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Research article

PET bottles recycling in China: An LCA coupled with LCC case study of blanket production made of waste PET bottles

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ABSTRACT

A large number of polyethylene terephthalate (PET) bottles are discarded daily after usage. Thus, plastic bottle recycling has elicited considerable attention in recent years. In this context, this study aims to quantify the environmental and economic impacts of blanket production from 100% recycled waste plastic bottles in China through a life cycle assessment coupled with life cycle costing method. In addition, the environmental impact of replacing coal with natural gas and solar energy was evaluated. Results show that impact categories of global warming and fossil depletion have significant influence on the overall environment. Carbon dioxide, water, iron, coal and chromium (VI) to water are the main contributors to the overall environmental burden. The internal and external costs are $6433/metric ton and $370/metric ton, respectively. Analysis results indicate that the optimization of organic chemicals, recycled polyester filament and steam production processes can reduce environmental and economic burdens substantially. Energy substitutions with natural gas and the use of solar photovoltaic in steam production and electricity generation are effective measures for decreasing environmental impacts. Finally, suggestions based on research results and the current status of waste plastic bottle recycling in China are proposed.

1. Introduction

Polyethylene terephthalate (PET) is widely consumed in industrial and residential areas because of its excellent properties (e.g., high thermal stability, clarity, low cost, excellent tensile, and impact strength; El Essawy et al., 2017; Zander et al., 2018), but its expansion and disposal have led to serious environmental issues (Zhang and Wen, 2014). Incineration and landfill are common methods of waste disposal (Song and Hyun, 1999). However, incineration results in the release of toxic substances that are harmful to health (Zander et al., 2018). Commercial PET and PET with high degrees of crystallinity have a melting point of 255 °C–265 °C and 260 °C–265 °C, respectively (Malik et al., 2016). Thus, PET is non-degradable under normal conditions. In 2017, the total global plastic production reached 348 million tonnes, 29.4% of which came from China (PlasticsEurope, 2018). However, half of the plastics produced are for single use (NERC, 2017). In 2015, approximately 7% of the plastic demand was constituted by PET worldwide, reaching 18.8 million tons (Taniguchi et al., 2019). Reports show that 62% of produced bottles are made of PET, and PET bottles account for 62% of all bottles collected for recycling (ACC, 2018). The recycling rate for PET plastic bottles increased from 28.4% in 2016 to 29.2% in 2017 (NAPCOR, 2018). Nevertheless, collection and processing of secondary PET do not exceed 50% worldwide (Aizenshtein, 2016). According to Shen et al. (2010), recycled PET offers significant environmental benefits compared with virgin PET. Currently, the world is paying attention to recycling with the intention of reducing PET waste and using resources rationally.

Extensive research efforts have been devoted to the recycling of waste PET bottles worldwide (Malik et al., 2016; Geyer et al., 2016; Song and Hyun, 1999). Life cycle assessment (LCA), an objective process of assessing the environmental burdens related to certain products, processes, or activities, was also conducted on the process of recycling waste PET bottles (Saleh, 2016; Patel et al., 2000; Zhang and Wen, 2014), proving that recycling results in a substantial decrease in environmental impacts, including reduced greenhouse gas emission and fossil resource consumption compared with other disposal schemes for

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used PET bottles (Nakatani et al., 2010). Another study (Foolmaun and Ramjeeawon, 2012a) indicated that a high the recycling rate equals to a high net environmental benefit. Therefore, production from waste PET bottles is increasing in view of its environmental benefits and social values.

According to Zhang and Wen (2014), China has been the largest PET bottle consumer in the world since 2010. Considering that huge amounts of PET waste have contributed to problems such as water pollution and public health concerns, the recycling of waste PET bottles is greatly encouraged in China. Recycled PET bottles are mostly (about 71% in 2014) used as recycled fiber materials worldwide (Aizenshtein, 2016). Meanwhile, 53% of the total collected PET bottles worldwide is currently being treated in China, and an estimated 30% of the country's total polyester fiber output comes from recycled PET bottles (Aizenshtein, 2016). Conversion of large amounts of waste PET bottles into high-value textile products is regarded as an eco-friendly and economically efficient technology that has huge ecological and economic benefits. However, such an enormous recycling industry entails high resource consumption and environmental emissions. LCA combined with life cycle costing (LCC) analysis is an effective approach for analyzing and managing environmental and economic burdens. Through systematically quantifying the inputs and outputs of targeted products, activities or processes, LCA and LCC can help considerably in decision making, product improvement, and policy formulation (Hong et al., 2018; Ye et al., 2018). Many manufacturing activities currently face problems regarding the overuse of materials, such as chemicals and water. Therefore, LCA combined with LCC should be conducted in China to reduce environmental and economic burdens and improve the resource use efficiency and sustainability of relevant industries.

Currently, few studies have concentrated on products from recycled PET wastes (Zander et al., 2018; Leng et al., 2018; El Essawy et al., 2017). Unfortunately, these studies did not evaluate the environmental and economic impacts of the different processes. Except for Shen et al. (2010), Intini and Kühtz (2011), and L'Abbate et al. (2018), most LCA studies related to waste PET bottles were focused on environmental disposal and waste management (Foolmaun and Ramjeeawon, 2012a; Nakatani et al., 2010; Shen et al., 2011). Based on our knowledge, there is no existing research on the environmental and economic impacts of the entire production process of recycling waste PET bottles into blankets. For the sustainable and eco-friendly management of waste PET bottles, and for the mitigation of environmental issues to improve the competitiveness of Chinese manufacturing enterprises, an investigation of production employing LCC coupled with LCA is needed. Thus, on the basis of onsite data from a factory, a study using LCC coupled with LCA method was conducted on blanket production from 100% recycled waste PET bottles in China. Key processes and improvements were also identified to provide useful information for decision makers in improving PET recycling technology and its industrial development from an environmental and economic perspective.

2. Methods of LCA and LCC

The LCA is conducted according to the standard described in ISO 14040 (2006). The ISO standards describes the principles and framework for LCA including four phases: (1) definition of the goal and scope; (2) Life cycle inventory analysis (LCI); (3) Life cycle impact assessment (LCIA); (4) Life cycle interpretation. The LCC is conducted according to the standardized methods ISO 15686-5:2017 (ISO, 2017). In this study, the internal and external cost were taken into consideration. Goal and scope definition of LCC are similar to that of LCA (Swarr et al., 2011).

2.1. Goal and functional unit

This study aims to quantify the environmental and economic impacts of blanket production from 100% recycled waste plastic bottles with LCC coupled LCA method. Furthermore, comparisons of environmental impacts and external costs of energy substitution are evaluated. A metric ton of blankets made from recycled PET bottles was used as a functional unit, which can serve as a quantitative reference for a comparison of the input and output of all related products (ISO 14040, 2006; ISO 14044, 2006). All calculated results (environmental and economic impacts) are expressed per functional unit.

2.2. Product system and system boundaries

The system boundary and mass flow of 1 metric ton blanket production (Fig. 1) in this study were set using a gate-to-gate approach, including the transportation of waste PET bottles, production of PET bottle flakes (i.e., sorting, crushing, washing with high temperature, rinsing with fresh water, and drying), filament production (i.e., oil dilution, spinning, extensional deformation, and weaving), and printing process. In particularly, the printing process consumes the largest amount of materials, and a boiler room was required to provide steam during production. Throughout each life cycle stage, raw materials, energy consumption, transport, waste treatment, and direct emissions were taken into consideration. Solid wastes were divided into general solid wastes (i.e., sorting waste, crushing waste, and filter waste) and hazardous solid wastes (i.e., shaping waste, waste dye package, waste printing screen, and shaping waste oil). The disposal method for general solid wastes was applied through selling to achieve comprehensive utilization, whereas hazardous solid wastes were sent to comprehensive utilization companies for disposal. A series of treatment processes (i.e., initial precipitation, hydrolysis acidification, activated sludge aeration, secondary sedimentation tank, and flocculation sedimentation) were conducted in a sewage treatment station. Wet desulfurization dust removal and bag-type filters were utilized for waste air treatment. The treated wastewater and exhaust gas were directly released into the river and air, respectively. The system boundary is applicable to both LCA and LCC.

2.3. Inventory and data sources

Table S1 shows the primary life cycle inventory (LCI) data (e.g., raw material, energy, and land use) based on the functional unit (Supplementary materials S.1). The onsite data from 2015 to 2018 used in this case study were acquired from a factory in Shandong Province, China. The selected factory is one of the 20 enterprises that meet the standard conditions of the comprehensive utilization of waste plastics in China (MIIT, 2017) and its production capacity ranks in the forefront of China. The enterprise was selected as a key enterprise of China's national new material industry in 2018 because of its contribution in the advanced production technology in China's chemical fiber industry (Supplementary materials S.2). This factory has a complete production line for recycling PET waste bottles into blankets and is the largest recycled filament fiber blanket producer that use 100% recycled PET. Its recycled polyester filament products are widely used in many industrial and civil fields. Annually, the factory can produce approximately 4553 metric tons of blankets, 4.8×10^4 metric tons of bottle flakes, and 1.1×10^4 metric tons of polyester filament. Specifically, production process-based data, including bottle flake production, filament production and blanket production stages, were obtained from 2015. The input and output of production remained steady in recent years due to the stable production of the investigated factory.

In 2017, the factory replaced coal with natural gas for steam production in response to the smog and air pollution that have long troubled China. To respond to the advocacy for clean production in China, the factory used a renewable energy source, solar power, to generate electricity rather than the conventional method of using coal in 2018. Comparisons of steam production with coal and natural gas, and electricity generation with solar photovoltaic (PV) and coal were conducted in this study to evaluate the effectiveness of emission reduction. Table S1 presents the primary LCI before energy substitution. Specifically, the

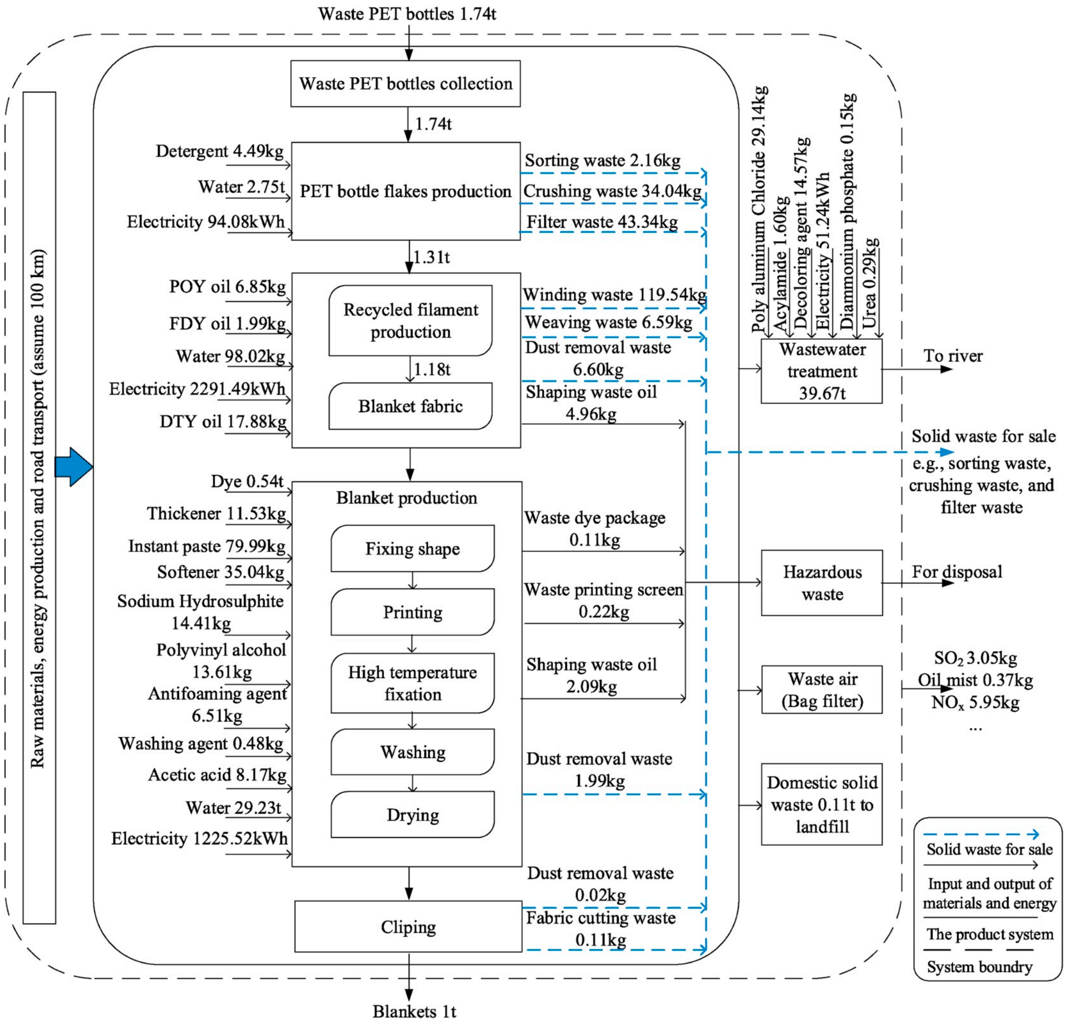

Fig. 1. System boundary.

amount of natural gas and PV used to replace coal was based on heat conversion and the inventory data of natural gas and PV were not provided in Table S1. Correspondingly, electricity consumption and the amount of coal consumed for steam production were presented.

Background data of each material flow associated with the blanket production (i.e., road transportation, national coal-based electricity production, domestic waste disposal, steam production, acetic acid production, tap water production, industrial hazardous waste incineration, and wastewater treatment) were obtained from the Chinese process-based LCI database (CPLCID, 2018. Supplementary materials S.3), which is an international reviewed database involving typical enterprises in China (Zhang et al., 2016). Background data on organic chemical production were obtained from the Ecoinvent database (Ecoinvent centre, 2015) because of the lack of data in China. To decrease the regional impacts of data utilization from Europe in Chinese context, the Chinese data on road transport (Chen et al., 2015) and national coal-based electricity generation (Cui et al., 2012) were used to replace the corresponding processes in the Ecoinvent database. Current market prices (according to November 25, 2019, exchange rate of USD 1.00 = CNY 7.039), such as raw materials and energy, and the rest of internal cost (i.e., labor, building, equipment, investment, and tax) based on per functional unit are shown in Table S1. Moreover, the lifetimes of the building and equipment were set to 40 and 10 years, respectively.

2.4. Methodology

LCA coupled with LCC was conducted in this study. The methodology of LCA integrated with LCC is presented in Fig. 2. The LCA was analyzed using the SDU (i.e., Shandong University) method which is a mixed and updated method for China's life cycle impact assessment (LCIA) analysis at the midpoint level with 15 impact categories (Chen et al., 2016b, 2018; Hong et al., 2016a). The different impact categories and their corresponding sources are shown in Fig. 2. Normalization was applied to further evaluate the respective share and compare the impact of each environmental impact category based on the total global effect of the year 2000 (Anneke Wegener et al., 2008). More detailed information about SDU model is available in the Supplementary materials S.4. The LCC method was conducted to evaluate the economic impacts brought about by the LCA of each process based on the investigations of Hong et al. (2015) and Hong et al. (2012) (Hong et al., 2016b, 2018; Ye et al., 2018). The system boundary of LCC was equal with that of LCA and the internal (e.g., raw materials, labor, and equipment) and external cost of blanket production were taken into consideration. The external cost (Qi et al., 2018) was calculated based on environmental emissions, ecosystem remediation, and health expenditure. In the meantime, indirect human health cost was qualified through the human capital method (Hanly et al., 2012). The external cost includes three categories (i.e., environmental emissions, ecosystem quality, and human health). The LCC were calculated based on Eq. (1).

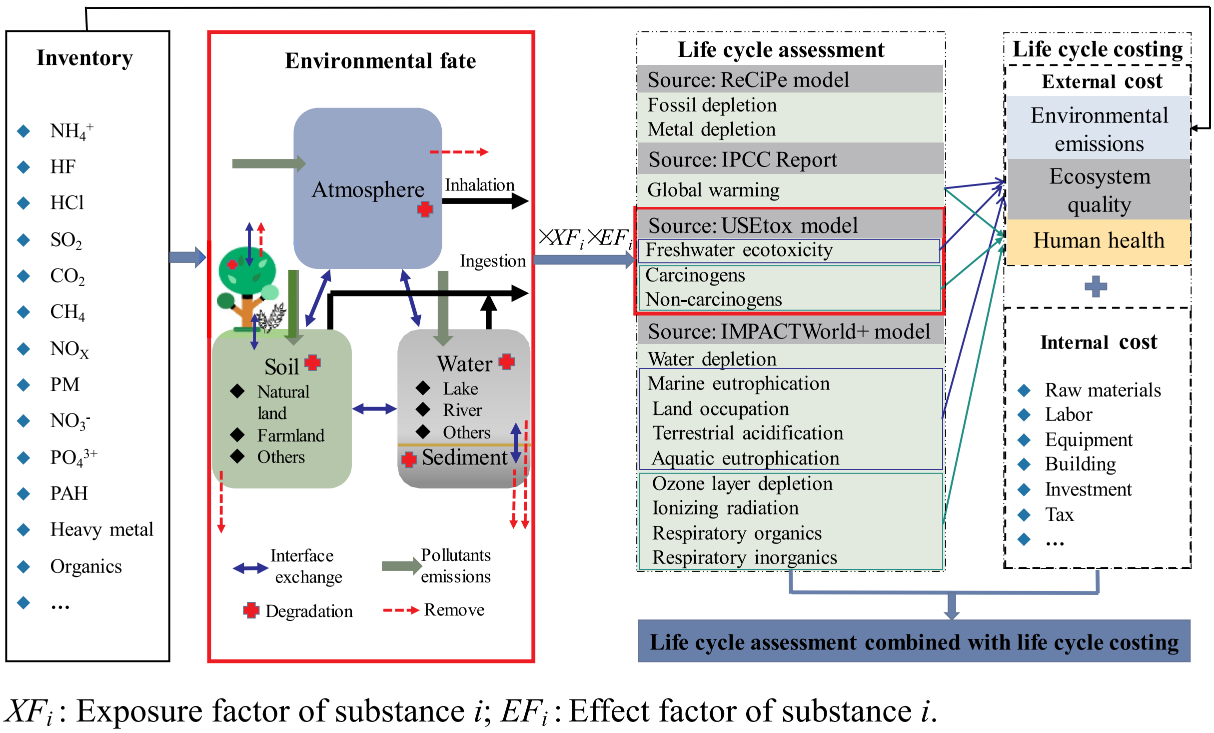

Fig. 2. The framework of LCA combined with LCC method.

$$LCC_{Total} = \sum_{i=1}^{n} LCC_{in,i} + \sum_{j=1}^{m} \left(LCC_{em,j} + LCC_{ec,j} + LCC_{hu,j} \right) \tag{1}$$

where LCC_{Total}, $LCC_{in,i}$, $LCC_{em,j}$, $LCC_{ec,j}$, and $LCC_{hu,j}$ represent the life cycle cost result in this study, the internal cost of item i in LCI, the cost arise in environmental emissions, ecosystem quality, and human health of substance j. $LCC_{in,i}$ was the integrated result of LCI and the cost database. The infrastructure of the blanket production factory was analyzed via LCC, but an LCA of the infrastructure was not conducted in this study because of data limitations. $LCC_{em,j}$ and $LCC_{ec,j}$ were calculated according to China's current carbon credits for voluntary emission reduction projects and the willingness-to-pay method respectively (Qi et al., 2018). In addition, the LCA results were further employed to assess the environmental LCC. Human health cost ($LCC_{hu,j}$) includes direct (DC) and indirect (IDC) cost, which were calculated with Eqs. (2) and (3).

$$DC = \sum_{j=1}^{m} LCIA_j \times \left(\frac{PE_r + GE_r + SE_r}{\theta \times C_{am} + \eta \times NC_{am}} \right) = \sum_{j=1}^{m} LCI_j \times FF_j \times XF_j \times EF_j \times \left(\frac{PE_r + GE_r + SE_r}{\theta \times C_{am} + \eta \times NC_{am}} \right) \tag{2}$$

$$IDC = \sum_{j=1}^{m} LCIA_j \times GDP_r \times \delta = \sum_{j=1}^{m} LCI_j \times FF_j \times XF_j \times EF_j \times GDP_r \times \delta \tag{3}$$

where PE_r, GE_r, and SE_r refer to regional health expenditure of person, government, and society. FF_j, XF_j, and EF_j refer to fate factor, exposure factor, and effect factor of substance j. C_{am} and NC_{am} refer to annual mortality of cancer and non-cancer. θ and η refer to conversion coefficient of disability adjusted on life years for cancer and non-cancer impact. GDP_r and δ refer to gross domestic product at regional level and regional labor productivity weight. The environmental and economic impacts were quantified using the SimaPro 8.4 software.

3. Analysis results

3.1. LCIA midpoint results and uncertainty analysis

The LCIA midpoint results, which are presented per functional unit as well as the squared geometric standard deviation (GSD^2) values, are shown in Table 1. Overall uncertainty was quantified using a Monte Carlo simulation, a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results, in which background inventories were used for 1000 iterations (Hong et al., 2010; Huijbregts et al., 2003; Supplementary materials S.5). The LCIA median value on the category of global warming was 1.54 × 10^4 kg CO_2 eq with a GSD^2 of 1.21. As the potential score range was defined by the division and multiplication results between the median value and the GSD^2 value of a category, this result denotes that the global warming score ranges from 1.28 × 10^4 kg CO_2 eq to 1.87 × 10^4 kg CO_2 eq with a 95%

Table 1
LCIA midpoint results and uncertainty analysis of recycled blanket production. Values are presented per functional unit.

Categories	Recycled blankets		
	Unit	Values	GSD^2
Global warming	kg CO_2 eq	1.54 QUOTE × $\times 10^{4}$	1.21
Land occupation	ha.yr arable	1.90 QUOTE × $\times 10^{-3}$	1.75
Terrestrial acidification	kg SO_2 eq	8.14	1.22
Aquatic eutrophication	kg PO_4^{3-} eq	0.55	1.35
Respiratory inorganics	kg $PM_{2.5}$ eq	0.86	1.34
Respiratory organics	kg NMVOC eq	10.41	1.28
Ionizing radiation	Bq C-14 eq	6.85 QUOTE × $\times 10^{3}$	3.94
Ozone Layer Depletion	kg CFC-11 eq	5.69 QUOTE × $\times 10^{-5}$	1.77
Water depletion	m^3	8.84 QUOTE × $\times 10^{2}$	1.53
Metal depletion	kg Fe eq	1.94 QUOTE × $\times 10^{2}$	1.76
Fossil depletion	kg oil eq	2.78 QUOTE × $\times 10^{3}$	1.21
Carcinogens	CTUh	1.29 QUOTE × $\times 10^{-4}$	2.29
Non-Carcinogens	CTUh	1.04 QUOTE × $\times 10^{-3}$	2.02
Freshwater ecotoxicity	CTUe	6.27 QUOTE × $\times 10^{4}$	1.44
marine eutrophication	kg N eq	0.79	1.47

GSD^2: The squared geometric standard deviation.

confidence interval. Similarly, the score of terrestrial acidification ranges from 6.67 kg SO_2 eq to 9.93 kg SO_2 eq, and similar calculations could be conducted for the remaining categories.

Fig. 3 shows the normalized midpoint results, where the effects on global warming, fossil depletion, water depletion, and carcinogens were considerable. Specifically, the global warming category contributed the most to the overall environmental burden. Blanket production had relatively minor effects on metal depletion, and the impact of the rest of categories (e.g., land occupation, terrestrial acidification, and aquatic eutrophication) is relatively small compared to the other categories, and hence these categories were not included in the analysis of the key factors in this study.

3.2. Key factors

Fig. 4 illustrates the relevant processes of the main categories that were selected based on the normalized midpoint results. For the global warming category, the primary processes were recycled polyester filament production and steam production, which contributed approximately 81% in total. Organic chemical production was the most influential contributor to water depletion, accounting for 80%. Similarly, organic chemical production played a dominant role in carcinogens, followed by recycled polyester filament production. The impacts of metal and fossil depletion were mainly attributed to the production of steam, organic chemical, recycled polyester filament, and electricity generation.

The most important contributor to water depletion was the water used in production. The rest of the key substances that contributed to the other key categories are presented in Fig. 5. Carbon dioxide (CO_2), which mostly came from coal-based steam production was the dominant substance in the global warming category, followed by methane. Iron contributed the most to metal depletion, accounting for 78%. Coal was the most considerable contributor to fossil depletion. By contrast, the contributions of oil and gas were relatively small, that is, 20% and 15%, respectively. Chromium (VI) to water generated primarily from organic chemical production was the primary substance that contributed to the carcinogens, accounting for 92%.

3.3. Life cycle costing analysis

The LCC analysis results are shown in Fig. 6a. The total economic cost is US$6803/metric ton, including US$370 for external cost and US $6433 for internal cost with a net profit of approximately US$511/metric ton. The main contributors to the overall economic burden were the cost of organic chemical and filament production. In addition, the cost of steam production, electricity, and several private expenses (e.g., equipment, investment in R&D, and labor) played secondary roles. Other costs, such as taxes, water, wastewater treatment, ecosystem quality, and environmental emissions, were small (Fig. 6a).

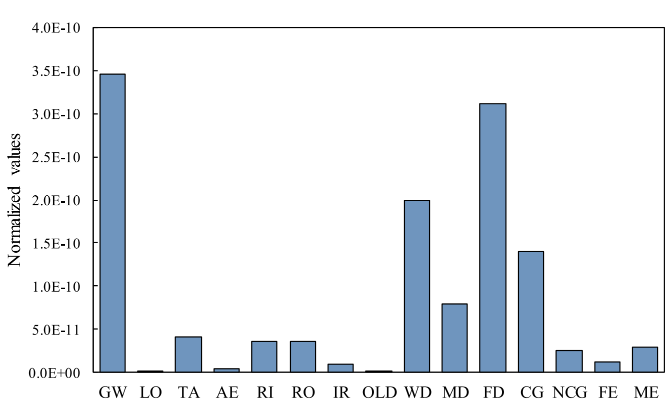

Fig. 3. Normalized midpoint results.

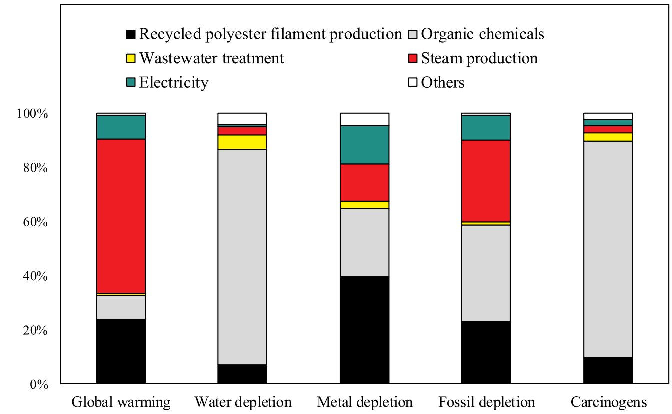

Fig. 4. Key processes to the main categories.

The economic costs associated with the LCA analysis results, in which the latter is described based on the normalized LCIA results, are presented in Fig. 6b. Organic chemicals from the blanket production stage exhibited the highest economic impact, which accounted for 54% of the overall economic burden and 37% of the overall environmental burden. The recycled filament production stage exerted high economic impacts (24%) and relatively high environmental impacts (22%). The impacts of electricity generation accounted for 2% of the overall economic burden and 8% of the overall environmental burden. The relatively small economic impacts of labor, investment in R&D, and equipment ranged from 2.5% to 4.5%, indicating low environmental impacts (~0%). Other factors during the coal-based steam production stage exhibited relatively low economic (5%) and high environmental (27%) impacts.

3.4. Sensitivity analysis

3.4.1. Sensitivity of main contributors

The sensitivity analysis results of the dominant contributors for all the stages are presented in Fig. 7a. A 5% variation in the important processes influencing the aforementioned main categories and economic impact was conducted. A decrease in recycled filament production and steam production had apparent influences on the global warming category, while the variation of organic chemical and electricity production had relatively small effects on global warming. Moreover, a decrease in organic chemicals, recycled filament production, steam production, and electricity production could remarkably reduce the impacts of metal and fossil depletion categories. The variation in organic chemicals had the highest impact on water depletion, carcinogens, and economic aspect. Generally, the variation in organic chemicals and recycled filament production resulted in high economic and environmental benefits in almost all of the affected categories, except for global warming. In other words, improving the utilization efficiency of materials and optimizing recycled filament production is crucial in reducing the overall environmental and economic burdens. By contrast, tap water production and wastewater treatment had minimal contribution in reducing the overall environmental and economic impact.

3.4.2. Sensitivity of PET botte flakes productivity

As a significant process, the production of recycled filament from PET bottle flakes has a vital role in environmental and economic impacts (Figs. 4 and 6a). In this filament production process, collected waste PET bottles are first processed into bottle flakes, then further processed into polyester filament fibers. Environmental impacts are mainly derived from the bottle flake production, electricity generation, and organic chemical production processes (Supplementary materials S.6). Several studies have shown that the yield of 1 metric ton of recycled PET flakes ranges from 75% to 80% (Arena et al., 2003; Detzel et al., 2004; Shen

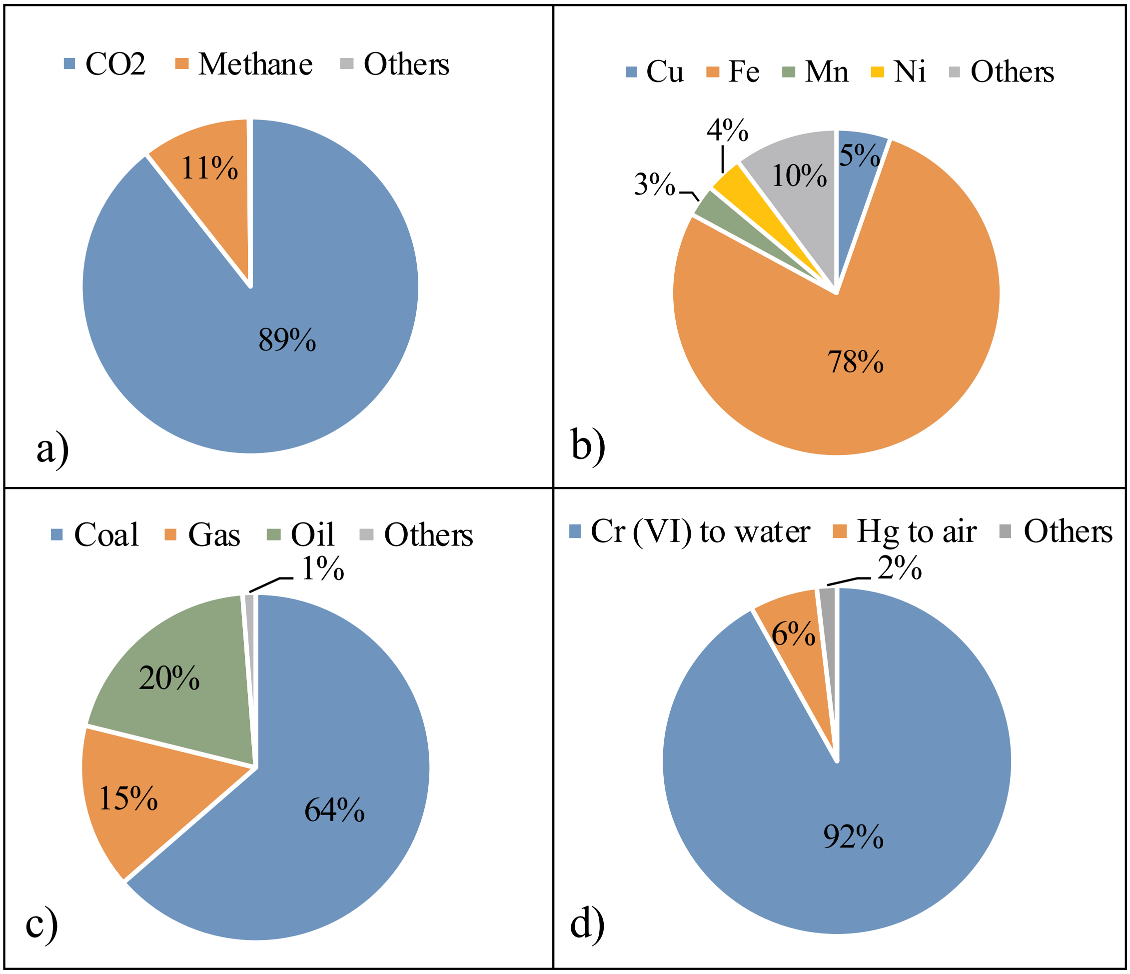

Fig. 5. Key substances contributed to the key categories: a) Global warming; b) Metal depletion; c) Fossil depletion; d) Carcinogens.

et al., 2010; Intini and Kühtz, 2011). This relatively high yield and the low price of waste PET bottles, as the material of recycled bottle flakes, guarantee considerable profits and environmental benefits. In this study, the material efficiency of bottles to bottle flakes is 75%, which is close to the values in previous studies. However, this value is relatively low. Fig. 7b shows the relationship between the productivity of PET bottle flakes and the reduction in global warming and fossil depletion, which have the most significant impacts in this study. The results shows that if the productivity of bottle flakes can be improved from 75% to 80%, then the environmental burdens of global warming and fossil deletion will be reduced by 49.32 kg CO_2 eq and 5.56 kg Oil eq based on the results of this study, respectively. Such results suggest that improvements in the production of PET bottle flakes from PET bottles will help further mitigate the environmental impact generated from blanket production.

3.5. The effects of energy substitution

In response to the national call for clean production in China and reduction of environmental burdens, the factory in this case study implemented two reforms in 2017 and 2018. The first reform was to replace coal with natural gas for steam production. The second reform was based on the first reform and involved the use of PV instead of coal to generate electricity. Approximately 20% of electricity consumption was substituted. The results of environmental impact changes before and after the reform are shown in Table 2, and the changes in external costs are also measured. The overall environmental impact and external costs of 1 metric ton of blankets prior to the reform were set at 100%. The results of the first and second reforms were evaluated relative to the pre-reform period. All environmental influences considered in this study decreased after changing the steam production, and the impacts of most categories were further reduced after the reform in partial electricity generation. Although the environmental burden increased slightly in several categories with PV power generation, power generation with PV generally had more advantages than coal-based electricity production, which was consistent with the result of Chen et al. (2016a). Similarly, a considerable reduction in external cost can also be observed from Table 2.

Steam production exhibited large environmental impacts at 27% (Fig. 6b). Specifically, steam production from coal accounted for 44% in human health protection and contributed considerably to the global warming, metal depletion, and fossil depletion categories (Fig. 4). Since 2017, the boiler room of the studied factory has been using natural gas instead of coal to provide steam as a response to national initiatives for clean production. Natural gas has less environmental emissions compared with coal. Ren et al. (2017) indicated that concentrations of pollutants (i.e., n-alkanes, PAHs, and oxygenated PAHs) decreased by 74%–82% with the replacement of coal to natural gas in heating. Given the dominant substances presented in Fig. 5, CO_2, 59% of which was generated from steam production, was the most substantial contributor to global warming (89%). In addition, 47% of coal, which was a dominant contributor (64%) to fossil depletion, was consumed in steam production. Accordingly, replacing coal with natural gas in steam production, is a key step in reducing the overall environmental burden.

For global warming, metal depletion, and fossil depletion (Fig. 4), another main contributor is electricity apart from the production processes of steam, recycled filament, and organic chemicals. As the first

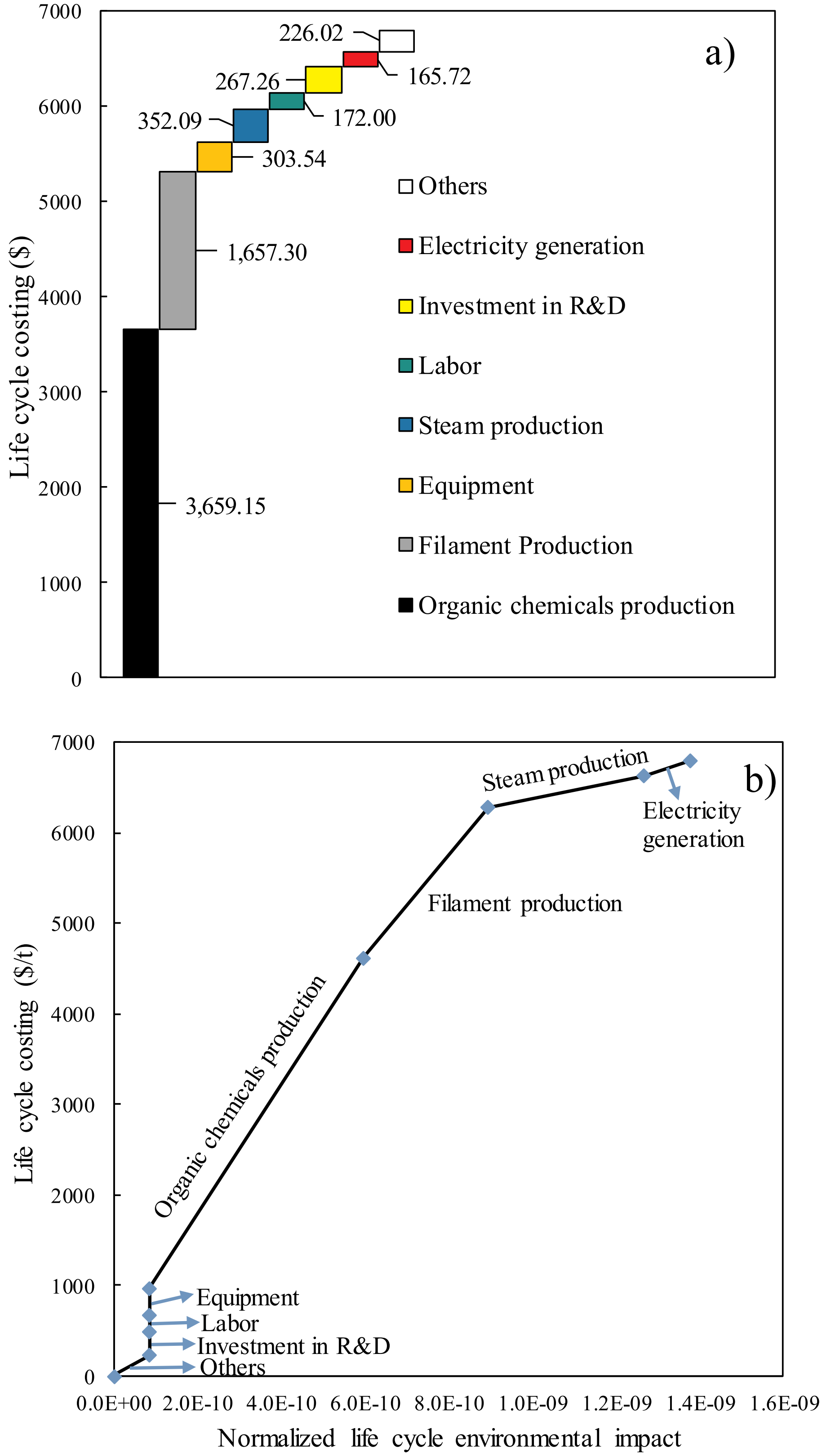

Fig. 6. LCC analysis results: a) contribution of processes; b) cost versus environmental impact.

ranked country in global energy consumption growth, China accounts for 23.2% of the global energy consumption and 33.6% of the global energy consumption growth (BP Statistical Review, 2018). Although the use of coal in China's energy structure decreased from 73.6% a decade ago to 62.0% in 2016 and 60.4% in 2017, coal is still the main fuel source in China's present energy consumption (BP Statistical Review, 2018). Thus, coal-based electricity generation was applied in this study. However, except for coal power, hydropower accounted for 19.6% in China's power generation in 2016 (NBS, 2016). The remaining power supply, such as wind, nuclear, natural gas, solar, and oil-based power,

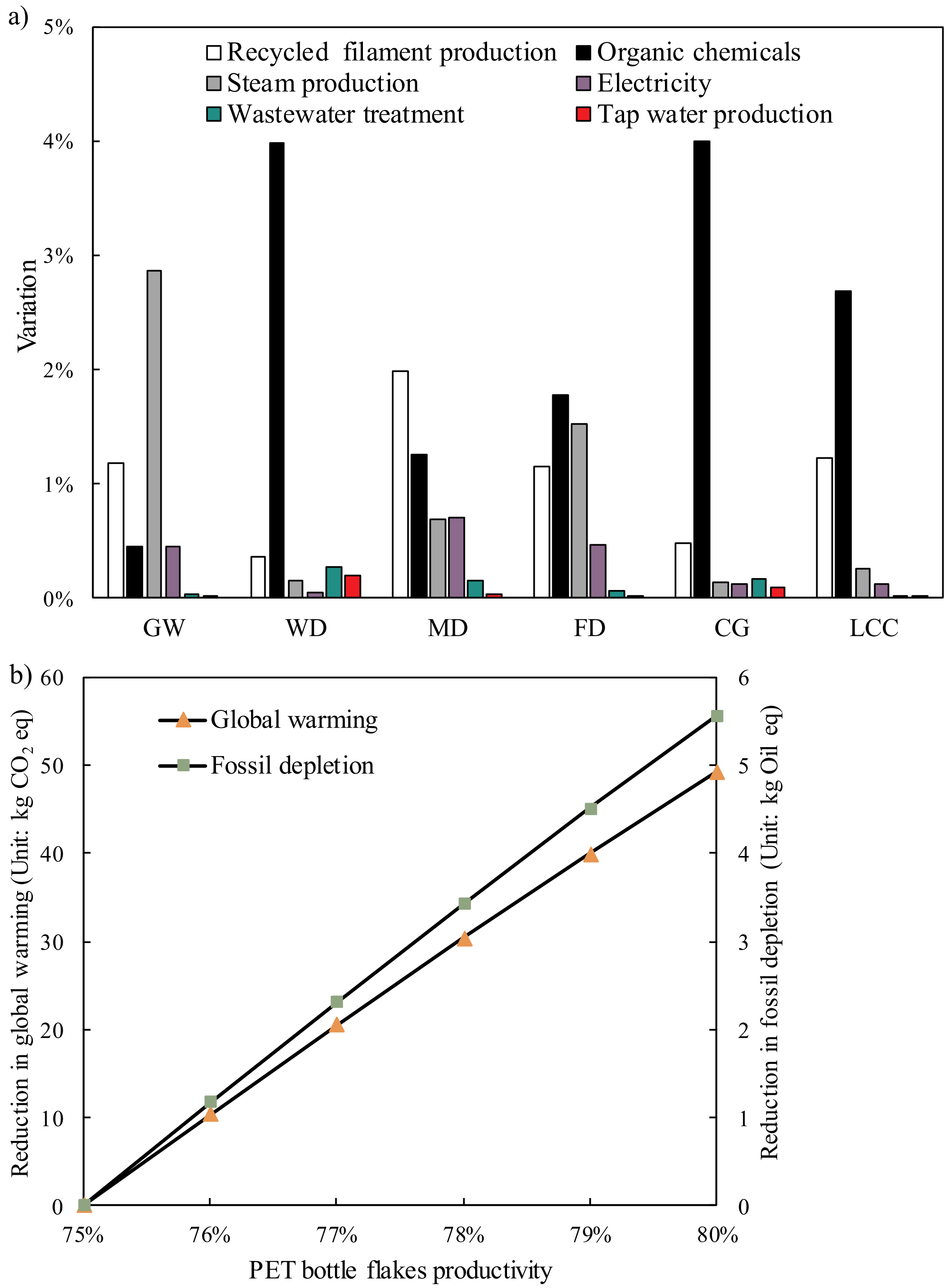

Fig. 7. Sensitivity analysis results: a) sensitivity of main contributors; b) relationship between the reduction of environmental impacts and the productivity of PET bottle flakes.

contributed approximately 3.9%, 3.6%, 3.1%, 1.1% and 3.3% in 2016, respectively (NBS, 2016). If coal-based electricity generation is replaced by mixed power generation, which is in line with China's actual situation, the environmental impacts of global warming, metal depletion, and fossil depletion will be reduced by 31%, 17%, and 23%, respectively. Therefore, energy production adjustment will be an effective way to reduce emission levels and thereby mitigate environmental impacts.

4. Discussion

4.1. Environmental benefits of waste PET bottle recycling

Extensive studies conducted LCA analyses for investigation of different waste PET disposal options (Chilton et al., 2010; Grant et al., 2001; Von Krogh et al., 2001). These studies compared either two or more scenarios (i.e., recycling, landfill, incineration, and incineration with energy recovery), all of which showed a preference for recycling. Nakatani et al. (2010) evaluated 10 disposal scenarios of post-consumer PET bottles and found that all the recycling scenarios contributed less environmental burden than incineration, which indicated the necessity of recycling waste PET bottles. Cremiato et al. (2018) used LCA to manage municipal solid waste and evaluated its environmental impact in a province of Southern Italy. In the study, the result demonstrated that the separate collection of recyclable materials, which could be utilized as substitutes for raw materials in goods production, helped to reduce the direct and indirect impacts in the overall life cycle. In other words,

Table 2
Results of energy substitution of steam and electricity production.

	Categories	Before reform	The first reform	The second reform
Environmental impact	Global warming	100%	41.9%	36.0%
	Land occupation	100%	90.5%	86.0%
	Terrestrial acidification	100%	60.1%	55.6%
	Aquatic eutrophication	100%	95.1%	96.1%
	Respiratory inorganics	100%	79.1%	70.2%
	Respiratory organics	100%	60.6%	57.2%
	Ozone Layer Depletion	100%	97.4%	98.8%
	Metal depletion	100%	89.0%	81.8%
	Fossil depletion	100%	65.8%	59.2%
	Carcinogens	100%	97.2%	102.8%
	Non-Carcinogens	100%	95.1%	81.3%
	Freshwater ecotoxicity	100%	66.4%	67.5%
	Marine eutrophication	100%	77.8%	77.4%
	Ionizing radiation	100%	97.6%	102.5%
	Water depletion	100%	96.0%	99.8%
External cost	Human health	100%	56.6%	49.8%
	Ecosystem quality	100%	65.1%	65.8%
	Environmental emission	100%	70.3%	67.1%

the utilization of non-virgin PET denoted the initial effort to mitigate environmental burdens. Intini and Kühtz (2011) compared the environmental impacts of thermal insulation panel from recycled PET and virgin fiber, and considerable reductions in environmental burden were noticed. Shen et al. (2010) showed that all recycled PET fibers (involved chemical recycling, mechanical and semi-mechanical recycling) had lower global warming values compared to virgin PET. In addition, a comparison of different fiber products presented good performance in recycled PET fibers, with no apparent differences between recycled PET and virgin PET, or even better than virgin PET in some aspects.

4.2. Waste PET bottles recycling status in China

In China, because of weak policies (Zhen-Shan et al., 2009), recycling is mainly relegated to households and farmers, regardless of the numerous factories and personnel engaged in large and stable recycling and plastic waste processing (Tang et al., 2013). In fact, workshop-type plastic waste recycling and processing sites in many places lack technical staff members and use antiquated production equipment because the plastic waste recycling industry has low barriers of entry and require low technical content (Tang et al., 2013). Currently, nearly 100% of PET bottles are recycled by small factories because of China's lack of formal recycling collection systems (Zhang and Wen, 2014). The current situation in China has led not only to unstable product quality but also to higher environmental impacts. In addition, Waste plastic bottles are prone to bacteria, raising various health problems that require special attention. The workflow of a small-scale factory lacks strict supervision and corresponding regulations, which greatly harms the health of workers. In this study, the production of filament from recycled bottle flakes accounted for around 27% in the human health category. Thus, a sound plastic waste recycling policy and environmental supervisory system for small-scale workshops are urgently needed.

4.3. Comparison with previous studies on recycling of PET bottles

Most LCA studies related to recycled PET have focused on waste management methods or technologies rather than recycling production (Foolmaun and Ramjeeawon, 2012a, 2012b). Hence, conducting a direct comparison of our results with those of these studies is difficult because of the different system boundary and function units (Shen et al., 2010). Furthermore, as mentioned by Shen et al. (2010), accessing data on PET recycling processes in public domains is difficult. As a result, the comparison of processes within this recycled blanket production is conducted. The environmental impact values of acidification pre-reform for 1 metric ton of filament fiber production described in this study are lower than the values for any of the recycling methods investigated by Shen et al. (2010). Approximately 23%, 74%, 84%, and 89% decreases are observed compared to mechanical, semi-mechanical, chemical recycling processes, and virgin-PET fiber in Shen et al. (2010), respectively. For eutrophication, the value pre-reform in this study (0.03 kg PO_4^{3-}eq.) is lower than that in the study of Shen et al. (2010) (0.8–2.3 kg PO_4^{3-}eq.), regardless of the recycling process, indicating good environmental benefits for recycled fibers. The low value in this study is mainly due to the extremely low levels inventory data on relevant pollutants discharged into the water according to extremely stringent local water pollution control standards. According to Shen et al. (2010), recycled PET fibers exert a considerable effect on reducing global warming impacts compared with virgin PET fibers. However, the global warming values of PET fibers recycled through mechanical, semi-mechanical, and chemical recycling processes and virgin-PET fibers are 0.96, 1.88, 2.59–3.08, and 4.06t CO_2 eq. respectively. Meanwhile, the result was 3.09 t CO_2 eq. for 1 metric ton filament fiber pre-reform in this study. The result of the present study still indicates a high global warming value, although it is less than that of virgin PET fibers. The reason mainly attributed to the fact that coal-based power was the only type of power generation considered in this study because of its dominant status in China's energy production. Therefore, these results indicate that the blanket production from recycled PET in this case have environmental benefits compared to that from virgin PET. Furthermore, The water consumption during recycled filament production from PET bottles in the present study was less than 3 metric tons for 1 metric ton of filament, which is at an advanced level in China (MEE, 2008). However, the material efficiency of producing recycled PET fiber from PET flakes is between 94% and 99% as reported by Shen et al. (2010), whereas only 85% was observed in the current study. Hence, production technologies should be optimized to minimize environmental and economic impacts. Thus, the comparison results indicate that environmental and economic burdens can be reduced by optimizing bottle flake production. Moreover, improving the recycling rates of raw materials in the production processes are suggested.

5. Conclusions

In this study, LCA coupled with LCC was conducted to evaluate the environmental and economic impacts of blanket production from recycled waste PET bottles. Uncertainty analysis was applied to ensure the credibility of the results, and the effect of energy substitution in steam production was qualified. Key factors were identified to reduce the environmental and economic burdens in production processes. The results showed that the environmental burden was mainly derived from global warming, fossil depletion, water depletion, carcinogens, and metal depletion. Production of organic chemicals, filament production, electricity, and steam production exerted substantial environmental impacts, in which organic chemicals and recycled filament production had apparent environmental and economic effects. The adjustment of energy structures from single-coal-based electricity to mixed power sources demonstrated huge environmental benefits. In addition, the improvement of the utilization rate of raw materials in production processes and the optimization of production technologies should be conducted to mitigate environmental and economic impacts. Notably, a sound plastic waste recycling policy and environmental supervisory system should be introduced for small-scale workshops in China. The LCI and LCA results of this study can provide useful information for the improvement of waste PET bottle recycling and reuse industry, as well as provide insights into policymakers in China so that they can guide the PET bottle recycling and the secondary utilization industry toward sustainable development. However, this study only showed a case of an actual production factory in China. To improve the representativeness of data and for a more comprehensive analysis of the environmental and economic impacts of PET bottle recycling, further studies on other recycled products from waste PET bottles in different regions are necessary.

Author contributions

Ruirui Zhang: Conceptualization, Methodology, Writing-original draft. Xiaotian Ma: Methodology, Software. Xiaoxu Shen: Software, Data curation. Yijie Zhai: Data curation, Investigation. Tianzuo Zhang: Visualization, Investigation. Changxing Ji: Investigation. Jinglan Hong: Supervision, Conceptualization, Writing-Reviewing and Editing.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2019.110062.

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