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

Jingnan ZHAO 1, Xiaolei MA1, Jian GUO1, Yan WANG1, Xuekang SI 1, Yinghuai Dong1*

1 Mechanical Engineering College, Tianjin University of Science and Technology, Tianjin, 300222, China

Corresponding author: Yinghuai Dong, dongyh@tust.edu.cn

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 CO₂ 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), polybutylene 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 (CO₂).

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].

![Comparison of China and foreign corn market price](image)

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 CO₂, SO₂, NOX, etc. Among them, more than 90% of the waste gas is CO₂. Therefore, this paper only estimates equivalent CO₂ 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):

\[ M = \frac{P_1 + P_2 + S_1 + S_2 + S_3}{N} \]  

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):

\[ C = Q + M \]  

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

![Biological packaging plastic life cycle system diagram](image)

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

| Name                      | Value   | Name     | Unit     | Value   |
|----------------------------|---------|----------|----------|---------|
| **Fuel consumption**       | 1.756   | CO₂      | t/t      | -1.47   |
| **Diesel prices**          | 1.2     | consumption | MJ/t   | 2.5E+03 |

Note: The net absorption of CO₂ 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 CO₂ and absorbs 1.47 kg CO₂ during the growth of the plants. The energy used to harvest corn grain is 2.5E³ MJ/t [8]. The process of processing biological packaging plastic is analyzed and the total energy consumption of raw material is 62.5E³ 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 CO₂ emission was calculated based on the amount of electrical consumption. CO₂ 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 32E³ MJ, producing 4.8 tons of carbon dioxide. The market price is $1483/t [1, 14].
Table 2. Energy consumption and CO2 emissions for production of 1 ton PLA [8, 10].

| Process                        | Material consumption | Energy consumption (MJ) | CO2 emissions (t) |
|--------------------------------|----------------------|-------------------------|------------------|
| Corn planting and harvesting   | diesel 2.09 Kg       | 2.5E+03                 | -4.26            |
| Starch processing              | electrical energy 610 KW | 6.2E+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 E3 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 $1.2E3/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, CO2 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, CO2 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, CO2 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 CO2 | t/t    | 3.115 |
| Operation maintenance costs | $/t | 6.17 | Diesel prices | $/t | 1.2E+3 |
| D1                | km     | 10.8  | D1 (Fuel consumption) | t | 3.478E-3 |
| D2                | km     | 42.5  | D2 (Fuel consumption) | t | 13.685E-3 |
| D3                | km     | 44    | D3 (Fuel consumption) | t | 14.168E-3 |
| Et1 (CO2 emissions)| t/t   | 8.72E-5 | D1 (Total cost) | $ | 4.3 |
| Et2 (CO2 emissions)| t/t   | 3.42E-4 | D2 (Total cost) | $ | 16.38 |
| Et3 (CO2 emissions)| t/t   | 8.827E-3 | D3 (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 account 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 CO₂ 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 CO₂ 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 S/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 CO₂ emissions in landfill disposal are 17.08 kg/t, which contain the CO₂ emitted during the landfill transportation and the CO₂ produced during the decomposition in the landfill, accounting for 52.52% and 47.48%, respectively [20].

| Symbol | Name                          | Value  | Percentage |
|--------|-------------------------------|--------|------------|
| 𝐶₃     | Collection cost               | 143.17 ($/t) | 59.13%     |
| 𝐶₄     | Transferring cost             | 32.27 ($/t)  | 13.32%     |
| 𝐶₅     | Landfill cost                 | 66.70 ($/t)  | 27.55%     |
| 𝐶₁     | Social costs                  | 242.14 ($/t) | ——         |
| 𝐸₃     | CO₂ emissions from landfill   | 7.98 (kg/t)  | 47.48%     |
| 𝐸₁     | CO₂ emissions from transportation | 8.83 (kg/t) | 52.52%     |
| 𝐸₁     | Total CO₂ 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 CO₂. 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CH₄ and CO₂; composting amount of CO₂ emissions mainly comes from the emissions in the process of compost and fertilizer emissions after compost. As shown in Table 7, the total CO₂ 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 ($/t)   | N_p    | The amount of electricity generated per kg of biological packaging plastic incineration. Electricity generated by incineration of 1 ton of biological packaging plastic | 0.78 (KW·h/kg) |
| C_v    | Variable cost                          | 47.51 ($/t)  | E_L    | Equivalent biological packaging plastic incineration power generation requires the quality of coal | 78 (KW·h/t)  |
| C_h    | Health cost                            | 120.98 ($/t) | Q_c    | Rate of coal consumption               | 0.3 (kg/KW·h) |
| C_s    | Social cost                            | 172.45 ($/t) | M_c    | Equivalent biological packaging plastic incineration power generation requires the quality of coal | 234 (kg/t)   |
| E_2    | CO₂ emission from transportation       | 8.827 (kg/t) | E_m    | CO₂ emission from the mass of M₄ coal combustion | 594.36 (kg/t) |
| E_3    | CO₂ emission from biological           | 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           | CO₂ and H₂O          | 180 (Day)         |

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

| Methane (CH₄) emissions during compost | CO₂ emissions during compost | CO₂ emissions from Fertilizer after compost | Total CO₂ emissions from PLA 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 emission |
|----------------|-------------------------|--------------|---------------------|
| 20%            | 83%                     | 10.6738E+3   | 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 CO2 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 CO2 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. CO2 is the main gas that affects the environment in the whole life cycle of biological packaging plastic. The biggest stage of CO2 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 (%) | CO2 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 plastic | PLA/PE |
|--------------------------------|--------|----------------------------------|------------|--------|
| CO2 emissions during production| Kg     | 1.86E+03                         | 4.8E+03    | 0.3875 |
| NOX                            | Kg     | 0.03                             | 0.63       | 0.0476 |
| SO2                            | 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 69E³ MJ, and the production of one ton of PE consumes 44.2E³ 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 CO₂ 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 SO₂, NOX, 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 CO₂ emissions from waste biological packaging plastic in landfill and incineration are 1.12% and 17.44% of the CO₂ 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 CO₂ 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 CO₂ 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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