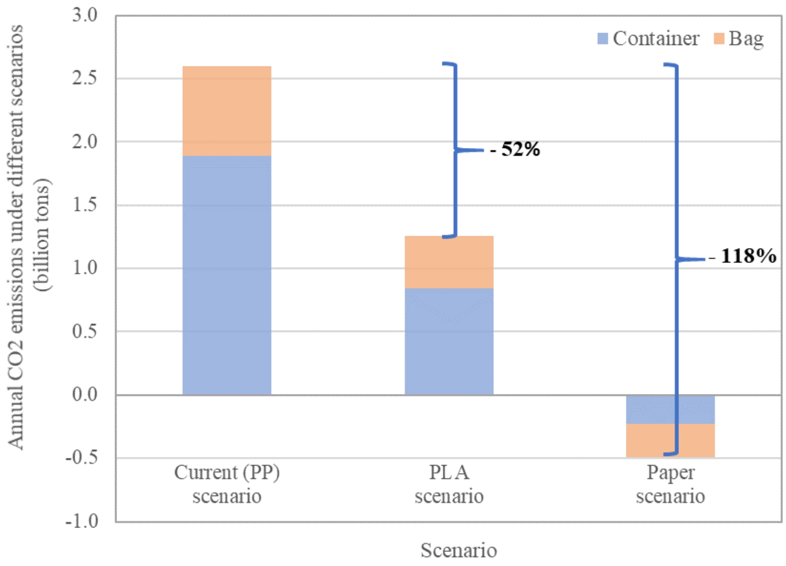

Fig4.Annual CO_2 emissions for different material take-out packaging applications

Typical take-out packaging combinations are generally plastic lunch boxes and plastic bags, and a single take-out can produce 0.066 $kgCO_2$. Based on the annual order volume of 3.5 billion take-out orders in China in 2019, the annual output of carbon emissions from take-out packaging is about 230 million $kgCO_2$. If biological carbon sequestration is considered, using paper or PLA take-out packaging, a single take-out can produce -0.014 $kgCO_2$ and 0.017 $kgCO_2$, which is 118% and 52% less CO_2 emissions respectively compared to plastic take-out packaging. Using PLA lunch boxes and paper bags, a single-use take-out can produce 0.017$kgCO_2$, and the annual output of carbon emissions from take-out packaging is 0.6 billion $kgCO_2$, which reduces CO_2 emissions by 74% compared to take-out packaging made of plastic.

3.3 Carbon Results for Optimal Disposal Scenarios

The disposal of take-out packaging of different materials was varied to dispose of all materials under optimal conditions, taking into account biochar. Among them, plastic and paper packaging are recycled and PLA is landfilled, after recalculating the results in the following table.

Table 7. Full life cycle assessment carbon emission inventory under ideal disposal of takeaway packaging portfolio

GHG emission based on product EF(kg CO_2e)				
Whether included biogenic carbon or not	Package type	Package type		
		PP Container	Paper Container	PLA Container
With biogenic carbon	PP Bag	0.042	-0.060	0.028
	Paper Bag	-0.026	-0.128	-0.040
	PLA Bag	0.038	-0.065	0.023
Without biogenic carbon	PP Bag	0.042	-0.023	0.080
	Paper Bag	0.001	-0.064	0.039
	PLA Bag	0.063	-0.003	0.101

Comparing with Table 5, it can be seen that the carbon emissions of take-out packaging of all three materials have decreased to a greater extent, which indicates that the disposal method has a greater impact on the carbon emissions of take-out packaging, and if the disposal method of take-out packaging can be improved effectively, it will have a certain effect on the reduction of carbon emissions.

4 Discussion and conclusions

In this paper, the carbon emissions of three different materials of take-out packaging, PLA, paper ,and PP plastic, were analyzed using the life cycle assessment method, and the carbon emissions of a single-use take-out were 0.036kgCO_2, -0.017kgCO_2, and 0.066kgCO_2, respectively.

The main processes of carbon emissions from different materials of takeaway packaging are different. The carbon emission of PP takeaway packaging mainly comes from the disposal stage, accounting for 40%, the carbon emission of paper takeaway packaging mainly comes from the assembly and transportation stage, accounting for 121%, the carbon emission of PLA takeaway packaging mainly comes from the production stage, accounting for 92%. Therefore, if we want to promote the application of bio-based material PLA take-out packaging, we need to upgrade the production process of PLA to reduce the product weight while ensuring product performance.

Using the life cycle assessment method, the highest and lowest carbon emission combinations of single-use takeaway packaging are plastic lunch boxes and plastic bags, and paper lunch boxes and paper bags, with carbon emissions of 0.066 kgCO_2 and -0.0014 kgCO_2. But there is more room for improvement compared with paper material. For both paper and PLA takeaway packaging, the biological carbon sequestration process shows good emission reduction.

Typical take-out packaging combinations are generally plastic lunch boxes and plastic bags, which can produce 0.066 kgCO_2 for a single take-out, and the annual carbon emission output is 230 million kgCO_2 based on the annual order volume of Chinese take-out in 2019. if considering bio-solidification, with PLA lunch boxes and paper bags, a single take-out can produce 0.017 kgCO_2, and the annual carbon emission output of take-out packaging is 0.6 billion kgCO_2. kgCO_2, which is 74% less CO_2 emission compared with plastic takeaway packaging.

When choosing a more environmentally friendly disposal method, the carbon emissions of paper take-out packaging are significantly reduced, and slightly reduced for take-out packaging made of PLA and PP, which indicates that the disposal method has an impact on the carbon emissions of take-out packaging, and if a more environmentally friendly disposal method of take-out packaging can be used, it will have a certain effect on the reduction of carbon emissions.

The EOL data are all selected from the US EPA data because there is no better Chinese data, which has caused some errors in the experimental results. China can consider establishing a public database of EOL for its situation, which will be more conducive to carbon emission research and control.

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