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Life cycle assessment and the willingness to pay of waste polyester recycling

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A B S T R A C T

As an important approach to recover solid waste, the recycling of waste polyester has drawn a growing level of public concern. This study aims to investigate the life cycle assessment and social cost of life cycle assessment of waste polyester recycling. The results show that the polyester recycling process itself has significant environmental impact on global warming, fossil resource scarcity, human carcinogenic toxicity, water consumption and terrestrial ecotoxicity. Global warming, terrestrial ecotoxicity and land use are the most influential categories of social cost of life cycle assessment, with a contribution of 55.7%, 10.9% and 6.3% respectively. Through key process identification, sensitivity analysis and integrated evaluation study, it is found that electricity generation, direct air emissions and transportation are key processes that affect social cost of life cycle assessment and life cycle assessment. The effects of these key processes on social cost of life cycle assessment are greater than that on life cycle assessment. Consequently, the corresponding optimization measures are proposed in order to improve the sustainability performance of polyester industry.

1. Introduction

With the rapid urbanization, polyester (PET) has become an indispensable part of social life (Debrot et al., 2013). In 2015, the global output of plastic products reached 269 million tons, 3.3% higher than that in 2014. In 2017, China's plastic products output reached 75.155 million tons, with an annual growth rate of 3.4% on average (Liu, 2018). Since waste PET cannot be degraded by itself, the traditional treatment approach such as direct landfill will cause serious environmental pollution and resource waste (Raqueline et al., 2018). Therefore, PET recycling has become an important approach to recover solid waste (Handy and Xiu, 2018; Kim et al., 2017). At present, waste PET recycling has gained rapid growth in China through the physical or chemical recycling methods (Lao et al., 2003; Bárány et al., 2007). Most recycled PET slices are used to produce short PET fibers (Zhao et al., 2018). However, there is no study to examine the impact of this kind of PET recycling technology on environment and society. The key processes for the environment and willingness to pay (WTP) are evaluated quantitatively from the perspective of life cycle assessment (LCA) in this research. Countermeasures and suggestions are proposed for mitigating its impact on environment and WTP.

LCA can quantify the environmental impacts of products from cradle to grave and identify the key processes and key substances (ISO, 2006; Leila et al., 2018). Lopes et al. (2003) applied LCA to the paper industry in Portuguese, the results showed that it was more environmentally friendly to use natural gas instead of fuel oil for

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production. Yang et al. (2004) applied LCA to evaluate mobile phone cases and believed that the main environmental impact of the mobile phone case manufacturing process was the formation of photochemical oxidants. Pasqua et al. (2018) analyzed the environmental life cycle performance of 100% PET fabric mattress cover produced by an Italian company and found that the yarn production process had the greatest environmental impact. Wai et al. (2017) combined LCA and lean manufacturing to reduce the negative impact of plastic injection molding products on the environment. In summary, existing studies paid more focus on analyzing PET production process than PET recycling. Similarly, most of these studies focused on environmental impact assessment rather than social impact.

With the acceleration of globalization and urbanization, the demand on high life quality is also increased. As a result, Social LCA (SLCA) has been introduced. In 2009, United Nations Environment Programme and International Society of Environmental Toxicology and Chemistry jointly published the Guidelines for Social Life Cycle Assessment of Products (UNEP, 2009). This is the world's first official guidance document in the field of SLCA to assess the social impact of products throughout their life cycle. It builds a SLCA methodology system for the key stakeholders, such as workers, consumers, and local communities, laying the foundation for SLCA development. The questionnaire survey method is typically used for SLCA research in the past. This method is subjective, resulting in high uncertainty and difficulty in quantification (Liu et al., 2018). In order to reduce the influence of subjectivity, some scholars employed WTP method to evaluate the social cost of life cycle assessment (LCA-SC) of environmental effects. Xie and Zhao (2018) investigated the WTP of residents for green power in Tianjin, China, and found that factors affecting WTP include income, belief, disease, gender, age, etc. Aygul and Glenn (2015) surveyed the family's WTP for improving electricity service and found that in order to avoid blackouts, families were willing to pay an additional 13.8% monthly electricity bill. Some scholars combined LCA and LCA-SC for integrated evaluation. Ting et al. (2018) used LCA and WTP to study the environmental impacts and benefits of recovering 1 ton demolition waste in Shenzhen. Li et al. (2005) established an environmental impact assessment model and weight determination method to measure the degree of environmental impact based on LCA and WTP theory, and endowed the economic implications of environmental impact assessment. Since PET recycling has significant impact on the society and environment, it is imperative to carry out the integrated evaluation of social and environmental impacts and WTP of PET recycling.

In summary, the WTP method do not has a widely acknowledged framework. Most of them use the Contingent Valuation Method (CVM)), which uses questionnaires to collect data, and then processes the data through SPSS or other models. This method is subjective and cause great uncertainty in the research results (Kelly and Christopher, 2019). Therefore, this paper introduces the concept of environmental compensation cost. An LCA-SC evaluation methodology system based on currency conversion factor to achieve a quantitative analysis of the social impact of the PET industry is established. In addition, the key processes affecting LCA-SC and LCA are identified through sensitivity analysis. The corresponding optimization measures are proposed to provide useful references for improving the sustainability of the PET industry.

2. Methodology

The traditional LCA method is used in this study to conduct the environmental impact assessment. WTP method is employed to undertaken the social impact assessment rather than the traditional questionnaire survey method. The essence of this methodology is to evaluate different WTPs (the cost that society is willing to pay for environmental compensation) for the endpoint environmental impact categories of the PET recycling. Therefore, it is possible to link the environmental compensation cost with each midpoint environmental impact corresponding to endpoint environmental impact through currency. As a result, the final WTP can be calculated in a quantitative manner. The research framework is shown in Fig. 1.

A company is taken as an example for LCA and LCA-SC evaluation. This company has built the world's only circular economy industrial chain which consists of waste PET recycling, bottle cleaning and spinning to arts and crafts textiles weaving. The technology adopted is cutting edge over the world.

2.1. LCA

2.1.1. Functional unit

The annual production of this enterprise is selected as the functional unit. The field investigation showed that this company produced 45129.17 tons of bottle slices, 10706.76 tons of PET yarn and 11,349.51 tons of recycled PET blankets in 2017.

2.1.2. System boundary

The system boundary is "gate to gate". The bottle workshop, the front spinning workshop, the elastic workshop, the warp knitting workshop, the front workshop, the printing workshop, the back workshop, the finished product workshop, and the waste treatment workshop are included. Inventory statistics and environmental impact quantification are carried out for each of the factors above, such as energy consumption, material consumption, pollutant discharge and disposal, and land occupation during evaluation. The system boundary is shown in Fig. 2.

2.1.3. Inventory construction

According to Fig. 2, the inventory refers to the energy, materials, resources, transportation, processing equipment and facilities of the company. To ensure the data quality, the inventory is mainly based on field research. In addition, in order to reduce the uncertainty of the data, the average of during the past three years was selected.

At present, the company mainly produces blankets from waste PET bottles that are purchased from overseas. The inventory data of inputs and outputs for three years from 2015 to 2017 are shown in Table 1.

2.1.4. LCA method

The ReCiPe model (De Schryver et al., 2009) is the most recognized model of LCA in the world and is one of the most widely used methods in LCA. Among them, the ReCiPe 2016 H1.01 model is the latest method currently introduced. This model transcends the geographical limitations of traditional LCA models, such as IMPACT 2002 + model (Jolliet et al., 2003) and TRACI model (Bare et al., 2003) etc. It is applicable to worldwide. Therefore, the ReCiPe 2016 H1.01 model is used in this paper as the basic model of the LCA evaluation method.

2.2. LCA-SC

2.2.1. Feasibility analysis of WTP application to SLCA evaluation

According to "Guidelines for Social Life Cycle Assessment of Products", the technical research framework of SLCA is consistent with ELCA, which includes the definition of goal and scope, inventory analysis and impact assessment. The definition of goal and scope and the inventory analysis are same as ELCA. The difference between SLCA and ELCA research focus on the different impact

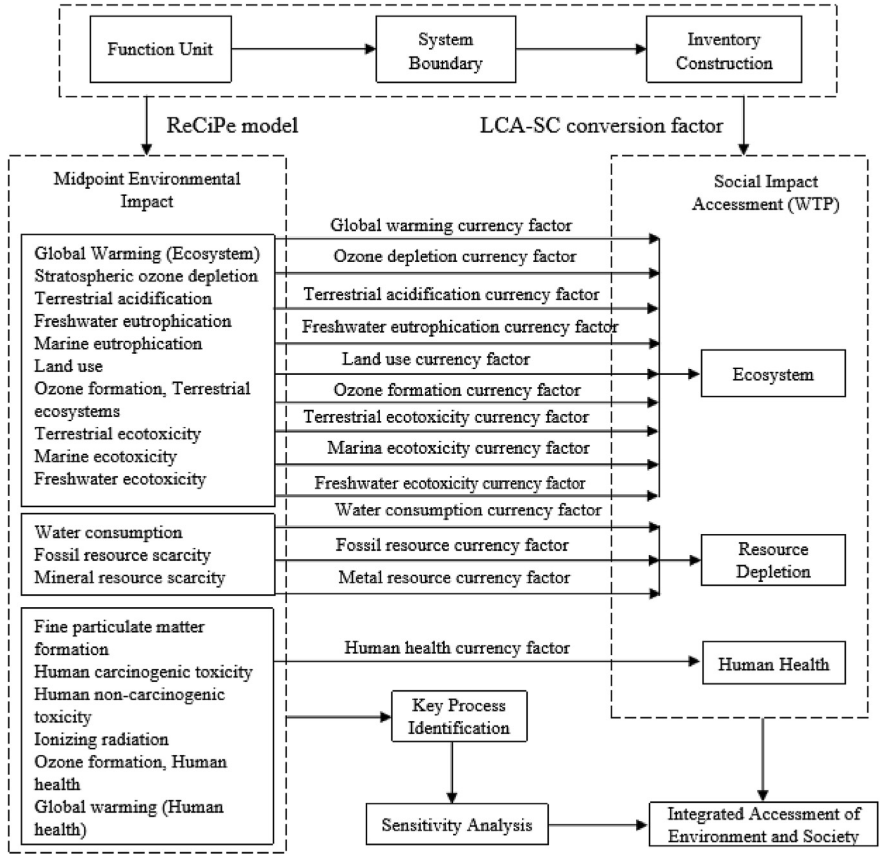

Fig. 1. Framework of WTP evaluation method for environmental impact of waste PET recycling process.

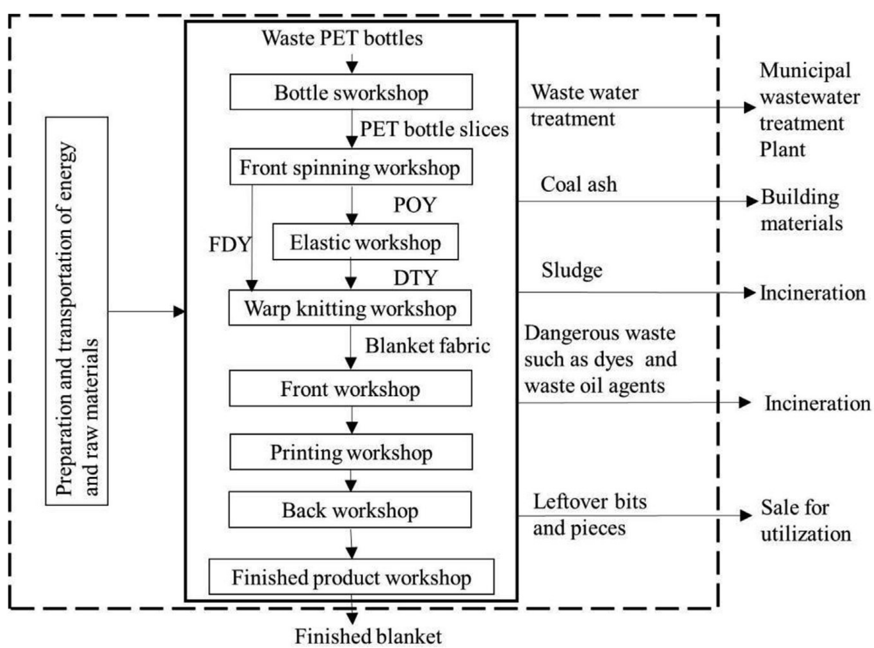

Fig. 2. LCA System boundary of waste PET recycling.

assessment methods.

The questionnaire survey method is typically used for SLCA research in the past. This method is subjective, resulting in high uncertainty and difficulty in quantification (Li et al., 2018). Therefore, the main innovation of SLCA is to explore new methods to assess social impact. SLCA is an analysis to assess the effects of production on social endpoints, i.e. human health, environment, welfare etc. Corporate Social Responsibility (CSR) theory points out

Table 1
The table of inputs and outputs data for recent three years from 2015 to 2017.

Materials	Unit	2015	2016	2017
Waste PET bottle	t	1.39×10^5	1.05×10^5	8.42×10^4
Cleaning agent	t	19.28	15.42	12.43
Sodium hydroxide	t	75.07	60.06	48.14
POY oil agent	t	94	52	45.2
DTY oil agent	t	11	14	12.3
FDY oil agent	t	353.59	173.52	150.26
Dye	t	110	98.29	96.98
Thickener	t	528.8	346.14	350.62
Instant paste	t	202.73	128	121.82
Softener	t	196.32	165.12	180
Insurance powder	t	133.39	84.39	44.18
Polyvinyl alcohol	t	175.59	125.04	192.72
Defoamer	t	43.45	8	15.62
Washing aid	t	1.95	2.25	2.17
Glacial acetic acid	t	37.34	43.68	20
Water	t	5.25×10^5	5.76×10^5	4.98×10^5
Electricity	10^4 kWh	4.35×10^3	3.57×10^3	3.91×10^3
Coal	t	1.39×10^4	9.70×10^3	–
Natural gas	m^3	–	–	3.96×10^6
Land occupation	m^2a	6×10^5	6×10^5	6×10^5
Waste water	t	4.98×10^5	5.47×10^5	4.74×10^5
SO_2	t	12.9	9.2	5.4
Particulates	t	2.6	3	0.9
NOx	t	19.8	15.6	7.1
Polyaluminum	t	211.36	204.48	195.11
Amide	t	10.82	8.99	10.66
Bleaching agent	t	51.56	48.10	50.96

Note: The factory has converted coal to gas in 2016, so only natural gas is used in 2017.

that any business must be responsible for the ultimate social impact of its actions (Sheldon, 2003). The endpoints of SLCA evaluation should be consistent with the final affects of production on the environment, i.e. corresponding to the environmental impact of ELCA. Therefore, SLCA assesses the stress on human society exerted by ELCA endpoint environmental impacts, which includes ecosystems, resource depletion and human health.

SLCA is mainly based on the needs of human health, environment and welfare. The core idea of WTP is that people are willing to pay a certain currency in order to pursue happiness or welfare to avoid or exchange certain environmental changes (Prosper and Emmanuel, 2019). Both are consistent in their evaluation purposes. Moreover, the WTP method can estimate the total economic value of public goods or services without prior market value, and transform social influence into economic indicators. It has become the most widely used method in non-use value assessment. Estimating results can help companies or governments make better social decisions (Li et al., 2019). In summary, the concept of environmental compensation costs can be introduced to evaluate LCA-SC using the WTP method.

2.2.2. Construction of WTP conversion factor calculation method

WTP practices vary according to countries. For example, the WTP in the United States focuses on environmental taxes, but does not consider resources consumption (Tellus Institute, 1992). China's WTP combines sewage charges with resource taxes. Therefore, different WTP calculation methods should be adopted in China according to the environmental impact category. According to the ReCiPe model, eighteen environmental impact categories can be divided into three endpoint impacts: ecosystem, resource depletion, and human health. Ecosystem and resource depletion impact categories can be characterized by environmental taxes. Environmental taxes are difficult to quantify human health damage. Therefore, the human health damage factors (Qi et al., 2018) are employed in this study to characterize the WTP for such environmental impacts. Various WTP conversion factors of LCA-SC are shown in Fig. 1.

2.2.2.1. Ecosystem

(1) Climate change: The WTP of climate change mainly aimed at the impact of global warming. According to the deputy director of the National Development and Reform Commission's Department of Climate Change, at this stage, the cost of carbon emissions paid by enterprises is relatively low. Since the launch of the national unified carbon market, 200 RMB to 300 RMB per ton is considered as the ideal value for the future carbon trading (Netease News, 2016). At the same time, with reference to the results of the China Carbon Emissions Study 2000–2030 estimated by the China Climate Change Special Research Group (China Climate Change Special Research Group, 2000), the currency factor for climate change is 0.22 RMB/kg Ceq.

(2) Stratospheric ozone depletion: China has introduced a series of measures to address ozone depletion and implemented a reduction policy on the use of related substances (ODP). However, since the chloro-fluoron-carbon (CFC) tax has not been levied, the WTP of ozone depletion can only be estimated indirectly. According to the statistics of the United Nations Development Programme (UNDP, 2018), it is estimated that an average of 1 kg of ozone depleting substances (ODS) use requires an investment of 12.23 RMB.

(3) Ozone formation, Terrestrial ecosystems: The Standing Committee of the Shandong Provincial People's Congress has decided on the specific applicable tax amount of the taxable air pollutants in Shandong Province. Similarly, the number of taxable pollutants levied on the same discharge port (2018) and the Environmental Protection Tax Law of the People's Republic of China (2017) were determined. Therefore, the national average value of NO_x is 2.96 RMB/eq, and its pollution equivalent value is 0.95 kg. The currency factor for the ecological impact of ozone formation is 3.12 RMB/kg NO_x eq.

(4) Terrestrial acidification: According to the literature (MEE, 2017; PCSP, 2017), the national average value of SO_2 and NO_x is 2.96 RMB/eq. The pollution equivalent value is 0.95 kg, and the currency factor of terrestrial acidification is 3.12 RMB/kg SO_2eq.

(5) Freshwater eutrophication: According to the literature (MEE, 2017; PCSP, 2017), the national average value of total applicable phosphorus is 3.21 RMB/eq, and its pollution equivalent value is 0.25 kg. The currency factor for obtaining freshwater eutrophication is 12.84 RMB/kg Peq.

(6) Marine eutrophication: Similar to freshwater eutrophication, the currency factor for marine eutrophication is 3.57 RMB/kg Neq.

(7) Land use: According to the Land Administration Law of the People's Republic of China (NPC, 2004) and the National Minimum Rate of Industrial Land Transfer (MNR, 2006), the land compensation costs include land compensation and resettlement subsidies, and the standard is around 3–6.5 million RMB/mu. The average level of land use currency factor is about 60 RMB/m^2.

(8) Terrestrial ecotoxicity: According to the literature (MEE, 2017; PCSP, 2017), the national average tax value of 1,4-DCB is 1.55 RMB/eq, and its pollution equivalent value is 0.02 kg. The currency factor for terrestrial ecotoxicity is 77.5 RMB/kg 1,4-DCBeq.

(9) Marine ecotoxicity: Similar to terrestrial ecotoxicity, the currency factor for marine ecotoxicity is 77.5 RMB/kg 1,4-DBCeq.

(10) Freshwater ecotoxicity: Similar to terrestrial ecotoxicity, the currency factor for freshwater ecotoxicity is 77.5 RMB/kg 1,4-DCBeq.

2.2.2.2. Resource depletion

(1) Water consumption: According to the "Administrative Measures on the Collection and Use of Water Resources Fees in Shandong Province" (WRDSP, 2010), with reference to the water resources fees of various provinces in China, the average land surface water collection standard is not less than 0.4 RMB, and the average groundwater collection standard is not less than 1.5 RMB. According to Table 2, the currency factor for water consumption is 0.89 RMB/m^3.

2.2.2.3. Human health. According to Fig. 1, human health includes a combination of effects. These include the effects of ozone on health, global warming (health effects), human toxicity formation, particulate matter formation, and ionizing radiation. Drawing on the findings of Qi et al. (2018), human health costs are represented by Eq. (1).

$$C_{HH} = \sum_{i=1}^{n} LCHA_i \times \left[\frac{(C_S + C_G + C_P)}{(a \times C + b \times NC)}\right] \quad (1)$$

Where C_{HH} indicates human health costs, C_P indicates personal health expenditures; C_G indicates government health expenditures; C_S indicates social health expenditures; C indicates annual cancer mortality; NC indicates non-cancer annual mortality; $LCHA$ indicates DALY values; and a indicates disability-adjusted life-year coefficient under carcinogenic effects; b represents the disability-adjusted life-year coefficient under non-carcinogenic effects.

The main data sources are the WHO (2018) and the China Statistical Yearbook (NBS, 2016). Consequently, the human health currency factor is 328891.6 RMB/DALY.

3. Results

3.1. Evaluation of LCA

3.1.1. Results of LCA

Using the ReCiPe 2016 H 1.01 model, combined with the Chinese process-based life cycle inventory database (Qi et al., 2018), a life cycle environmental impact assessment is carried out in this study. The assessment covers the direct production process (direct air emissions, electricity consumption, material consumption, waste water treatment), the indirect production process (transportation, coal mining, etc.). This is to ensure the reliability of the evaluation results. The midpoint environmental impact assessment is shown in Table 3. The standardized midpoint environmental impact assessment is shown in Fig. 3.

As shown in Table 3, the indirect environmental impacts are greater than direct environmental impacts in vast majority of those 18 midpoint impact categories evaluated by the ReCiPe model, except global warming. The indirect impact of most categories is much larger than the direct impact. This indicates that the environmental impact of indirect production processes of the PET industry is greater than that of direct production processes.

The standardized midpoint environmental impact assessment is shown in Fig. 3. According to Fig. 3, the production of each function unit product has the greatest impact on global warming. Secondly, it has a large environmental impact on the shortage of fossil resources. In addition, the environmental impact on human carcinogenic toxicity, water consumption, and terrestrial ecotoxicity is relatively large. Health effects on ozone formation, fine particulate matter formation, terrestrial ecosystems of ozone formation, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, ionizing radiation have lower environmental impact. Other categories (land use, mineral resource scarity, stratospheric ozone depletion, and marine eutrophication) have less environmental impact and therefore can be neglected.

The results of the endpoint impact assessment are shown in Table 4. Analyzed by Table 4, both direct and indirect environmental impacts are greatest in terms of resource depletion. In terms of human health, the indirect impact is much higher than the direct impact. In terms of ecosystem, the direct impact is 0.19 Species. year, which is similar to indirect effects.

3.1.2. Identification of key processes

The ReCiPe model is used to identify the key processes of the entire production process of the company, as shown in Fig. 4. It is found that electricity generation and transportation are the main contributors to the environmental impact, and the contribution ratio to the total environmental impact is 29.4% and 15.3%, respectively. The preparation of organic chemicals such as

Table 2
The currency factor for water consumption.

(2) Mineral resource scarcity: According to the Provisional Regulations of the People's Republic of China on Resource Tax (CSC, 2011), the fee of Cu is 51.1 RMB/t. Therefore, the mineral resource scarcity currency factor is 51.1 RMB/kg Cueq.

(3) Fossil resource scarcity: Since 2011, China's resource tax collection method has been changed from a quantitative survey to an ad valorem (Yang and Fu, 2015). Due to the large fluctuations in oil prices, according to Gao and Duan (2015), the resource tax paid by the actual rate of 3.8% of the ad valorem rate cannot cover the user cost under the 7% discount rate. Only when the resource tax rate increases to 18% can the user cost under each discount rate be compensated. According to the BP World Energy Statistical Yearbook (BP, 2017), the average price of oil in 2017 was $44/barrel, equivalent to 2.03 RMB/kg. The fossil resource scarcity currency factor is calculated as 0.37 RMB/kg oileq.

Water consumption in 2016	Billion m^3	Water fee (RMB/m^3)	Influence potential coefficient
Surface water	491.24	0.4	0.55
Groundwater	105.70	1.5	0.45

Table 3
The characterization value of midpoint environmental impacts.

Impact category	Unit	Direct impact	Indirect impact	Total impact
Ozone formation, Human health	kg NOx eq	4.22×10^4	6.89×10^4	1.11×10^5
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.11×10^4	2.45×10^4	3.56×10^4
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.24×10^4	7.04×10^4	1.13×10^5
Terrestrial acidification	kg SO_2 eq	3.67×10^4	6.66×10^4	1.03×10^5
Freshwater eutrophication	kg P eq	–	378.99	378.99
Freshwater ecotoxicity	kg 1,4-DCB eq	1.32×10^3	6.15×10^3	7.47×10^3
Marine ecotoxicity	kg 1,4-DBC eq	2.36×10^7	4.41×10^7	6.77×10^6
Human carcinogenic toxicity	kg 1,4-DBC eq	9.87×10^5	1.62×10^7	1.72×10^7
Land use	m^2a crop eq	2.19×10^4	1.02×10^5	1.25×10^5
Mineral resource scarcity	kg Cu eq	–	486.43	486.43
Fossil resource scarcity	kg oil eq	6.22×10^6	9.68×10^6	1.59×10^7
Water consumption	m^3	3.21×10^5	5.05×10^6	5.37×10^6
Terrestrial ecotoxicity	kg 1,4-DCB eq	2.72	1.66×10^5	1.66×10^5
Human non-carcinogenic toxicity	kg 1,4-DCB eq	1.63	2.16×10^4	2.16×10^4
Global warming	kg CO_2 eq	6.22×10^7	6.10×10^7	1.23×10^8
Stratospheric ozone depletion	kg CFC11 eq	–	1.47	1.47
Ionizing radiation	kBq Co-60 eq	–	3.51×10^5	3.51×10^5
Marine eutrophication	kg N eq	–	111.97	111.97

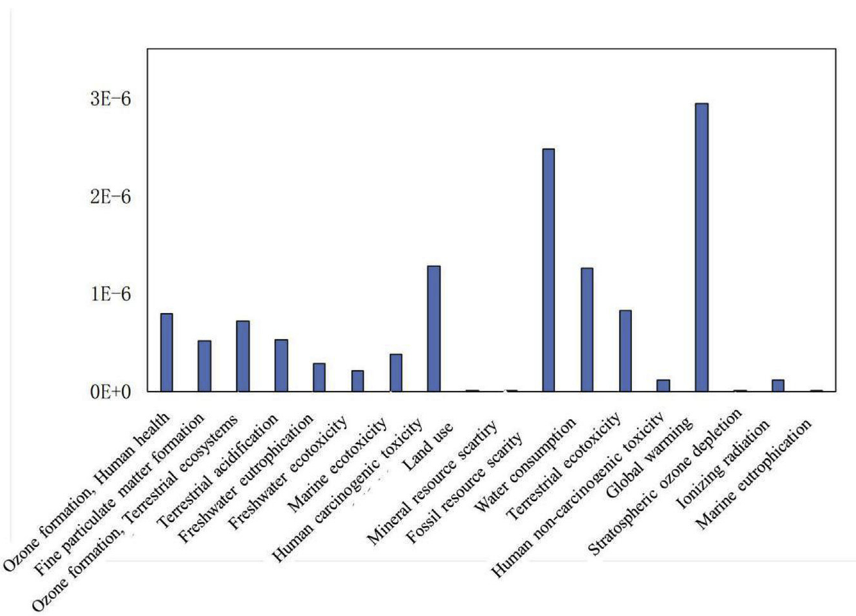

Fig. 3. The standardized midpoint environmental impact.

Table 4
Endpoint environmental impact evaluation results.

Category	Unit	Direct impact	Indirect impact	Total
Human health	Daly	48.02	117.08	165.10
Ecosystem	Species.year	0.19	0.26	0.45
Resource depletion	$	1.87×10^5	9.59×10^5	1.15×10^6

detergent, DTY oil agent, FDY oil agent and dyes, especially the production of dyes, also contribute significantly to the environmental impact, contributing to 17% of the total environmental impact. The production of these four chemical substances contributes to more than 50% of the environmental impacts of four types of impacts such as human carcinogenic toxicity, water consumption, terrestrial ecotoxicity and ionizing radiation. Direct air emissions in production process have great impact on 9 environmental impact categories of ozone formation, human health, ozone formation, terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, land use and global warming. The environmental load contribution is also significant, contributing to 14% of those nine impact categories. The contribution of waste water treatment to the environmental impact during the production process is also very obvious. This is especially the case for freshwater eutrophication, with contribution ratio of 72.8%. Coal mining plays an important role in the fossil resource scarcity, with a contribution ratio of 55.1%.

3.2. Sensitivity analysis

According to the principle of 5% change in input and output of key processes (Ye et al., 2018), the sensitivity of key processes of waste PET recycling is analyzed. The analysis results are shown in Table 5.

Sensitivity coefficient is introduced to reveal the sensitivity of key process to environmental impacts. It is the ratio between the

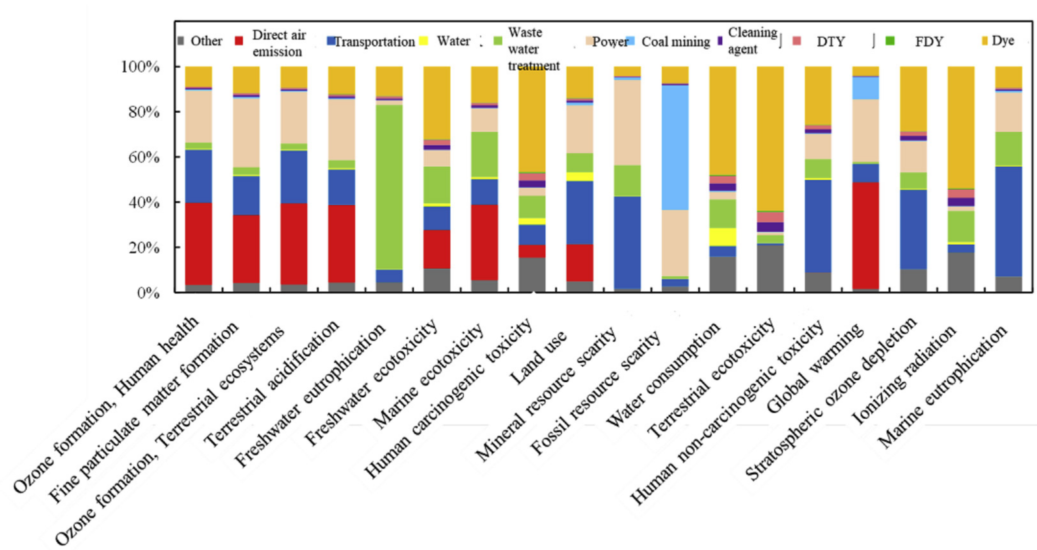

Fig. 4. Identification of key process of midpoint impacts.

Table 5
Sensitivity analysis of key processes.

Impact category	Unit	Transportation	Organics	Direct air emissions	Electricity production	Waste water treatment	Coal mining
Ozone formation, Human health	kg NOx eq	39269.7	7441.1	180.5	36474.7	4997.1	293.3
Fine particulate matter formation	kg $PM_{2.5}$ eq	9150.5	2937.9	0	15377.6	1956.1	121.1
Ozone formation, Terrestrial ecosystems	kg NOx eq	39593.2	7966.6	290.9	36748.3	5082.1	296.0
Terrestrial acidification	kg SO_2 eq	24305.6	8736.1	0	39021.7	6110.0	304.2
Freshwater eutrophication	kg P eq	33.7	40.6	0	11.4	481.8	0.1
Freshwater ecotoxicity	kg 1,4-DCB eq	1158.1	1818.0	1248.6	751.3	2025.1	7.2
Marine ecotoxicity	kg 1,4-DBC eq	11449005	7360288	22398325	10022695	22301968	82276.7
Human carcinogenic toxicity	kg 1,4-DBC eq	2243847.3	6162992.5	935425.3	853443.5	2770666	12348.8
Land use	m^2a crop eq	53383.6	11644.5	0	38599.1	17382.4	751.1
Mineral resource scarcity	kg Cu eq	312.3	18.3	0	272.1	116.3	3.0
Fossil resource scarcity	kg oil eq	1084722.3	1206384.5	0	8816512	377858.9	5888409
Water consumption	m^3	380837.3	1878577.3	0	252557.8	1101787	13916.9
Terrestrial ecotoxicity	kg 1,4-DCB	2000.3	81253.2	2.6	3013.0	9134.1	106.6
Human non-carcinogenic toxicity	kg 1,4-DCB	13725.0	4481.7	1.6	3556.0	3118.1	32.7
Global warming	kg CO_2 eq	15418816	3913979.6	58900816	49587859	1527800	6387642
Stratospheric ozone depletion	kg CFC11 eq	0.8	0.3	0	0.3	0.2	0.0
Ionizing radiation	kBq Co-60 eq	18597.6	133284.1	0	9615.9	76730.3	271.2
Marine eutrophication	kg N eq	86.3	8.6	0	29.7	29.3	0.45

change percentage of the dependent variable and the change percentage of the independent variable (Bi, 2002; Yao et al., 2009). The calculation formula of environmental impact sensitivity is shown as Eq. (2).

$$\text{Sensitivity coefficient} = \left| \frac{(EE_2 - EE_1)/EE_1}{(C_2 - C_1)/C_1} \right| \quad (2)$$

Sensitivity coefficient is the sensitivity coefficient of input amount of key process substances on the environment impact. EE_2 and EE_1 corresponds to the environmental impact loads before and after the substance input change respectively. C_2 and C_1 corresponds to the input quantities of the substances before and after the change respectively. The Sensitivity coefficient is calculated according to Eq. (1), as shown in Table 6.

According to Table 6, the sensitivity rankings of the above six processes are electricity generation > direct air emission > transportation > organic > coal mining > waste water treatment. Among them, the electricity generation, direct air emissions and transportation are the most sensitive processes to environmental impact, and their sensitivity coefficient is 6.19, 3.06 and 3.00 respectively. Therefore, these three processes are the primary targets for mitigating environmental impacts. After optimizing the three processes, the environment impacts of enterprise production can be greatly reduced. First, the equipment demand for electricity can be reduced through equipment and system energy conservation. At the same time, it is necessary to optimize the power consumption structure and increase the percentage of renewables. At present, the company has acquired the photovoltaic facilities that will be implemented in the second half of 2018. Secondly, the production level of the process should be improved and the air emissions should be reduced. Thirdly, the transportation efficiency should be improved via proper transportation plan.

3.3. Results of LCA-SC

Combining Fig. 1 with the WTP conversion factor, the LCA-SC calculation of the waste PET recycling process is conducted (see Table 7).

Table 6
The sensitivity coefficient results of key processes.

Category	Transportation	Organics	Direct air emission	Electricity generation	Waste water treatment	Coal mining
Ozone formation, Human health	7.08	1.34	0.03	6.57	0.07	0.05
Fine particulate matter formation	5.14	1.65	0.00	8.64	1.10	0.07
Ozone formation, Terrestrial ecosystems	7.01	1.41	0.05	6.50	0.90	0.05
Terrestrial acidification	4.72	1.70	0.00	7.58	1.19	0.06
Freshwater eutrophication	1.78	2.14	0.00	0.60	25.43	0.01
Freshwater ecotoxicity	3.10	4.87	3.34	2.01	5.42	0.02
Marine ecotoxicity	3.38	2.17	6.62	2.96	6.59	0.02
Human carcinogenic toxicity	2.61	7.17	1.09	0.99	3.22	0.01
Land use	0.09	0.02	0.00	0.06	0.03	0.00
Mineral resource scarcity	12.84	0.75	0.00	11.19	4.78	0.12
Fossil resource scarcity	1.36	1.52	0.00	11.09	0.48	7.41
Water consumption	1.42	7.00	0.00	0.94	4.10	0.05
Terrestrial ecotoxicity	0.24	9.79	0.00	0.36	1.10	0.01
Human non-carcinogenic toxicity	12.71	4.15	0.00	3.29	2.89	0.03
Global warming	2.51	0.64	9.58	8.06	0.25	1.04
Stratospheric ozone depletion	10.75	3.95	0.00	3.95	2.31	0.03
Ionizing radiation	1.06	7.59	0.00	0.55	4.37	0.02
Marine eutrophication	15.41	1.54	0.00	5.30	5.24	0.08
Environment impact loads	3.00	1.80	3.06	6.19	1.35	1.64

Table 7
The results of the LCA-SC calculation of the waste PET recycling process.

	Impact category	Unit	Currency factor	WTP(RMB)
Ecosystem	Ozone formation, Terrestrial ecosystems	kg NOx eq	3.12 RMB/kg NO_xeq	3.46×10^5
	Terrestrial acidification	kg SO_2 eq	3.12 RMB/kg SO_2eq	3.20×10^5
	Freshwater eutrophication	kg P eq	12.84 RMB/kg Peq	4547.88
	Land use	m^2a crop eq	60 RMB/m^2	7.5×10^6
	Global warming	kg CO_2 eq	0.22 RMB/kg CO_2eq	2.7×10^7
	Stratospheric ozone depletion	kg CFC11 eq	12.23 RMB/kgCFC11eq	17.98
	Marine eutrophication	kg N eq	3.57 RMB/kg N eq	419.9
	Terrestrial ecotoxicity	kg 1,4-DCB eq	77.5 RMB/kg 1,4-DCBeq	1.29×10^7
	Marine ecotoxicity	kg 1,4-DBC eq	77.5 RMB/kg 1,4-DBCeq	5.0×10^6
	Freshwater ecotoxicity	kg 1,4-DCB eq	77.5 RMB/kg 1,4-DBCeq	5.7×10^5
Recourse depletion	Mineral resources scarity	kg Cu eq	51.1 RMB/kg Cueq	24856.573
	Fossil resource scarity	kg oil eq	0.37RMB/kg oileq	5.8×10^6
	Water consumption	m^3	0.89RMB/m^3	4.78×10^6
Human health	Ozone formation, Human health	0.067DALY	328891.6RMB/DALY	2×10^4
	Human carcinogenic toxicity	20.72 DALY		6.8×10^6
	Human non-carcinogenic toxicity	0.002 DALY		658
	Fine particulate matter formation	25.46 DALY		8.4×10^6
	Ionizing radiation	0.001 DALY		329
	Global warming (Human health)	118.85 DALY		3.9×10^7
Total				1.18×10^8

According to Table 7, human health accounted for the largest proportion of LCA-SC, reaching 45.8%. Global warming is the main reason for the large WTP in this category. The ecosystem accounted for the next step in the LCA-SC evaluation, reaching 45.3%. Resource depletion accounted for a minimum of 8.9% of LCA-SC evaluations. To further identify key processes from social cost perspective, the contribution of 18 midpoint impact categories to LCA-SC impact was analyzed. The first four categories are global warming (health impact), global warming (ecological impact), terrestrial ecotoxicity and land use, with contribution of 32.9%, 22.8%, 10.9% and 6.3% respectively. Global warming not only affects the ecological environment, but also causes high incidence of respiratory diseases, asthma, and allergies. According to Fig. 4, the key processes that contribute the most to the above three impact categories are direct air emissions, electricity generation and transportation. According to Table 6, the order of sensitivity of key processes to LCA-SC is in consistent with the results of LCA. Therefore, improving the exhaust gas recovery process, reducing greenhouse gas emissions, improving the electricity structure, using clean energy, and saving electricity are the main means of reducing WTP. In addition, the use of DTY oil agent, FDY oil agent and dyes in the recycling process has a great impact on terrestrial ecotoxicity (see Fig. 4). Therefore, in order to reduce WTP, the production process should be further improved. Similarly, the use of such chemicals should be minimized or alternatives to such chemicals should be taken into consideration.

3.4. Integrated evaluation of LCA and LCA-SC

In order to deeply analyze the synergistic effects of different production processes on environment and WTP, LCA and LCA-SC are combined for an integrated evaluation. The results are shown in Fig. 5.

According to Fig. 5, the impact of each production process on WTP and the environment varies. Among them, the electricity generation has a great impact on both WTP and environment, though its impact on WTP (31.20%) is greater than the impact on environment (31.15%). Secondly, direct air emissions also have a greater impact on both WTP and environment. WTP accounted for 29.22%, and environmental impact accounted for 14.87%. Third, transportation and organics also exhibit high WTP and environmental impact. The conclusion of this integrated evaluation is

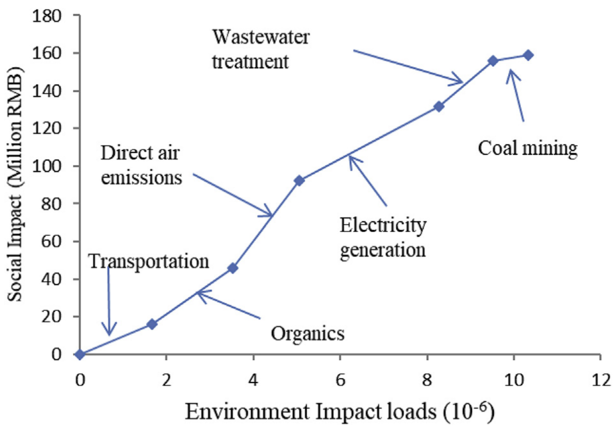

Fig. 5. Integrated evaluation of LCA and LCA-SC.

consistent with the results of Table 6. The latter only draws a ranking of the sensitivity of key processes to LCA, but Fig. 5 can clarify the difference between WTP and the environment of a key process. Based on the above analysis, optimization measures for each key process can be proposed from the social perspective first then the environmental perspective next, to achieve the coordinated development of society and environment.

4. Discussion

Based on the key process identification, three optimization scenarios are constructed according to the optimization sequence of key processes. The optimization schemes for each key process to mitigate environmental and social impacts are proposed.

Scenario 1: The electricity generation process consumes a large amount of coal and has large environmental impacts. Companies should take various measures to reduce electricity consumption to reduce the pressure on the environment and society. Firstly, increasing the number and coverage area of solar photovoltaic panels on the roof of the plant should be considered. Secondly, increase the proportion of windows in the factory and use energy-saving lamps such as light pipes. It will bring better economic and social benefits by increasing the proportion of solar energy-based clean energy. Assuming that 9 MW photovoltaic facilities will be put into use, the annual power generation is expected to reach 7.02 million kWh, which can save 17.8% of electricity consumption. The environmental load and social impact of waste PET recycling can be reduced by 5.55% and 4.38%, respectively.

Scenario 2: Pollutants directly discharged from exhaust gas will cause health damage to employees and surrounding residents. At present, the company's waste gas treatment only relies on the dust collector. The cleaning system of the dust collector directly affects its service life and removal efficiency. As the usage time increases, the filter bag will become clogged or even damaged. If the dust collector is modified into a pulse bag type dust collector for regular cleaning, it can not only improve removal efficiency, but also extend the service time of the dust collector. If the pulse bag filter is implemented in this company, pollutant emissions can be reduced by 5%, the environmental load of waste PET recycling can be reduced by 0.71%, and the social impact can be reduced by 1.46% simultaneously.

Scenario 3: The environmental impact caused by the organic process is also very large. Organic substances such as dyes that utilized in the PET recycling process are harmful to human. In order to reduce environmental load and social impact, the optimization of raw material reduction can be considered. By improving the production process, the consumption of some organic substances is reduced. If a new technology of negative pressure dyeing is introduced, the amount of dye can be reduced by 15% under negative pressure conditions. The environmental load of waste PET recycling can be reduced by 0.9%, and the social impact can be reduced by 0.93%.

The environmental and social impact of the entire system will be improved if the proposed optimization schemes can be implemented. The comparison of environmental and social impact results before and after the optimization is shown in Table 8.

According to Table 8, after optimization, the environmental load of the system is 9.56×10^{-6}, which is 7.16% lower than that before optimization. The social cost is 1.10×10^{8}, which is 6.77% lower than that before optimization. It shows that the implementation of the above optimization measures has alleviated environmental pressure, reduced the social cost, and improved the competitiveness of enterprises.

5. Conclusions

A novel WTP-based LCA-SC methodology system is developed in this study. The WTP conversion factor calculation method is developed to enable LCA-SC evaluation by means of currency quantification. In addition, the sensitivity coefficient method is introduced to identify key processes. The construction of the methodology is a useful complementary to the traditional SLCA evaluation method.

The waste PET recycling process of a company is taken as an example to carry out the integrated evaluation of LCA and LCA-SC. The results show that the environmental impact and WTP caused by the indirect production process of the industry is much larger than the direct production process. The key processes are energy consumption (electricity), direct air emissions and organics. Focusing on the social and environmental impacts of these key processes, specific recommendations and measures for improving production are proposed, such as improving employee welfare, improving electricity consumption structure, using clean energy, optimizing waste PET recycling process to reduce the use of chemical substances and reducing exhaust emissions.

The findings can not only provide optimization suggestions for the sustainable development of enterprises, but also provide theoretical and practical reference for the government to formulate relevant policies. With the increasing attention to environmental protection in the world, various green development policies of social category will be improved. Since the calculation of the WTP conversion factor is closely related to policies, this will bring a greater impact on WTP conversion factor. Therefore, this research is hopefully to appeal to more attention for methodology development of WTP conversion factor.

Table 8
Comparison of social and environmental impacts before and after optimization of the system.

	Before optimization	After optimization	Change
Standard environmental load	1.03×10^{-5}	9.56×10^{-6}	−7.16%
Social cost/RMB	1.18×10^{8}	1.10×10^{8}	−6.77%

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