Life cycle assessment on environmental effect of polylactic acid biological packaging plastic in Tianjin

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Abstract: In this paper, corn - based polylactic acid (PLA) biological packaging plastic is selected for the life cycle assessment-LCA. Taking Tianjin, China as an example, the PLA bio-package plastic is analyzed from four aspects: raw material acquisition, processing, use and final treatment. Produce costs, energy consumption, and greenhouse gas (GHG) emissions (equivalent carbon dioxide in this paper) over the entire life cycle of biological packaging plastic were calculated, and compared with traditional petroleum based Polyethylene（PE）plastic products in terms of environmental impacts. Based on LCA results, this paper puts forward corresponding suggestions and countermeasures from the perspective of sustainable development. The study found that the CO_2 emissions of biological materials are reduced by 61.25% compared with that of PE.

1.Introduction

With the improvement of people's environmental consciousness and the development of science and technologies, for ecological protection and sustainable economic development, biodegradable packaging plastic will be the mainstream of plastic products. Ideal of biodegradable plastic can be decomposed completely by microbes into low-molecular compounds, eventually become a part of the carbon cycle in nature of the polymer materials. From the classification of raw material, biodegradable plastics mainly have polycaprolactone (PCL), poly butylene succinate (PBS), polyvinyl alcohol (PVA) biodegradable plastic and carbon dioxide copolymer etc.

Currently, biodegradable plastic is mainly used in packaging, agriculture, engineering parts, medical and personal consumer products and other fields.

For now, the research on biodegradable plastic is mainly focused on production, and the comprehensive assessment of environmental impact is few. So, in this paper, the life cycle of the PLA biodegradable plastic has been comprehensively evaluated. The life cycle assessment model from the cradle to the grave is established from two aspects of production cost and GHG emissions.

LCA consists of all stages from raw material extraction to production, transportation, distribution, use, and final waste treatment, which is a systematic and full-process environmental load analysis and environmental impact assessment of a product [1, 2]. The first step is to quantify the environmental load of the product, and then evaluate the potential damage of the product system to the environment based on a certain method. According to the current situation of packaging materials in Tianjin market and the development of biodegradable plastics, some assumptions have been made and a lot of data has been collected in this paper.

Its impact on the environment is the 1st objective of this paper and analyzed from direct energy consumption, production costs, and greenhouse gas emissions (CO_2).

As one of the most important factors for the promotion of industrial products, production cost has a very important influence on the practical market application of biodegradable plastic. Therefore, the second objective of this paper is to compare the production costs of biodegradable plastic and petroleum-based plastic. This paper takes into consideration of the biodegradable plastic produce cost and environmental impact, and puts forward some constructive suggestions to the Tianjin Government based on the life cycle assessment results. It is hoped that the promotion of biodegradable plastic products can further alleviate the GHG emission in China.

2.Materials and methods

2.1 Main materials

In this paper, the life cycle assessment of PLA biodegradable plastics was selected and compared with the widely used PE plastics in the market from GHG emission, energy consumption and production cost.

Biological packaging plastic is a polymer obtained from lactic acid. The raw material is abundant and can be regenerated, mainly fermenting and polymerizing with corn and cassava. Corn is planted at 0.718 billion hectares worldwide, and the price of corn is cheaper than other food crops such as wheat. So this paper chooses corn as the raw material for the production of biological packaging plastic [3, 4]. As shown in Fig. 1, the price of imported corn is lower than that of domestic corn, so this paper uses imported corn as reference price for raw material [5, 6].

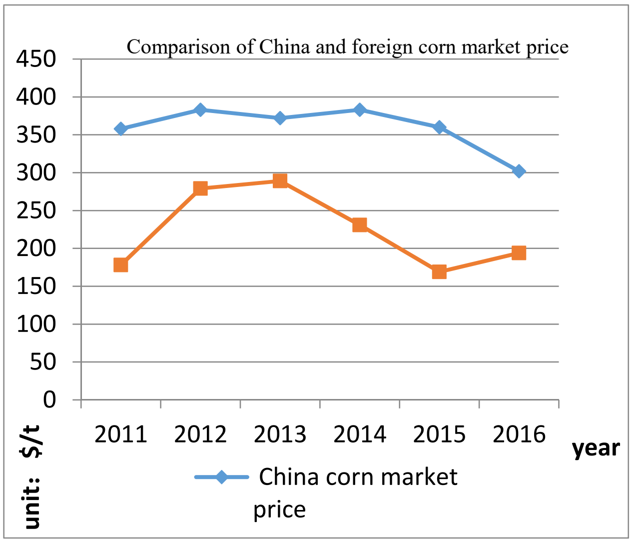

Fig. 1. Comparison of China and foreign corn market price.

2.2 LCA model

2.2.1 Biological packaging plastic life cycle system boundary

The life cycle of biological packaging plastic consists of multiple stages (as shown in Fig. 2): raw material production, transportation, product processing, and final treatment. The transportation process and energy input are included between every two stages. Raw material processing is mainly divided into raw material cultivation, starch processing, lactic acid processing and PLA processing. The product processing is mainly divided into the melting of PLA particles, the forming process of biological packaging plastics and the sale of biological packaging plastic. The final treatment is divided into two parts: recyclable and non-recyclable. The final treatment of non-recyclable plastics consists of compost, incineration, and landfill. Each stage contains carbon dioxide emissions.

2.2.2. Production costs and GHG

The cost of biological packaging plastic in the whole life cycle is composed of the raw material cost, transportation cost, processing cost and, final treatment cost.

In the whole life cycle of biological packaging plastic, GHG emissions from manufacturing process and final treatment are the largest environment burden, including CO_2, SO_2, NOX, etc. Among them, more than 90% of the waste gas is CO_2. Therefore, this paper only estimates equivalent CO_2 emissions as GHG emission.

3. Results and analysis

3.1 Model of cost establishment and data collection

3.1.1 Cost model establishment

There are two parts in the processing of plastic products. The first is the synthesis of raw material, such as the PLA and PE. Then the product is formed, such as injection molding. Therefore, the cost of a plastic product is generally estimated in the following two aspects.

The processing cost of raw material can be calculated according to eq. (1):

$$M = \frac{P_1 + P_2 + S_1 + S_2 + S_3}{N} \tag{1}$$

where,
M: cost of raw material of PLA ($/kg);
P1: cost of process equipment including mixer, extruder and granulator ($);
P2: cost of corn consumed ($);
S1: power cost ($);
S2: labor cost and equipment maintenance cost ($);
S3: other cost such as site lease cost and management cost ($);
N: weight of PLA material (kg).

The processing cost of biological packaging plastic can be calculated according to eq. (2):

$$C = Q + M \tag{2}$$

where,
C: cost of biological packaging plastic ($/kg);
Q: the processing cost per kilogram of biological packaging plastic ($).

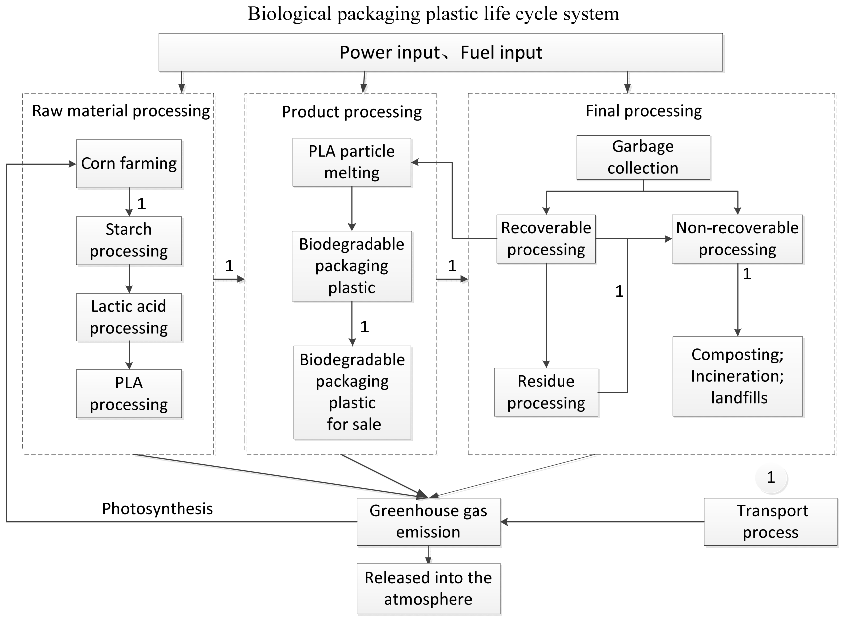

Fig. 2. Biological packaging plastic life cycle system (1 in this figure represents the transport process).

3.1.2 Calculation of production cost

Corn promotes its growth through photosynthesis [7]. As shown in Table 1, the net absorption of carbon dioxide in the whole growth cycle is 1.47 t/t, and the main fuel consumption are transportation, mechanical irrigation, mechanical sowing, mechanical harvesting and other processes, which the total amount is 2.09E-3 t/t [8-10].

Table 1. Energy input for corn production [11-13].

Name	Value	Name	Unit	Value
Fuel consumption	1.756	CO_2 emissions	t/t	-1.47
Diesel prices	1.2	consumption	MJ/t	2.5E+03

Note：The net absorption of CO_2 of 1t corn is 1.47t.

The energy consumption of each processing stage in the production process is shown in Table 2. All of the electricity has been converted into the energy consumption of coal-fired power generation. In a "Cradle to Gate" life cycle analysis on fermented products from corn, it is shown that the raw material acquisition of corn, which includes all agricultural activities, produces 0.15 kg CO_2 and absorbs1.47 kg CO_2 during the growth of the plants. The energy used to harvest corn grain is $2.5E^3$ MJ/t [8]. The process of processing biological packaging plastic is analyzed and the total energy consumption of raw material is $62.5E^{3}$ MJ/t. As shown in Table 2, the production of lactic acid consumes 71% of the total energy consumption. In this paper, the energy was assumed as provided by coal combustion. Therefore, the CO_2 emission was calculated based on the amount of electrical consumption. CO_2 emissions in the whole process are 2.1 t/t. The market price of the PLA is $3952/t.

The energy consumption of production of a ton of polyethylene is $32E^3$ MJ, producing 4.8 tons of carbon dioxide. The market price is $1483/t [1, 14].

Table 2. Energy consumption and CO_2 emissions for production of 1 ton PLA [8, 10].

Process	Material consumption	Energy consumption (MJ)	CO_2 emissions (t)
Corn planting and harvesting	diesel 2.09 Kg	2.5E+03	-4.26
Starch processing	electrical energy 610 KW	6.2 E+03	0.50
Lactic acid processing	electrical energy 2000 KW、fuel 0.54 t	44.2 E+03	4.73
PLA processing	electrical energy 1000 KW	9.6 E+03	0.87
aggregate		62.5 E+03	1.84

atmosphere by the raw of 1t PLA

The production equipment required for processing of PLA and PE are assumed same on both products. They can be shaped by extrusion, blow molding or injection molding. This paper selects the processing of the most commonly used bags for analysis. The price of PE products in the market is \$2/kg, and the price of biological packaging plastic bags is \$4.58/kg, so the difference between the prices of the two products is mainly in the raw material. The energy consumption of production of PE and biological packaging plastic bags is 7.2 E^3 MJ/t.

3.2 Transportation cost

The distance from Tianjin Xingang to TEDA is 10.8 km (D1) and the distance from TEDA to Hexi district of Tianjin is 42.5 km (D2) and the distance from Tianjin Municipal solid waste disposal center to the landfill site is 44.0 km（D3）. In this paper, the vehicle of garbage transport is selected as Futian new compression car, with its own weight is 10 t and the rated load (M) is 5 t. The vehicle of cargo transport is the Dongfeng dump truck, its own weight is 25 t, and the rated load (M) is 75 t [15, 16].

The diesel price is \$1.2E^3/t, and the operating maintenance fee is \$6.17/t. "F" is 0.322E-3 t/km, "E" is

3.115 t/t [14, 15]. As shown in Table 3, the total transportation cost, CO_2 emissions (Et1), and fuel consumption from Tianjin xingang to TEDA is \$4.3, 8.72E-5 t/t, and 3.478e-3t respectively. The total transportation cost, CO_2 emissions (Et2) and fuel consumption from TEDA to Hexi district of Tianjin is \$16.38, 3.42E-4 t/t and 13.685e-3t respectively. The total transportation cost, CO_2 emissions (Et3) and fuel consumption from Tianjin municipal solid waste disposal center to landfill site is \$17.48, 8.827E-3 t/t and 14.168E-3t, respectively.

Table 3. Transportation cost of transport truck [9, 16,17].

Name	Unit	Value	Name	Unit	Value
Fuel consumption	L/km	0.27	Releasing amount of CO_2	t/t	3.115
Operation maintenance costs	\$/t	6.17	Diesel prices	\$/t	1.2E+3
D_1	km	10.8	D_1 (Fuel consumption)	t	3.478E-3
D_2	km	42.5	D_2 (Fuel consumption)	t	13.685E-3
D_3	km	44	D_3 (Fuel consumption)	t	14.168E-3
Et_1 (CO2 emissions)	t/t	8.72E-5	D_1 (Total cost)	\$	4.3
Et_2 (CO2 emissions)	t/t	3.42E-4	D_2 (Total cost)	\$	16.38
Et_3 (CO2 emissions)	t/t	8.827E-3	D_3 (Total cost)	\$	17.48

Note：The price of diesel is based on the average price of Tianjin in 2017

3.3. The final treatment

On acount of its unique advantages, biodegradable plastic also gives better degradation effect than conventional plastic after use. Currently, the final treatment for large quantities of waste plastic is mainly sanitary landfill and incineration [18]. A small amount of waste plastic is recycled for simple sorting and grinding to granulate. The raw material of biodegradable plastic in this paper is corn, and the final treatment is mainly divided into two parts: recyclable and non-recyclable. The final treatment of non-recyclable plastics consists of compost, incineration, and landfill. The environmental benefits and economic benefits of non-recyclable plastics were studied, which are CO_2 emissions in different treatment processes and treatment costs. In this paper, the relevant computational model is established, which is divided into cost model "C" and CO_2 emission model "E".

3.3.1 An estimate model for landfill
The landfill disposal of biological packaging plastic should consider the location of the landfill site and the impact on the surrounding environment, and also consider the land price of the landfill site. Since PLA is biodegradable, landfill sites can be reused, so the cost of landfill and the property values of landfill sites are not considered. The social costs of landfill disposal mainly include garbage collection cost, transfer cost and sanitary landfill cost [19].

3.3.2 Analysis of landfill estimation mode
According to the established model of calculation, the landfill disposal of biological packaging material is verified, and the results are shown in Table 4. The social cost of landfill disposal is 242.14 $/t, which includes the biological packaging plastic collection cost, transportation cost and landfill cost, accounting for 59.13%, 13.32% and 27.55% [19], respectively [20]. The total CO_2 emissions in landfill disposal are 17.08 kg/t, which contain the CO_2 emitted during the landfill transportation and the CO_2 produced during the decomposition in the landfill, accounting for 52.52% and 47.48%, respectively [20].

Table 4. A comprehensive inventory of landfill.

Symbol	Name	Value	Percentage
C_s	Collection cost	143.17 ($/t)	59.13%
C_t	Transferring cost	32.27 ($/t)	13.32%
C_{lf}	Landfill cost	66.70 ($/t)	27.55%
C_l	Social costs	242.14 ($/t)	——
E_{lf}	CO_2 emissions from landfill	7.98 (kg/t)	47.48%
E_t	CO_2 emissions from transportation	8.83 (kg/t)	52.52%
E_l	Total CO_2 emissions	16.80 (kg/t)	——

3.3.3 An estimate model for incineration
The used biological packaging plastic is incinerated for power generation and the main gas emitted during incineration is CO_2. The social costs of biological packaging plastic incineration include fixed cost, variable cost and health cost, among which fixed cost includes land cost and construction cost, variable cost includes waste disposal fee, electricity price subsidy, fly ash subsidy, etc. Health cost mainly refers to the harm of waste gas, dust and other harmful effects on health [23].

This paper assumes that the CO_2 emissions from the incineration of biological packaging plastic is the same as that of municipal solid waste (MSW) incineration. Therefore, the following data are derived from the CO_2 emissions in the actual incineration of MSW. Research shows that emissions are 257 kg/t [22]. China's power system power supply is mainly coal, which can be replaced by burning biological packaging plastic.

3.3.4 Analysis of the incineration estimation model

As shown in Table 5, social cost of biological packaging plastic incineration is \$172.45/t, which contains a fixed cost, variable cost and health costs, the proportion is 2.30%, 27.55% and 70.15%, respectively. Total CO_2 emissions from incineration are 266.10 kg/t. Incinerating a ton of biological packaging plastic is equivalent to saving 234 kg of coal and reducing CO_2 emissions by 337.36 kg.

3.3.5 Compost

According to the statistical analysis of the data of MSW removal and disposal, landfill, incineration and composting accounted for 60.0%, 32.3% and 1.9%, respectively, while the remaining 5.8% are stacking and simple landfill disposal [23].

As shown in Table 6, the degradation temperature and humidity of biological packaging plastic is 58 ± 2 ° C and 98%, respectively. Degradation requires certain microorganisms. All biodegradation can be achieved within 180 days, and the final product of degradation is carbon dioxide and water.

Gas emissions of biological packaging plastic compost are mainly CH_4 and CO_2, composting amount of CO_2 emissions mainly comes from the emissions in the process of compost and fertilizer emissions after compost. As shown in Table 7, the total CO_2 emissions are 1.526 kg/kg [20].

Table 5. Comprehensive inventory of incineration.

Symbol	**Name**	**Value**	**Symbol**	**Name**	**Value**
C_f	Fixed cost	3.96 (\$/t)	N_p	The amount of electricity generated per kg of biological packaging plastic incineration.	0.78 (KW·h/kg)
C_v	Variable cost	47.51 (\$/t)	EL	Electricity generated by incineration of 1 ton of biological packaging plastic	78 (KW·h /t)
C_h	Health cost	120.98 (\$/t)	Q_c	Rate of coal consumption	0.3 (kg/KW•h)
C_2	Social cost	172.45 (\$/t)	M_C	Equivalent biological packaging plastic incineration power generation requires the quality of coal	234 (kg/t)
E_2	CO_2 emission from transportation	8.827 (kg/t)	E_m	CO_2 emission from the mass of M_c coal combustion	594.36 (kg/t)
E_3	CO_2 emission from biological packaging plastic incineration	257 (kg/t)	E_4	Reduced CO2 emissions when biological packing plastic is used to replace coal for power generation	337.36 (kg/t)

Table 6. The condition of biological packaging plastic compost degradation.

Temperature（℃）	**Humidity（%）**	**Microorganism**	**Degradation products**	**Degradation cycle**
58±2	98	Yes	CO_2 and H_2O	180 (Day)

Table 7. Gas emissions of biological packaging plastic compost [22].

Methane (CH_4) emissions during compost	**CO_2 emissions during compost**	**CO_2 emissions from Fertilizer after compost**	**Total CO_2 emissions from P LA compost**
1.03g/kg	1464g/kg	62g/kg	1526g/kg

3.3.6 Recycling

In China, the recycling rate of plastics was about 22% on 2008 [24]. Considering the biological packaging plastic has just started to use in the China, there are still many deficiencies in the process of recycling and technology. This paper assumes that the recycling rate is 20%, and the conversion rate of recycled materials in the process of secondary processing is 83% [20]. As shown in Table 8, the energy saved by recycling the recycled plastic is 10.6738E+3 MJ/t, and reduced CO2 emissions are 0.5 t/t.

Table 8. The recycling data of 1 ton biological packaging plastic [20].

Recycling rate	**Overall conversion rate**	**Energy saved**	**Reduced CO2 emissions**
20%	83%	10.6738E+3 MJ	0.5 t

4.Conclusions and recommendations

The life cycle assessment of biological packaging plastic is evaluated based on the plastic use and the treatment of MSW in Tianjin. As shown in Table 9, the energy consumption and CO_2 emissions in the four stages of raw material processing, product production, final treatment and transportation during the life cycle were calculated. The transportation process includes the energy consumption and CO_2 emissions of all transportation in the life cycle. The final treatment based on the model of municipal solid waste disposal in Tianjin on 2014 is accounted, landfill disposal accounted for 49.33% and the incineration disposal accounted for 48.15%.

As can be seen from Table 9, the energy consumption of raw material processing stage is the biggest in the whole life cycle of biological packaging plastic, accounting for 93.90% of the total energy consumption. Proportion of the energy consumption of the product production and final treatment is 10.82% and 4.96% respectively (- represents the energy savings). The energy consumption of final treatment refers to the net energy consumption, which is mainly the energy savings in electricity generation by incinerating biological packaging plastic instead of coal. CO_2 is the main gas that affects the environment in the whole life cycle of biological packaging plastic. The biggest stage of CO_2 emissions is the raw material processing and product production, accounting for 53.32% and 43.17% of the total emissions respectively. Therefore, the raw material processing stage and the production stage have the greatest impact on the environment.

The comprehensive benefit of biological packaging plastic and PE is compared, mainly from the environmental impact of energy consumption, the results are shown in Table 10, and some data are derived from references [1].

Table 9. PLA biological packaging plastic life cycle inventory.

Stage	**Energy consumption （MJ/t）**	**Percentage (%)**	**CO_2 emissions (kg/t)**	**Percentage (%)**
Raw material processing	62.50 E+03	93.90	2100	53.32
Product production	7.20 E+03	10.82	1700	43.17
Final treatment	-3.3 0E+03	-4.96	137	3.48
Transport process	1.60 E+02	0.24	1.3	0.03
Total	66.56 E+03	100	3938.3	100

Table 10. Comparison of life cycle inventory of 1 ton biological packaging plastic and 1 ton PE

Project	Unit	PLA biological packaging plastic	PE packaging plastic	PLA/PE
CO2 emissions during production	Kg	1.86E+03	4.8E+03	0.3875
NO_X	Kg	0.03	0.63	0.0476
SO_2	Kg	0.03	1.03	0.0291
CO	Kg	0.03	2.64	0.0114
HC	Kg	0.03	7.10	0.0042
Energy consumption	MJ	69E+03	44.2E+04	1.5611
Cost of production	RMB	4.60E+03	2.06 E+03	2.2330

Energy consumption is analyzed, the energy consumed for producing one ton of biological packaging plastic throughout the production process is $69E^3$ MJ, and the production of one ton of PE consumes $44.2E^3$ MJ, which is 64.1% of the production of biological packaging plastic. It can be seen that the energy consumption of bio-packaging plastic is higher than that of PE. Therefore, its production cost is 1 to 2 times higher than PE products, which restricts the widespread use of biodegradable plastics. Due to the production of lactic acid consumes most of the energy in the biodegradable plastic production process, it can reduce total energy consumption by improving the production technology of lactic acid, such as increasing the conversion rate of starch in the production process.

The environmental assessment is analyzed, and the CO_2 emissions in the production process of biological packaging plastic are 38.75% of the emissions during the production of PE products. As a biodegradable material, biological packaging plastic mainly releases carbon dioxide into the air in the life cycle compared with PE packaging plastic which emits harmful dust and harmful gases such as SO_2, NO_X, CO and HC. Therefore, PE packaging plastic has a much higher impact on the environment than biological packaging plastic in the life cycle.

The final treatment is analyzed, the CO_2 emissions from waste biological packaging plastic in landfill and incineration are 1.12% and 17.44% of the CO_2 emissions from composting respectively. By incineration instead of coal for power generation, each ton of waste biological packaging plastic can reduce 234 kg of coal, while CO_2 emissions will be reduced 337.36 kg, which not only saves energy but also reduces the greenhouse effect; 20% of waste biological packaging plastic is recycled and reused to produce products, which can save energy 10673.8 MJ and reduce CO_2 emissions by 0.5t per ton. So, this paper advocates incineration and recycling.

Although the production cost of PE packaging plastic is lower than that of biological packaging plastic, its impact on the environment is much higher than that of biological packaging plastic. From the perspective of environmental protection and resource regeneration, bio-packaging plastic has a better prospect of development and conforms to the country's green development strategy. Therefore, it is necessary for countries and enterprises to make joint efforts to promote the widespread application of bio-plastic in life. It is suggested to consider the following aspects:

(1)The research and development of biological plastic and its industrialization should be enhanced.
(2)The biological plastic recycling system should be improved.
(3)Policies and regulations should be enacted first.

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