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Life Cycle Assessment of Biodegradable Polylactic Acid (PLA) Plastic Packaging Products—Taking Tianjin, China as a Case Study

ZHAO Menglei[1], YANG Zeng[1], ZHAO Jingnan[1,2,*], WANG Yan[1,2], MA Xiaolei[1], GUO Jian[1]

1. Mechanical Engineering College, Tianjin University of Science and Technology, Tianjin 300222, China;
2. Tianjin Key Laboratory of Integrated Design and On-line Monitoring for Light Industry & Food Machinery and Equipment, Tianjin 300222, China

Abstract: In this paper, the life cycle assessment (LCA) method is used to evaluate and quantify the energy consumption and environmental impacts of biodegradable polylactic acid (PLA) plastic packaging from the five stages of raw material acquisition, raw material transportation, product production, products use and final disposal. Seven impact categories were selected for the impact analysis: abiotic depletion potential fossil fuels (ADP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical ozone formation potential (POCP), human toxicity potential (HTP), and terrestrial ecotoxicity potential (TETP). The results of the LCA are discussed and the results show that production of products is the highest stage of the environmental impact. Meanwhile, in the entire life cycle, the top three environmental impact categories are GWP, ADP and HTP, which account for 32.63%, 24.83% and 14.01%, respectively. The LCA results show that the environmental impact can be reduced in several ways: reducing the consumption of electricity, increasing the input of new energy, increasing the conversion rate of materials in the production process, using organic and water-soluble fertilizers instead of conventional fertilizers, using environment-friendly fuels and establishing a sound recycling system.

Key words: life cycle assessment; energy consumption; environmental impacts; polylactic acid; plastic packaging

1 Introduction

Plastics constitute a family of hundreds of different materials with a wide variety of properties. They are designed to meet the needs of each individual application in the most efficient manner. Plastic materials are organic materials that can be either fossil fuel based or bio based. According to plastics market data from Plastics Europe, the world production of plastic materials in 2018 was 359 million t (EPRO, 2019), and the output increased by 11 million t compared with 2017. The proportion of China's plastic production in the global production has also increased from 29.4% in 2017 to 30% in 2018, and the production has increased year by year, now being close to one-third of the global production (EPRO, 2018, 2019). China has become one of the world's major producers and consumers of plastic products, and continues to maintain a surplus in import and export trade (China Plastics Processing Industry Association., 2018). With the growth of the national economy and the improvement of people's living standards, the demand for plastic products is also increasing year by year. However, the resource consumption and environmental pollution problems this demand brings cannot be underestimated. Substituting petrochemical resources and reducing white pollution to promote environmental protection have become two major driving forces for the development of biodegradable materials, and biodegradable materials have be-

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First author: ZHAO Menglei, E-mail: dreamleir@163.com
***Corresponding author:** ZHAO Jingnan, E-mail: jingnanzhao@tust.edu.cn

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come the focus of sustainable and circular economic development (Wang et al., 2017). Biodegradable materials are a type of polymer materials that can be decomposed into carbon dioxide and water by microorganisms in industrial or urban composting facilities, and they are mainly based on either polycaprolactone (PCL), polybutylene succinate (PBS), polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyvinyl alcohol (PVOH) or plastarch (Martien et al., 2017).

Currently, biodegradable plastic is mainly used in food packaging and tableware, foam packing, compost bags, agricultural and horticultural planting products, paper coating and other packaging, as shown in Fig. 1. In 2014, the global consumption of biodegradable plastics was about 3.73×10^4 t, and the total global consumption is expected to reach 7.50×10^4 t by 2020, with an annual growth rate of about 13% (Lu, 2016).

PLA, as one of the biodegradable materials, is a type of fat polyester that is polymerized by the fermentation products (lactic acid) of microorganisms. It has a sufficient source of raw materials and can be recycled. The production process is pollution-free and the products can be biodegradable. Therefore, PLA has become the most actively studied and rapidly developed biodegradable material in recent years. PLA has excellent biocompatibility and high strength, it is non-toxic, non-irritating, and easily processed and shaped, as well as having good tensile strength, elongation and processing performance. Thus, it is widely used in the manufacture of products for various applications, such as living plastic packaging, agro-forestry environmental protection plastics, textile fibers, composite materials for electrical appliances, automobiles and buildings, medical tissue materials, 3D printing materials, etc. (Jiang, 2010; Shen, 2013; Zhou, 2014).

In order to protect the environment and save resources, China implemented the "plastic limit order" nationwide in 2008, in which the production and use of traditional petroleum-based plastic packaging products has been greatly restricted, and PLA biodegradable material has become the main alternative to petroleum-based materials. However, research on the life cycle evaluation of PLA in China is still limited at present, which affects the development and application of new plastics in China to a certain extent. However, foreign research on this topic has been very common, especially in the area of food packaging. For example, Hermann et al. (2010) focused on the production of thin films and laminates for snack packaging, and compared the bio-based materials with traditional materials. In addition, Bertoluci et al. (2014) assessed the environmental impact of three different olive packaging systems and found that proper consideration in packaging design should be given to garbage collection and disposal to minimize the environmental impact. Of course, Ingrao et al. (2015) used the carbon footprint to simulate the life cycle of PLA trays and evaluated two different PLA particle transport systems. In a subsequent study, Ingrao et al. (2017) studied the life cycle evaluation of foam PLA trays, and found that the processes with the greatest impact on the environment were production and transportation. To sum up, most of the relevant literature focuses on the comparison of environmental impacts of different products, the impact analysis of different transportation routes, or the evaluation of life cycle stages such as the life spans of different products.

But the focus of our study on the production and use of the link is different. In this paper, the PLA plastic food box life cycle assessment is used to reveal the major factors affecting the environment, and environmental protection recommendations are given for the production, use and final treatment stages. By comparison with the traditional polyethylene materials, the differences in the environmental impact and energy consumption are obtained, which make a due contribution to the research on the production of polylactic acid plastics in China and even the whole world. As a municipality directly under the Central government of China, Tianjin boasts a unique geographical location, superior water and land transportation features, and many large industrial parks, which facilitate the centralized production of products.

Hence, this paper chose PLA plastic packaging products for life cycle evaluation, taking Tianjin, China as a case study.

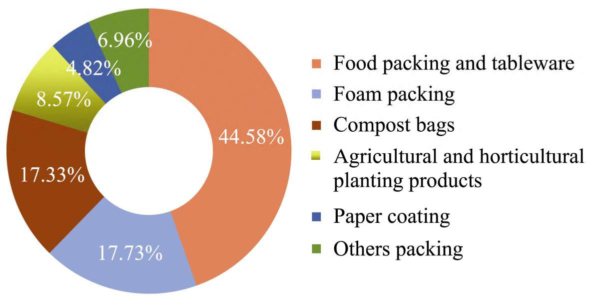

Fig. 1 The main global biodegradable plastic consumption categories in 2014

2 Methodology

In this study, life cycle assessment (LCA) was used to quantify the environmental impacts of the life cycle stages of the products. LCA is defined in ISO14040 as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle, so it is a tool for the analysis of the environmental burden of products at all stages of their life cycles from the extraction of resources, through the production of materials, including product components and the product itself. After use, products are managed after they are discarded, either through reuse, recycling, or final disposal (Guinee, 2002; International Organization for Standardization, 2006).

2.1 Definitions of the goal and scope

The purpose of this study is to conduct the energy consumption and environmental impact assessments of PLA food lunch box plastic packaging throughout its life cycle by summarizing the energy input and output. Then they are compared with those of traditional PE materials to find the step that contributes the most to the environmental impact, so as to choose the optimal scheme for reducing the energy consumption and environmental pollution. All phases of the life cycle are considered, from the acquisition of raw materials to the final disposal.

2.2 Functional unit

This study referred to Meng's process of PLA life cycle evaluation (Meng, 2010), and based on the data analysis from raw material acquisition to final processing of PLA packaging plastic, the evaluation functional unit was set as 1 t of PLA food box plastic.

2.3 System boundary

The entire life cycle of PLA plastic packing is considered in this LCA for estimating energy consumption and environmental impacts. So, the system boundary is from cradle to grave. Figure 2 shows the life cycle flow chart and all the five stages including raw material acquisition, raw material transport, product production, products use, and final disposal.

3 Life cycle inventory analysis

3.1 Raw material acquisition

PLA plastic packaging mainly uses corn, sugarcane and sugar beet as the raw materials that are adequately sourced and can be recycled. The planting areas of corn, sugar cane and sugar beet in China are shown in Fig. 3. Corn is used as the main raw material for PLA packaging because it has a much larger planting area than sugar cane or sugar beet.

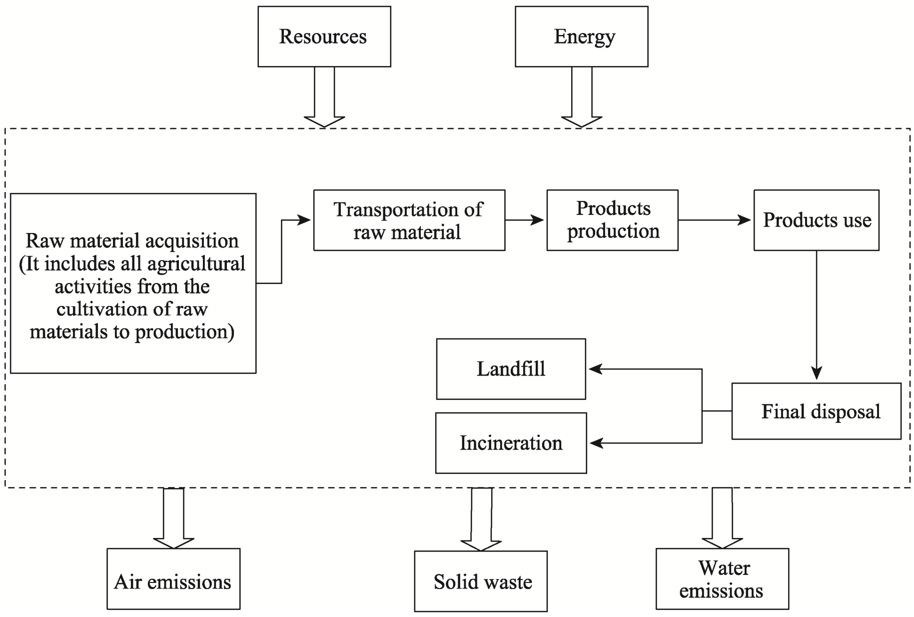

Fig. 2 LCA system boundary for PLA plastic packaging products

Table 1 Cost and energy analysis of raw corn

Term	Land lease	Corn seeds	Fertilizer	Harvest fee	Machine farming/Manual farming/Pesticides	Total
Cost (10^3 yuan ha^{-1})	3.00	0.80	1.50	1.00	1.00	7.30

In China, the specialized production and development regions of corn are mainly divided into the Northeast, Jin-Shan, north China, central China and south China region, and the raw materials in this study are all from the Liaoxi region in northeast China (Li et al., 2010). The raw material acquisition calculation includes all data from the planting to harvesting stages of corn. Corn is a light-loving C_4 plant (i.e., the original products of CO_2 assimilation are the four-carbon compounds malic acid or aspartic acid), its photosynthesis absorbs carbon dioxide and water to synthesize oxygen and organic materials, and the materials are synthesized by photosynthesis to promote the growth of the corn (Zhang et al., 2018). The resource consumption of corn during the whole growth cycle is mainly the energy consumption of transportation, mechanical irrigation, mechanical seeding, and mechanical harvesting, which totals 2.5×10^3 MJ t^{-1}. According to the data in Table 1, the production cost of corn raw material is 624 yuan t^{-1}. At the same time, the production of one ton of polylactic acid requires 2.25 t of corn (Li, 2020), so the energy consumption in the production of one ton of polylactic acid from raw corn is 7.35×10^3 MJ, and the production cost is 1.83×10^3 yuan (Akiyama et al., 2003; He et al., 2017).

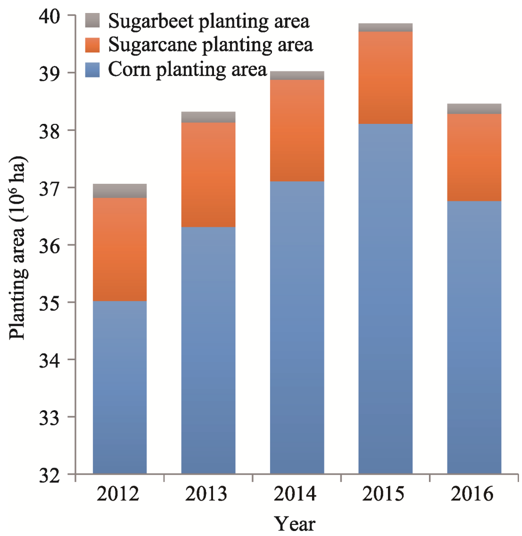

Fig. 3 The planting area of the three crops in China

3.2 Transportation of raw materials

Raw materials are transported by truck (carrying capacity, 10 t; the truck consumes diesel only) from the western region of Liaoning to the fabrication plant of TEDA (Tianjin Economic Development Area) of Tianjin. Freight transport is measured in ton-km, and the distance is approximately 450 km (Ma et al., 2006).

3.3 Product production

The production process of PLA plastic packaging products is shown in Fig. 4. This paper selects corn as the raw material, so the production steps are: extract corn starch, starch fermentation to produce glucose, glucose is further processed to generate lactic acid, and then the lactic acid undergoes direct polycondensation or lactide ring-opening polymerization to yield polylactic acid (Li et al., 2017). The PLA particles can be processed by extrusion, blow molding or injection molding into the final PLA corn-based packaging plastic.

It is assumed that the production steps of the products are all carried out in the same place, which is the fabrication plant of TEDA. The transfer of products between two production processes is done by machinery and each step in the process involves an input of energy and an output of waste. The production of starch adopts the wet process, the production of lactic acid is accomplished by anaerobic fermentation and electrodialysis extraction, the synthesis of polylactic acid uses the indirect condensation process and the final plastic packaging is produced by blow molding. The process of glucose production requires enzymes, activated carbon and catalysts, which have little influence on the entire life cycle of the products, so they are ignored (Meng et al., 2010).

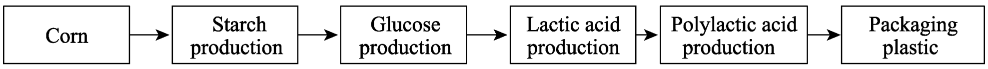

Fig. 4 Production flow chart of PLA plastic packaging

3.4 Product use

The use stage only considers the impact of transportation on the environment. Because the product itself has very little impact on the environment during its usage, that part of the analysis is not carried out in this paper. The transportation distance in the use stage is subject to the distance from the fabrication plant to the centralized distribution point in the urban area, which is estimated at 45 km and the transport vehicle is a 2 t light transport vehicle (Ma et al., 2006).

3.5 Final disposal

According to a statistical analysis of domestic garbage transport volume data, the proportions of landfill, incineration, and composting disposal account for 60.0%, 32.3% and 1.9%, respectively (including the data of an integrated disposal plant), while the remaining 5.8% represents stacking and simple landfill treatment (Xu, 2018). The Tianjin environmental sanitation science and technology network shows that Tianjin mainly adopts the single disposal method of landfill and incineration in its waste disposal. As a result, PLA plastic packaging products in Tianjin are ultimately treated as 60.0% landfill and 32.3% incineration. The other 7.7% are not centrally disposed of, with individuals simply burying them in landfills or burning them with other waste, so this analysis does not take into account the environmental impact of this part. The transportation distance from the Tianjin municipal solid waste disposal center to the landfill is 44 km, and from the center to the Shuang Gang waste incineration power plant it is 10 km. The full load of a garbage truck is 2 t.

PLA plastic packaging products are naturally degraded into water and carbon dioxide in the landfill under the action of soil microorganisms, and these degradation products are non-toxic and non-stimulating to human body and will not cause any pollution to the environment. The water and carbon dioxide generated by PLA degradation can be absorbed through the photosynthesis of green plants, but their natural degradation efficiency in soil is relatively low (Zheng et al., 2014). For a material such as PLA, for which only 1% of the material degrades over 100 years in landfill conditions, most of the emissions occur after 100 years, the amount of carbon dioxide released as waste products from the landfill are calculated for the first 100 years in this study

(Rossi et al., 2015). Incineration is an oxidation process, and assuming that PLA plastic packing products are completely burnt during incineration, this treatment will only produce water and carbon dioxide.

Based on the above analysis, we obtained the relevant source data from the China LCA Basic Database (CLCD) in the database of Sichuan University, and additional required data through on-site consultation with relevant departments and factories, web searches, literature searches and other means, and then imported all the data into an Excel table with editing functions. Finally, the data are summarized in the product life cycle evaluation checklist shown in Table 2.

Table 2 LCA inventory of one ton PLA plastic packing products (ISO14040:2006) (Unit: kg t^{-1})

Type	Substances	Life cycle stages						
		Raw material acquisition	Transportation of raw material	Product production	Product use	Final disposal		Total
						Landfill	Incineration	
Resources	Coal	2.05×10^{2}	1.99	2.88×10^{3}	0.13	7.75×10^{-2}	9.48×10^{-3}	3.08×10^{3}
	Crude oil	16.10	55.00	4.84×10^{2}	3.65	2.14	0.26	5.61×10^{2}
	Natural gas*	1.59	3.31×10^{-3}	35.30	2.20×10^{-4}	1.29×10^{-4}	1.58×10^{-5}	36.80
	CO_2**	-4.15×10^{3}	0	0	0	0	0	-4.15×10^{3}
Air emissions	CO_2	1.59×10^{3}	1.40×10^{2}	2.84×10^{3}	7.42	9.12	5.91×10^{2}	5.18×10^{3}
	CO	0.91	0.74	12.80	0.93	0.54	6.64×10^{-2}	15.98
	CH_4	0.59	1.43×10^{-2}	11.90	1.95×10^{-3}	2.26	1.40×10^{-4}	14.77
	N_2O	21.70	4.05×10^{-3}	0.00	5.40×10^{-4}	3.17×10^{-4}	3.88×10^{-5}	21.70
	SO_2	2.24	0.15	41.60	4.97×10^{-3}	2.92×10^{-3}	3.57×10^{-4}	43.99
	NO_X	6.31	3.15	34.20	6.40×10^{-2}	3.75×10^{-2}	4.59×10^{-3}	43.76
	SO_X	4.12	0	0	0	0	0	4.12
	PO_4^{3-}	0.35	0	0	0	0	0	0.35
	NO_3^-	4.76	0	0	0	0	0	4.76
	NH_3	4.23	0	0	0	0	0	4.23
	NMVOC	1.09×10^{-2}	0.56	1.49	0.18	0.11	1.29×10^{-2}	2.35
	Dust	0.30	1.47×10^{2}	0.40	25.30	14.80	1.81	2.29×10^{2}
Water emissions	Cu	1.61	0	0	0	0	0	1.61
	Zn	2.31	0	0	0	0	0	2.31
	Cd	0.33	0	0	0	0	0	0.33
	Pb	1.76×10^{-2}	0	0	0	0	0	1.76×10^{-2}
	Waste liquid	54.70	32.10	6.08×10^{3}	2.14	1.25	0.15	6.17×10^{3}
	Waste sludge	3.44	0.32	4.46×10^{2}	2.15×10^{-2}	1.26×10^{-2}	1.54×10^{-3}	4.50×10^{2}

Note: * Natural gas's unit is $m^3\ t^{-1}$; ** CO_2 refers to the amount of carbon dioxide that corn absorbs from the atmosphere through photosynthesis. NMVOC: Non methane volatile organic compounds.

4 Life cycle impact assessment

4.1 Impact assessment categories

The CML 2001 method is the base method used in this LCA for analyzing the environmental impact. CML 2001 is a problem-oriented approach based on the traditional life cycle inventory analysis features and standardized methods, and its use of intermediate point analysis reduces the number of assumptions and the complexity of the model, so it is easy to operate (Guinee, 2002; Duan et al., 2008). In this paper, seven impact categories are chosen and calculated: the abiotic depletion potential (ADP fossil fuels), indicated by MJ equivalents; global warming potential (GWP), indicated by kilograms of CO_2 equivalents; acidification potential (AP), expressed as kilograms of SO_2 equivalents; eutrophication potential (EP), indicated by kilograms of PO_4^{3-} equivalents; photochemical ozone formation potential (POCP), in units of kilograms of C_2H_4 equivalents; and human toxicity potential (HT) and terrestrial ecotoxicity potential (TETP), expressed as kilograms of (1,4)-DCB equivalents.

4.2 Characterization and normalization

Characterization is used to transform the data obtained from the life cycle inventory into the corresponding environmental impact indicators according to the classification of environmental impacts. After multiplication by their characterization factors, the numbers of emissions are summed up to obtain the total impact. The related environmental impact characterization factors and mineral resource consumption characterization factors involved in this study are shown in Table 3.

Table 3 The characterization factors of environmental impact (ISO14040:2006)

Impact category characterization factor	ADP	GWP	AP	EP	POCP	HTP	TETP
Coal	27.91	–	–	–	–	–	–
Crude oil	41.87	–	–	–	–	–	–
Natural gas	38.84	–	–	–	–	–	–
CO_2	–	1.00	–	–	–	–	–
CO	–	2.00	–	–	2.70×10^{-2}	–	–
CH_4	–	21.00	–	–	7.00×10^{-3}	–	–
N_2O	–	3.10×10^{2}	–	0.27	–	–	–
SO_2	–	–	1.00	–	–	9.60×10^{-2}	–
NO_X	–	–	0.70	0.13	2.80×10^{-2}	1.20	–
SO_X	–	–	0.80	–	–	–	–
PO_4^{3-}	–	–	–	1.00	–	–	–
NO_3^-	–	–	–	0.42	–	–	–
NH_3	–	–	1.88	0.33	–	–	–
NMVOC	–	–	–	–	0.42	–	–
Dust	–	–	–	–	–	0.82	–
Cu	–	–	–	–	–	–	14.00
Zn	–	–	–	–	–	–	25.00
Cd	–	–	–	–	–	–	1.70×10^{2}
Pb	–	–	–	–	–	–	33.00

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone formation potential; HTP: human toxicity potential; TETP: terrestrial ecotoxicity potential.

In order to further identify the relative sizes of the different environmental impact categories, the characterization results are normalized. On the basis of the characterization, the environmental impact index is standardized and weighted to obtain the global equivalent of each environmental impact category in the life cycle, and the corresponding reference value is divided by the corresponding characterization results. The standardized reference values used in this study are shown in Table 4 (Haes, 1999; Yang and Nielsen, 2001).

The relative significance is called the weight. The weight in LCA refers to the allocation of the relative significance of the impact categories according to social, ethical and political values (Navajas et al., 2014). Therefore, when the final

Table 4 The reference values of the normalization (ISO14040:2006)

Impact category	Unit	Reference value
Abiotic depletion potential fossil fuels (ADP)	MJ eq yr^{-1}	3.80×10^{14}
Global warming potential (GWP)	kg–CO_2 eq yr^{-1}	4.22×10^{13}
Acidification potential (AP)	kg–SO_2 eq yr^{-1}	2.39×10^{11}
Eutrophication potential (EP)	kg–PO_4^{3-} eq yr^{-1}	1.58×10^{11}
Photochemical ozone formation potential (POCP)	kg–C_2H_4 eq yr^{-1}	3.68×10^{10}
Human toxicity potential (HTP)	kg–(1,4)–DCB eq yr^{-1}	2.58×10^{12}
Terrestrial ecotoxicity potential (TETP)	kg–(1,4)–DCB eq yr^{-1}	1.09×10^{12}

environmental impact of the products is evaluated, the normalization result will be multiplied by the corresponding weighting factor. The weight factors of the seven influence categories are shown in Table 5 (Huppes and Van Oers, 2011).

In this study, both the characterization factor and the normalized reference value come from CML-IA, which is a database for life cycle impact assessment (LCIA), and they are easily read by the CMLCA software program. This database contains the characterization factors for all baseline characterization methods mentioned in the Handbook on LCA, such as GWP, POCP, HTP and AP, as well as the normalization data for all interventions and impact categories at different spatial and temporal levels. These data can be downloaded directly from the website in Excel format.

The characterization and normalization results of the LCA inventory of one ton of PLA plastic packing products are shown in Table 6.

Table 5 Weighting factors of the impact categories (ISO14040:2006)

Impact category	Weighting factor
Abiotic depletion potential (ADP fossil fuels)	0.12
Global warming potential (GWP)	0.23
Acidification potential (AP)	0.04
Eutrophication potential (EP)	0.07
Photochemical ozone formation potential (POCP)	0.05
Human toxicity potential (HTP)	0.20
Terrestrial ecotoxicity potential (TETP)	0.11

Table 6 The characterization and normalization results of the LCA inventory (ISO14040:2006)

Impact category	Substances	Mass (kg)	Characteristic factor	Characterization result	Reference value	Normalization result	Weighting factor	Environmental impact value	Percentage of the total (%)
ADP	Coal	3.08×10^{3}	27.91	1.11×10^{5}	3.80×10^{14}	2.92×10^{-10}	0.12	3.36×10^{-11}	24.83
	Crude oil	5.61×10^{2}	41.87						
	Natural gas	36.80	38.84						
GWP	CO_2	1.03×10^{3}	1.00	8.11×10^{3}	4.22×10^{13}	1.92×10^{-10}	0.23	4.42×10^{-11}	32.63
	CO	15.90	2.00						
	CH_4	14.80	21.00						
	N_2O	21.70	3.10×10^{2}						
AP	SO_2	44.00	1.00	85.90	2.39×10^{11}	3.60×10^{-10}	0.04	1.44×10^{-11}	10.64
	NO_X	43.80	0.70						
	SO_X	4.12	0.80						
	NH_3	4.23	1.88						
EP	PO_4^{3-}	0.35	1.00	15.30	1.58×10^{11}	9.67×10^{-11}	0.07	6.77×10^{-12}	5.00
	N_2O	21.70	0.27						
	NO_X	43.80	0.13						
	NO_3^-	4.76	0.42						
	NH_3	4.23	0.33						
POCP	CO	15.90	2.70×10^{-2}	2.74	3.68×10^{10}	7.44×10^{-11}	0.05	3.72×10^{-12}	2.75
	CH_4	14.80	7.00×10^{-3}						
	NO_X	43.80	2.80×10^{-2}						
	NMVOC	2.35	0.42						
HTP	SO_2	44.00	9.60×10^{-2}	2.44×10^{2}	2.58×10^{12}	9.48×10^{-11}	0.20	1.90×10^{-11}	14.01
	NO_X	43.80	1.20						
	Dust	2.29×10^{2}	0.82						
TETP	Cu	1.61	14.00	1.36×10^{2}	1.09×10^{12}	1.25×10^{-10}	0.11	1.37×10^{-11}	10.14
	Zn	2.31	25.00						
	Cd	0.33	1.70×10^{2}						
	Pb	1.76×10^{-2}	33.00						

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone formation potential; HTP: human toxicity potential; TETP: terrestrial ecotoxicity potential.

5 Results and discussion

Table 7 clearly shows the proportions of the seven impact categories at different stages of the life cycle. The orders of magnitude of the environmental impact values in the table vary greatly. In order to more intuitively compare the sizes of the impacts of the seven impact categories at the same stage, the environmental impact values in Table 7 were obtained to make a bar chart as shown in Fig. 5.

Table 7 The detailed environmental impacts of each stage

Impact category		Raw material acquisition	Transportation of raw material	Product production	Product use	Final disposal	Total
ADP	Normalization result	1.70×10^{-11}	6.21×10^{-12}	2.68×10^{-10}	4.12×10^{-13}	2.71×10^{-13}	2.92×10^{-10}
	Environmental impact value	1.95×10^{-12}	7.14×10^{-13}	3.09×10^{-11}	4.74×10^{-14}	3.12×10^{-14}	3.36×10^{-11}
	Percent (%)	5.81	2.13	91.82	0.14	0.09	100.00
GWP	Normalization result	9.92×10^{-11}	3.39×10^{-12}	7.38×10^{-11}	2.24×10^{-13}	1.54×10^{-11}	1.92×10^{-10}
	Environmental impact value	2.28×10^{-11}	7.79×10^{-13}	1.70×10^{-11}	5.16×10^{-14}	3.53×10^{-12}	4.42×10^{-11}
	Percent (%)	51.67	1.76	38.45	0.12	8.00	100.00
AP	Normalization result	7.50×10^{-11}	9.86×10^{-12}	2.75×10^{-10}	2.08×10^{-13}	1.37×10^{-13}	3.60×10^{-10}
	Environmental impact value	3.00×10^{-12}	3.94×10^{-13}	1.10×10^{-11}	8.34×10^{-15}	5.49×10^{-15}	1.44×10^{-11}
	Percent (%)	20.84	2.74	76.33	0.06	0.04	100.00
EP	Normalization result	6.59×10^{-11}	2.59×10^{-12}	2.81×10^{-11}	5.35×10^{-14}	3.52×10^{-14}	9.67×10^{-11}
	Environmental impact value	4.61×10^{-12}	1.82×10^{-13}	1.97×10^{-12}	3.74×10^{-15}	2.46×10^{-15}	6.77×10^{-12}
	Percent (%)	68.15	2.68	29.07	0.06	0.04	100.00
POCP	Normalization result	5.70×10^{-12}	9.25×10^{-12}	5.44×10^{-11}	2.75×10^{-12}	2.24×10^{-12}	7.44×10^{-11}
	Environmental impact value	2.85×10^{-13}	4.63×10^{-13}	2.72×10^{-12}	1.38×10^{-13}	1.12×10^{-13}	3.72×10^{-12}
	Percent (%)	7.67	12.44	73.18	3.70	3.01	100.00
HTP	Normalization result	3.11×10^{-12}	4.81×10^{-11}	3.02×10^{-11}	8.06×10^{-12}	5.31×10^{-12}	9.48×10^{-11}
	Environmental impact value	6.23×10^{-13}	9.62×10^{-12}	6.04×10^{-12}	1.61×10^{-12}	1.06×10^{-12}	1.90×10^{-11}
	Percent (%)	3.29	50.75	31.86	8.50	5.60	100.00
TETP	Normalization result	1.25×10^{-10}	0	0	0	0	1.25×10^{-10}
	Environmental impact value	1.37×10^{-11}	0	0	0	0	1.37×10^{-11}
	Percent (%)	100.00	0	0	0	0	100.00

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone formation potential; HTP: human toxicity potential; TETP: terrestrial ecotoxicity potential.

The contributions of the different life cycle stages to the same impact category are shown in Fig. 6. Figure 7 shows the proportional distribution of the seven impact categories over the entire life cycle.

In the stage of raw material acquisition, the weighted environmental impact values of TETP, EP, GWP accounted for 100%, 68.15% and 51.67% of the entire life cycle, respectively. The proportion of TETP is 100% due to the heavy metal residues in the planting stage of the starting material corn, including the heavy metals contained in the fertilizers and organic fertilizers used in the process of growing the corn, which will eventually remain in the soil and cause soil pollution. At the same time, Table 8 shows that the relatively high contributions to TETP are Zn and Cd, which are 42.38% and 40.68%, respectively, because the nitrogen, phosphorus, potash fertilizer and organic fertilizer used contain zinc and cadmium. The most significant contributions to GWP are CO_2 and N_2O, which are –61.02% and 160.68%, respectively. The contribution of CO_2 is negative because the amount of carbon dioxide that corn absorbs from the atmosphere through photosynthesis is much greater than the total amount of carbon dioxide emissions during the entire stage. N_2O mainly comes from the gas emissions in the process of nitrogen fertilizer production, and a small part comes from the exhaust emissions of motor vehicles burning diesel during farming. Meanwhile, the contributions of N_2O and NO_3^- to EP are 56.22% and 19.18%, respectively, which are also attributed to the use of phosphate and nitrogen fertilizer during corn planting. The major contributions to AP are NO_X and NH_3, which are

24.67% and 44.43%, respectively, and mainly caused by the use of fertilizers and diesel. The other impact categories account for a relatively small proportion, less than 10%. At this stage, the seven impact categories sorted by environmental impact size are in the order of: GWP>TETP>EP>AP>ADP>HTP>POCP, which can be observed in Fig. 5.

In the stage of raw material transportation, POCP and HTP respectively account for 12.44% and 50.75% of the environmental impact value of the entire life cycle, and they come mainly from the exhaust emissions of freight vehicles in the long-distance transportation process. Table 9 shows that the major contributions to POCP are NO_X and NMVOC, at 25.88% and 68.23%, respectively. HTP is mainly attributed to the dust generated during transportation, and its contribution is 96.94%. The order of environmental impact for this stage is: HTP>GWP>ADP>POCP>AP>EP.

Table 8 The contributions of different substances to different environmental impacts in the stage of raw material acquisition

Impact category	Substance	Raw material acquisition		Contribution (%)	Impact category	Substance	Raw material acquisition		Contribution (%)
		Mass (kg)	Characterization				Mass (kg)	Characterization	
TETP	Cu	1.61	22.50	16.52	AP	SO_2	2.24	2.24	12.50
	Zn	2.31	57.80	42.38		NO_X	6.31	4.42	24.67
	Cd	0.33	55.50	40.68		SO_X	4.12	3.29	18.39
	Pb	1.76×10^{-2}	0.58	0.43		NH_3	4.23	7.96	44.43
	Total		1.36×10^{2}	100.00		Total		17.90	100.00
GWP	CO_2*	-2.56×10^{3}	-2.56×10^{3}	−61.02	EP	PO_4^{3-}	0.35	0.35	3.34
	CO	0.91	1.83	0.04		N_2O	21.70	5.86	56.22
	CH_4	0.59	12.30	0.29		NO_X	6.31	0.82	7.87
	N_2O**	21.70	6.73×10^{3}	160.68		NO_3^-	4.76	2.00	19.18
	Total		4.19×10^{3}	100.00		NH_3	4.23	1.40	13.39
						Total		10.40	100.00

Note: GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; TETP: terrestrial ecotoxicity potential; * The amount of carbon dioxide that corn takes out of the atmosphere through photosynthesis, so the value is negative; ** N_2O emissions divided by total emissions, so the result is greater than 100%.

Table 9 The contributions of different substances to different environmental impacts in the transportation of raw material stage

Impact category	Substance	Transportation of raw material		Contribution (%)	Impact category	Substance	Transportation of raw material		Contribution (%)
		Mass (kg)	Characterization				Mass (kg)	Characterization	
POCP	CO	0.74	2.00×10^{-2}	5.86	HTP	SO_2	0.15	1.44×10^{-2}	0.01
	CH_4	1.43×10^{-2}	1.00×10^{-4}	0.03		NO_X	3.15	3.78	3.05
	NO_X	3.15	8.82×10^{-2}	25.88		Dust	1.47×10^{2}	1.20×10^{2}	96.94
	NMVOC	0.56	0.23	68.23		Total		1.24×10^{2}	100.00
	Total		0.34	100.00					

Note: POCP: photochemical ozone formation potential; HTP: human toxicity potential.

In the production stage, Table 7 shows that each impact category (except TETP) accounts for a large proportion of the environmental impact value of the entire life cycle. The proportions of each impact category are as follows: ADP 91.82%, GWP 38.45%, AP 76.33%, EP 29.07%, POCP 73.18%, and HTP 31.86%. Table 10 shows the contributions of each substance to the six impact categories. These data show that the consumption of coal is greater than the consumption of crude oil and natural gas in the production process, so its contribution to ADP reaches 78.78%, while the contributions of crude oil and natural gas are only 19.88% and 1.34%, respectively. At the same time, as a large amount of energy substance is consumed in the production stage, there are emissions of CO_2, SO_2, NO_X and other gases, which make great contributions to the environmental impact. The contributions of NO_X to EP, AP, POCP and HTP are 100%, 36.53%, 47.81% and 52.73%, respectively. The contribution of CO_2 to GWP is 91.17% and the contribution of SO_2 to AP is 63.47%. The production of NMVOC also leads to the production of photochemical ozone, which contributes 30.85% to POCP, and the dust generated during the production process causes harm to the human body and contributes 42.13% to HTP. In this stage, the environmental impact size comparison of the seven categories is in the order of: ADP＞GWP＞AP＞HTP＞POCP＞EP.

In the stage of product use, because only transportation has an impact on the environment, the environmental impact at this stage is relatively small, and the proportion of its environmental impact value in the entire life cycle is also small. Among them, HTP accounts for 8.5%, mainly caused by NO_X and dust. The environmental impact sequence for this stage is HTP＞POCP＞GWP＞ADP＞AP＞EP.

In the stage of final disposal, the activities involved are the transportation and treatment of wastes, and their impacts are mainly from the generation of CO_2 and dust. Therefore, the environmental impact values of GWP and HTP at this stage are relatively high, at 8.0% and 5.6%, respectively. The environmental impact sequence of the final disposal stage is GWP>HTP>POCP>ADP>AP>EP.

Table 10 The contributions of different substances to different environmental impacts in the stage of product production

Impact category	Substance	Product production		Contribution (%)	Impact category	Substance	Product production		Contribution (%)
		Mass (kg)	Characterization				Mass (kg)	Characterization	
ADP	Coal	2.88×10^3	8.03×10^4	78.78	EP	PO_4^{3-}	0.00	0.00	0.00
	Crude oil	4.84×10^2	2.03×10^4	19.88		N_2O	0.00	0.00	0.00
	Natural gas	35.30	1.37×10^3	1.34		NO_X	34.20	4.45	100.00
	Total		1.02×10^5	100.00		NO^{3-}	0.00	0.00	0.00
GWP	CO_2	2.84×10^3	2.84×10^3	91.17		NH_3	0.00	0.00	0.00
	CO	12.80	25.50	0.82		Total		4.45	100.00
	CH_4	11.90	2.50×10^2	8.01	POCP	CO	12.80	0.35	17.19
	N_2O	0.00	0.00	0.00		CH_4	11.90	8.33×10^{-2}	4.15
	Total		3.12×10^3	100.00		NO_X	34.20	0.96	47.81
AP	SO_2	41.60	41.60	63.47		NMVOC	1.49	0.62	30.85
	NO_X	34.20	24.00	36.53		Total		2.00	100.00
	SO_X	0.00	0.00	0.00	HTP	SO_2	41.60	4.00	5.13
	NH_3	0.00	0.00	0.00		NO_X	34.20	41.10	52.73
	Total		65.60	100.00		Dust	40.00	32.80	42.13
						Total		77.90	100.00

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone formation potential; HTP: human toxicity potential.

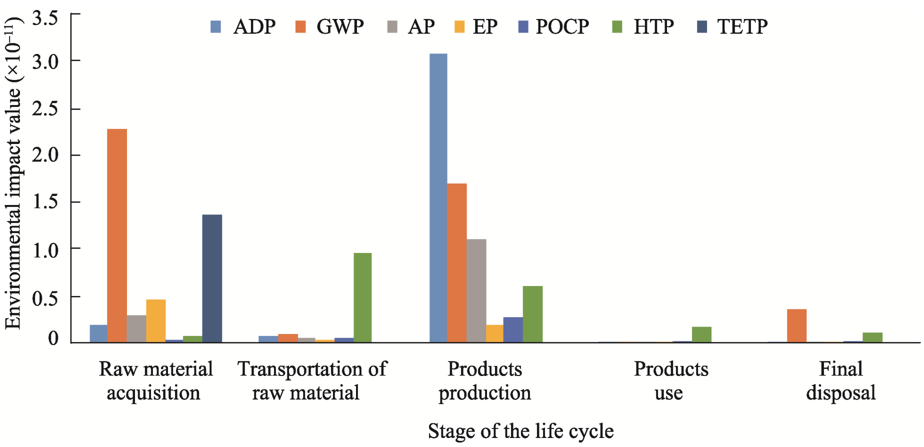

Fig. 5 Results of the environmental impact values of different life cycle stages

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone formation potential; HTP: human toxicity potential; TETP: terrestrial ecotoxicity potential.

The data in Fig. 6 show that among the five stages of the entire life cycle, the one with the greatest contribution to TETP is the raw material acquisition stage, and the stage of raw material transportation contributes the most to HTP, followed by the stage of product production. The main contribution to POCP is product production, and the most significant contribution to the EP is raw material acquisition. The stage that contributes most to AP is the stage of product production. The most significant contribution to GWP is the acquisition stage of raw materials, followed by the production stage of products. The stage that contributes the most to ADP is the stage of product production. Combining the data in Fig. 5 and Fig. 6, the environmental impact of the stage of product production is the highest in the entire life cycle of PLA plastic packing products.

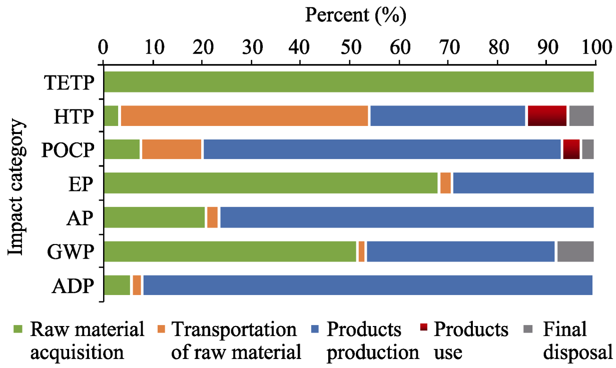

Fig. 6 The proportions of different life cycle stages in the seven impact categories

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential, POCP: photochemical ozone formation potential; HTP: human toxicity potential; TETP: terrestrial ecotoxicity potential.

In Fig. 7, the size of each wedge represents the environmental impact proportion of that category in the entire life cycle of PLA plastic packaging products. Among them, GWP ranks first, accounting for 32.63%, while ADP is second at 24.83%, and HTP comes in third at 14.01%. AP and TETP account for only 10.64% and 10.14% of the total environmental impact, respectively. The proportions of EP and POCP are relatively small, at 5.00% and 2.75%, respectively.

By comparing the data obtained from the analysis of the entire life cycle of bio-packaging plastics with the more widely used PE products in the current market, the comprehensive benefits of the two products can be assessed from the two aspects of energy consumption and environmental impact in the process of obtaining raw materials. The results of this comparison are shown in Table 11 (Chen et al., 2000).

From the energy consumption analysis, the energy consumption for producing one ton of bio-packaging plastic during the whole life cycle assessment is 66.52×10^3 MJ, and the energy consumption for producing 1 t of PE plastic bags is 6.08×10^3 MJ. Clearly the energy consumption of bio-packaging plastic production is higher than PE.

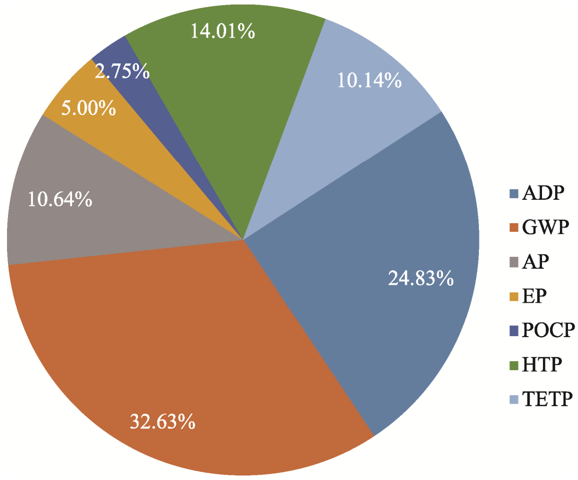

Fig. 7 Environmental impact proportions of each impact category in the entire life cycle

Note: ADP: abiotic depletion potential fossil fuels; GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone formation potential; HTP: human toxicity potential; TETP: terrestrial ecotoxicity potential.

Table 11 Comparison of life cycle evaluation results between PLA and PE food packaging products

Term	Unit	PLA packaging plastic	PE plastic bag	PLA/PE
CO_2 emissions	kg	1.03×10^3	4.10×10^3	0.25
NO_x emissions	kg	43.80	1.90	23.1
SO_x emissions	kg	4.12	5.55	0.74
C_xH_y emissions	kg	14.80	21.00	0.71
Total energy	MJ	66.52×10^3	6.08×10^3	10.90

From the environmental assessment analysis, the CO_2 emissions during the production of bio-packaging plastics are 25.10% of the CO_2 emissions during the production of PE products. In the production process and the final treatment of biodegradable plastics the gas emissions are mainly CO_2. In comparison, PE packaging plastics emit harmful gases such as SO_X, CO and hydrocarbons, so the PLA packaging plastics have less impact on the environment. Therefore, the impact of PE packaging plastics on the environment during the entire life cycle is much higher than that of biological packaging plastics. Furthermore, the environmental performance of the biocomposite improves in the life cycle energy consumption, fossil energy use, ozone depletion and non-carcinogenic impact categories when a blend of PLA and TPS is used (Mahalle et al., 2014).

Considering that Tianjin is a coastal city, some packaging plastics may flow into the sea and become marine garbage. Plastic products such as PE cannot decompose in the ocean all year round. As a result, the packaging products themselves and the additives therein will have a great impact on marine ecology. For PLA degradable packaging plastic, this problem can be harmlessly solved, thereby preventing or greatly reducing marine pollution, and providing an effective method for solving the problem of marine litter disposal (Sonnemann and Valdivia, 2017).

The research results of LCA are usually affected by data collection and system boundaries, which can introduce a degree of uncertainty. For example, the improvements of product production technology and personal habits of product use will affect the carbon emission and energy consumption of the whole life cycle. In this paper, some scenarios are assumed during data processing and setting up the system framework, so as to improve the environmental impact assessment. However, this paper strictly follows the principles and framework provided by international standards in order to obtain the most realistic environmental impact assessment. As a system analysis study, some assumptions were made about the emissions during the use of the product, the final treatment of the product, and the transportation process. Therefore, in order to support implementation decisions, it is recommended that future research work focus on reducing the uncertainties. For example, the uncertainties could be reduced by measuring energy consumption and waste emissions using raw materials at specific locations and processing by specific manufacturers, which would improve the evaluation system of the impact of PLA products on the environment throughout the life cycle.

6 Conclusions

In this study, the life-cycle assessment method was used to evaluate and identify the energy consumption and environmental impacts of PLA plastic packaging products throughout the entire life cycle in China. All life cycle stages, from raw material acquisition to final disposal, were considered. Energy consumption was represented by ADP, and environmental impacts were assessed by six impact species: GWP, TETP, EP, AP, HTP and POCP. The LCA results indicated that in the entire life cycle of LCA plastic packaging products the stage with the greatest environmental impact is the stage of product production. The seven impact categories sorted by environmental impact size are in the order of: GWP＞ADP＞HTP＞AP＞TETP＞EP＞POCP.

The LCA results show that CO_2 and N_2O make great contributions to GWP, both of which are from the emissions in the process of energy consumption, especially in the two stages of product production and raw material acquisition, and since they contain many production activities, their energy consumption and environmental impacts are also relatively high. The nitrogen fertilizer applied in the growth of corn will release a lot of CO_2 and N_2O in the production process. Based on the LCA results, it is reasonable to focus on the stage of product production in order to reduce the environmental impact. In the process of product production from corn to polylactic acid, since there are multiple production processes, immature production technology and low conversion rates between substances, the processing will consume a large amount of electric energy, which will increase the impact on the environment. Therefore, reducing the consumption of electricity, increasing the input of new energy and increasing the conversion rates of substances in the process are the main ways to reduce the overall impact. In the raw material acquisition stage, the first priority is to reduce the use of fertilizer. China currently advocates the development of green agriculture and the use of as little chemical fertilizer as possible, because chemical fertilizers contain harmful substances and the soil and water are polluted, which is ultimately harmful to the healthy development of society, agriculture and people's diet. Therefore, the use of organic and water-soluble fertilizers is now being advocated to replace the traditional fertilizers. Secondly, the process of vehicle transportation consumes diesel and gasoline and generates a lot of gas emissions. In order to reduce the environmental impact, we can actively respond to the call of the country for green environmental protection, energy conservation and emission reduction, adopt new energy vehicles, and use new fuels (ethanol, gasoline, fuel cells, etc.) to reduce the consumption of traditional fuels. In addition, recycling can also be used as an option for the final disposal of products. Currently, the disposal of waste plastics in Tianjin is mainly by landfill and incineration, and the recycling rate is not high. Therefore, the recycling rate of degradable PLA plastics can be improved by setting a clear mark for the degradable plastics, refining the recycling process and improving the recycling system, in addition to reprocessing the plastics that conform to the recycling and reasonable disposal of the non-reusable plastics.

Currently, the use of biodegradable PLA plastics is still in the initial stage in China, with immature production technology and imperfect policies. This paper analyzes the impact of the first generation of biomass on energy and environment. In the face of the first generation of energy crops such as corn, rice, etc., it is expected to become human alternative energy at the same time, it also produces net energy output, the decrease of arable land for food crops, and a series of negative effects. Therefore, it will inevitably face the second generation of biomass raw materials to enter the market. This paper provides a theoretical basis for the development and application of the second generation of biomass raw materials, so as to reduce environmental pollution and energy consumption.

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生物可降解聚乳酸塑料包装产品的生命周期评价——以中国天津为例

赵梦磊[1]，杨　增[1]，赵静楠[1,2]，王　岩[1,2]，马晓磊[1]，郭　健[1]

1. 天津科技大学机械工程学院，天津 300222；
2. 天津轻工业与食品机械设备集成设计与在线监测重点实验室，天津 300222

摘　要：本文采用生命周期评价（LCA）的方法，从原料获取、原料运输、产品生产、产品使用和最终处置五个阶段对可降解聚乳酸（PLA）包装塑料的能耗和环境影响进行了评价和量化。并选择 7 个影响类别进行影响分析：非生物耗竭潜力（ADP）、全球变暖潜力（GWP）、酸化潜力（AP）、富营养化潜力（EP）、光化学臭氧形成潜力（POCP）、人类毒性潜力（HTP）和陆地生态毒性潜力（TETP）。通过对生命周期评价结果的讨论，发现对环境影响最大的是产品生产环节。同时，在整个生命周期中，环境影响排名前三的类别分别为 GWP、ADP 和 HTP，分别占 32.63%、24.83%和 14.01%。根据 LCA 的研究结果，减少环境影响的途径有：降低电耗、增加新能源的投入、提高生产过程中物料的转化率、使用有机和水溶性肥料代替传统肥料、使用环保型燃料建立完善的回收体系。

关键词：生命周期评价；能源消耗；环境影响；聚乳酸；包装塑料