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Research article

# Integrated assessment of environmental and economic impact of municipal solid waste incineration for power generation: A case study in China

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ABSTRACT

Municipal solid waste incineration for power generation is significant for reducing and reusing solid waste. The study conducted an integrated assessment of environment and economy on municipal solid waste incineration in China, from a "cradle to grave" perspective using 1 tonne of municipal solid waste incineration as the functional unit. The environmental impacts of each month are also calculated to analyze the dynamic change throughout one year. The results indicate that the environmental impacts are mainly concentrated in marine ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity. Flue gas purification, waste incineration and transportation are the key processes, which account for 65.61 %, 18.50 %, and 11.93 % of the overall environmental impact, respectively. Urea, activated carbon, chelating agent (EDTA) and diesel fuel for transportation are key factors. The life cycle cost (LCC) is 132.26 RMB/t of waste, of which the initial capital causes the largest economic cost. When considering power generated from municipal solid waste incineration to replace electricity supply from the power grid, it achieves significant environmental benefits and the normalized environmental impact value changes from 0.85 to −12.19. The findings provide references for municipal solid waste treatment to mitigate the environmental impact and reduce the economic burden across the entire life cycle.

## 1. Introduction

With most economies around the world growing, the amount of municipal solid waste (MSW) generated worldwide has been increasing each year [1]. It is predicted that the total MSW generated globally will be $3.4 \times 10^9$ tonnes by 2050 Kaza et al., [2]. In 2020, the quantity of MSW generation in China reached 235.12 million tonnes, which is 1.5 times of that in 2010 [3,4]. Landfill was regarded as the main way of waste management in the past due to its cost benefit; however, one quarter of the cities in China do not have suitable landfill sites at present [5]. The proportion of incineration in urban waste management is increasing because of the government

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subsidies for waste power generation and inadequate landfill space Damgaard et al., [6]; [7]. The number of waste incineration plants in China has increased from 104 in 2010 to 463 in 2020 [3,4]. Annual treatment capacity of this method has grown from 23.17 million tonnes to 146.08 million tonnes, increasing from 19.15 % to 62.3 % of waste non-hazardous treatment [3,4].

MSW incineration is the complete oxidation reaction of combustible components at 800–1000 °C to reduce, recycle and dispose of the waste innocuously [8]. Through the incineration process, the pathogens are eliminated, and the combustible components can be reduced by 80 %–90 %; the internal energy of waste can also be converted into heat and electricity [9,10]. A series of problems of sanitary landfill, such as large area, leachate, odor, and insufficient recovery can also be solved Abd Kadir et al., [11]; [12,13].

Although MSW incineration power generation technology has been widely applied, several limiting factors still exist. In China, waste classification has not been widely promoted Bian et al., [14] so all the waste in a furnace will be burnt directly, resulting in a large amount of sulfur oxides and nitrogen oxides; and under certain circumstances, heavy metals, dioxins and other strong carcinogens will also exist in the flue gas [15]. To eliminate them, expensive purification systems should be installed in the plant, which incurs expensive construction and operation costs. It is therefore important to conduct environmental impact assessment and economic cost analysis of waste incineration power plants throughout their life cycle.

As an effective environmental management tool, life cycle assessment (LCA) is introduced to quantify the environmental impact of a system throughout the whole life cycle from extraction, transportation, production, use, end-of-life, to reuse Zuliani et al., [16]; [17,18]. It has been widely applied in the environmental impact assessment of MSW incineration [19,20]. Istrate et al. [21] applied LCA method to evaluate the environmental impact of MSW incineration in Madrid, Spain. Clavier et al. [22] conducted a comprehensive review of MSW incineration fly ash reuse and optimal conditions for environmentally sustainable disposal. Liikanen et al. [23] employed LCA to determine refuse-derived fuel production and found that its incineration would have a more positive impact on the environment than the incineration of coal in Hangzhou, China. Guo et al. [24] accessed the life cycle environmental impacts of MSW incineration in a typical Chinese industrial park. Chaya et al. [51] compared the environmental impacts of MSW incineration and anaerobic digestion in Thailand based on LCA. Chang [25] conducted LCA for the high-parameter MSW incineration power system and

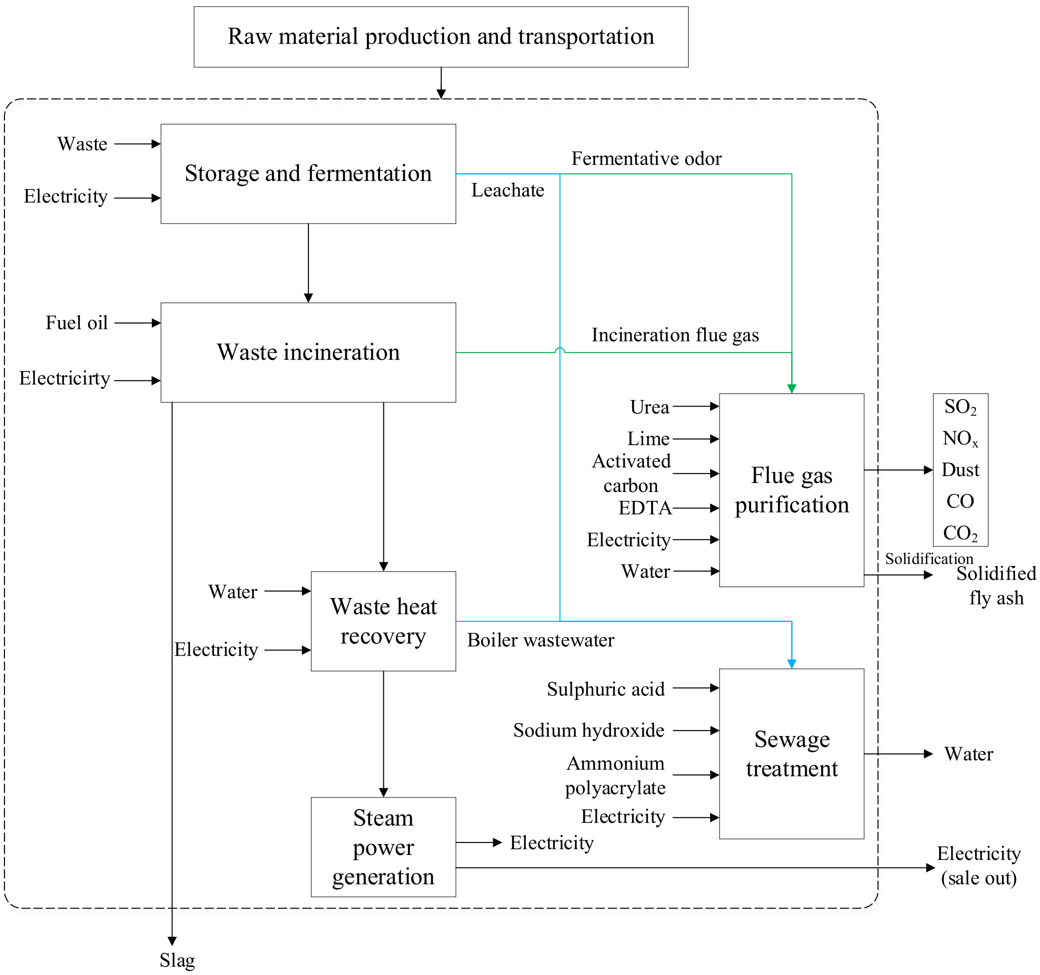


**Fig. 1.** System boundary of MSW incineration for power generation.

the middle one, and found the former has lower environmental load. Beylot and Villeneuve [26] compared the environmental impact of 110 waste incinerators in France and found that it depends on the type and technology of incinerators. Most of these studies focus on the single mature MSW treatment technology and pay attention to the environmental impact categories such as global warming, human toxicity, acidification and eutrophication.

Life cycle cost (LCC) is a popular method for cost accounting in MSW management currently [27]. It refers to all the costs related to a product during its entire life, including design, manufacture, procurement, use, maintenance, and disposal [28]. Suggestions on how to reduce the cost of a product, select a better scheme can be provided through LCC research Milić et al., [29]. Li et al. [30] investigated the LCC of an MSW incineration power plant project in China with a capacity of 600 tonnes per day. Lee et al. [31] compared six current waste treatment scenarios including electricity generation through LCC analysis in Hillsborough County, USA. Mohsenizadeh et al. [32] explored an optimization model aimed at minimizing the cost of operating a MSW system and reducing carbon dioxide emissions during transportation.

These studies analyzed the environmental impact and economic cost of MSW incineration. However, most of these studies paid more attention to the environmental load or cost occurred during the operation stage instead of the entire life cycle from collection, storage, incineration to final disposal. The factors like policy support, environmental and economic benefits of by-products, and the change of environmental impacts over time are rarely considered comprehensively. The monthly fluctuation of MSW incineration to environmental sustainability is unexplored in the previous researches. Therefore, an integrated environmental impact and economic cost assessment of the entire life cycle of MSW incineration is necessary. In this study, a waste incineration power plant is selected as the object of research to conduct an environmental impact and economic evaluation from a life cycle perspective, involving extraction, storage, incineration, and disposal. This will fill the research gap of MSW incineration technology and provide optimization suggestions for sustainable development in this field.

## 2. Methods

### 2.1. Goal and scope

An MSW incineration power plant in China was selected for a case study. The power plant can absorb 700 tonnes of MSW per day. The system boundary of “cradle to grave” is shown in Fig. 1, including the processes of raw materials collection, energy production, transportation, storage and fermentation, waste incineration, waste heat recovery, steam power generation, flue gas purification, and sewage treatment. The steam is produced by steam generator, then transmitted to the turbine for power generation. Electricity generated is directly sold to the national grid. The flue gas purification system includes an SNCR denitrification system, deacidification reaction system, activated carbon injection, dedusting system, induced draft system, smoke extraction system and fly ash stabilization system, which can reduce air pollutants effectively. The fly ash collected in the storage bin is sent to the fly ash mixer, which is solidified by adding chelating agent (EDTA) and water.

A functional unit is usually used as the reference unit as it enables all inputs and outputs of one investigated system to be normalized [17]. One tonne of MSW to be treated was defined as the functional unit.

MSW from surrounding areas is collected as raw material, and the water supply is from the municipality. Fuel, urea, lime, activated carbon, EDTA, sulfuric acid, sodium hydroxide and ammonium polyacrylate are purchased in the locality, with short transport distance and low cost. Apart from being used for transporting vehicles, diesel also serves as fuel in waste incineration. Urea, lime and activated carbon are prepared for flue gas purification to realize denitrification, desulfurization, and the adsorption of heavy metals and dioxins. EDTA is used to stabilize incineration fly ash. Sulfuric acid, sodium hydroxide and ammonium polyacrylate are required in the process of sewage treatment, in which the first two are used to adjust the pH value of sewage tank, and ammonium polyacrylate is used for the cleaning of the filter membrane. The produced slag can be sold to manufacture building materials. The remaining fly ash after purification is classed as hazardous waste and should be solidified.

### 2.2. Life cycle inventory

In this case, data concerning the consumption of raw materials and direct emissions of common pollutants are from field research. Background data on raw materials and fuels are collected from the [52]. The environmental impacts of slag and solidified fly ash are ignored since they are not directly discharged into the environment. According to test data, the amounts of heavy metals and dioxins are far below the national standard value, so their environmental impacts need not be considered.

Carbon emissions mainly come from the stages of transportation and incineration Bian et al., [34]. Diesel is consumed by trucks during land transportation and their fuel consumption is 0.06 L/(t km). Waste is gathered from urban or rural areas of the city, with a highway transportation distance of 30 km. The density of diesel is 0.85 kg/L. One tonne of the waste will consume 1.53 kg of the diesel Gu, [35]. Emissions of carbon dioxides from diesel combustion during raw material transportation are calculated on the basis of the emission coefficients [36]. The calculation method for $CO_2$ generated by 1 tonne of diesel is shown as Eq. (1).

$$D_{diesel} = NCV \times A \times O \times \frac{44}{12} \tag{1}$$

where $D_{diesel}$ represents the carbon emission of 1 tonne of diesel oil; $NCV$ denotes the net calorific value, which is 42.705 MJ/kg [37]; $A$ is the carbon content per unit calorific value, which is 20.2 t/TJ [38]; and $O$ is the carbon oxidation rate of the fuel, which is 0.98. It is calculated that the amount of $CO_2$ generated by one tonne of diesel is 3.16 tonnes.

CDM method is adopted for accounting carbon dioxides emitted during incineration stage, which can also be applied for identification of baseline scenarios Samal and Tripathy, [39], demonstration of additionality Kaku, [40], calculation of baseline GHGs emissions [41], etc. The $CO_2$ generated during incineration is calculated with Eq. (2).

$$D_{burn} = (1-\omega) \times C \times \frac{44}{12} \tag{2}$$

where $D_{burn}$ represents the carbon emission of 1 tonne of waste; ω denotes the moisture of waste, which is 52.93 %; C is the carbon content of wet-based fossil carbon, which is 15.87 %. By calculation, the amount of $CO_2$ generated by 1 tonne of waste in the incineration process is 0.27 tonnes.

The composition, characteristic, and low calorific value of MSW varied greatly in different time and region. In this study, the average water content of MSW is 60.73 %, and the low calorific value is 5522 kJ/kg. Based on field investigations and a comprehensive literature review, the life cycle inventory (LCI) of the input and output of each process measured by the average annual value method, is shown in Table 1.

### 2.3. Life cycle impact assessment and life cycle cost methodology

In this study, the ReCiPe Midpoint (H) model is used to implement environmental quantitative analysis Goedkoop et al., [42]; [43]. All LCA results can be translated into 18 midpoint environmental impacts based on the ReCiPe2016 model Huijbregts et al., [44]. According to midpoint characteristic factors, a total of 18 midpoint levels are quantified. The 18 midpoint impacts can be converted into three endpoint impact categories, namely human health, ecological damage, and resource depletion, which are quantified by disability adjusted life years (DALY), species disappearance, and additional costs Huijbregts et al., 2017.

The data of each impact category should be normalized to further analyze their contributions; accordingly, information of the LCA results determining the relative importance can be provided [45]. The method is described as Eq. (3).

$$NS_c = \frac{CS_c}{NF_{c,world}} \tag{3}$$

where *c*, *CS*, *NF*, *NS* and *world* were, in 2010, the category, characterization scores, normalization factor, normalization scores, and the global environmental potential of ecosystems caused by emission and extraction, respectively [46].

The LCC method is used to evaluate the economic cost of MSW incineration throughout its entire life cycle, from the cost of collecting raw materials to waste recovery and final disposal Obuobi et al., [47]. The calculation method is expressed as Eq. (4).

$$LCC = \frac{(I_0/N) * (M+F+L+R)}{W} \tag{4}$$

where $I_0$ is initial capital cost, $M$ represents raw material cost, $F$ is fuel cost, $L$ denotes labour cost, $R$ is operation and maintenance cost, $W$ represents the amount of annual treated MSW, $N$ represents the equipment lifetime.

The unit price of each material in this study is obtained from the case study enterprise. The average annual salary of local workers is 84,000 RMB. The unit price of raw materials and fuel are shown in Table 1. It can be seen the LCC of MSW incineration will be higher without the subsidy from the government. The basic information of the MSW power plant can be seen in Table 2.

**Table 1**
Inventory of MSW incineration for power generation.

| Process | Input/Output | Item | Unit | Amount | Price | Data sources |
|---|---|---|---|---|---|---|
| Transportation | Input | Fuel oil | kg | 1.53 | 5.6 RMB/kg | Field investigation |
| | Output | $CO_2$ | tonne | 4.84 E−03 | / | |
| Storage and fermentation | Input | Waste | tonne | 1 | / | |
| Waste incineration | Input | Fuel oil | kg | 4.60E-01 | 5.6 RMB/kg | Field investigation |
| Waste heat recovery | Input | Water | tonne | 7.31E-02 | 5.4 RMB/t | Field investigation |
| Steam power generation | Output | Electricity | kWh | 3.19 E+02 | / | |
| Flue gas purification | Input | Urea | kg | 1.12 | 2.2 RMB/kg | Field investigation |
| | Input | Lime | kg | 12 | 6.5 RMB/kg | Field investigation |
| | Input | Activated carbon | kg | 4.98E-01 | 4.75 RMB/kg | Field investigation |
| | Input | EDTA | kg | 1.83 | 4.8 RMB/kg | Field investigation |
| | Input | Water | tonne | 1.83E-02 | 5.4 RMB/t | Field investigation |
| | Output | $SO_2$ | tonne | 9.92E-05 | / | |
| | Output | $NO_x$ | tonne | 7.50E-04 | / | |
| | Output | CO | tonne | 1.92E-05 | / | |
| | Output | HCl | tonne | 6.75E-05 | / | |
| | Output | $CO_2$ | tonne | 2.74E-01 | / | |
| Sewage disposal | Input | Sulfuric acid | kg | 4.46E-01 | 1 RMB/kg | Field investigation |
| | Input | Sodium hydroxide | kg | 1.92E-02 | 5.8 RMB/kg | Field investigation |
| | Input | Ammonium polyacrylate | kg | 3.58E-02 | 35 RMB/kg | Field investigation |

## 3. Results

### 3.1. Life cycle impact assessment

The environmental impact categories are quantified using the ReCiPe2016 model when not considering the benefits of MSW incineration taking the place of electricity from the local power grid. To distinguish the differences between the impact categories, their characterization results are normalized. As shown in Fig. 2, this power generation mode mainly has environmental impacts related to marine ecotoxicity, human carcinogenic toxicity, freshwater ecotoxicity, and human non-carcinogenic toxicity, accounting for 30.67 %, 22.32 %, 18.12 %, and 6.18 % of the total environmental impact load, respectively.

### 3.2. Life cycle cost

Fig. 3 shows the cost compositions of treating one tonne of MSW. Without considering any revenue of government subsidies, the cost of MSW disposal is 132.26 RMB for each functional unit. It can be seen the initial capital causes the largest economic cost, accounting for 65 %; raw materials and fuels are the second largest cost factor, accounting for 15 %. In terms of labour cost, operation and maintenance, they account for 11 % and 9 % of the total LCC, respectively.

As for the revenue, it mainly comes from three parts, namely, waste disposal fees, revenue from slag sale and on-grid electricity income. The waste disposal fee is 55 RMB/t and the price of slag is 25 RMB/t. The price of electricity generating from MSW is 0.65 RMB/kWh. In this case, each tonne of MSW can bring a revenue of 212.43 RMB including government subsidies, on-grid electricity and slag sale.

### 3.3. Identification of key processes

As shown in Fig. 4, the environmental contributions of each process of the MSW incineration are identified. Marine toxicity is the category with the highest environmental impact (30.67 %). The primary process that contributes to this category is flue gas purification, which contributes 73.07 %; and the process of transportation, sewage treatment and waste incineration accounts for 15.92 %, 6.22 % and 4.78 %, respectively.

In addition to marine toxicity, the other impact categories accounting for more than 5 % of the total environmental impact burden include freshwater ecotoxicity (19.01 %), human carcinogenic toxicity (14.90 %), human non-carcinogenic toxicity (6.71 %), ozone formation (terrestrial ecosystems) (6.07 %), ozone formation (human health) (5.24 %) and global warming (5.07 %). The environmental impacts of freshwater ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity come mainly from the process of flue gas purification, which contributes 74.39 %, 82.82 % and 77.42 % of the whole life cycle, respectively. The transportation stage also makes significant contribution to the above three environmental impact categories, accounting for 14.90 %, 11.95 % and 13.34 %, respectively. The waste incineration process shows the largest environmental contribution, with 95.35 %, 95.20 %, and 91.35 % for the three impact categories, namely ozone formation (human health), ozone formation (terrestrial ecosystems) and global warming respectively. Sewage treatment and waste heat recovery processes account for less than 7 % of the seven major environmental impact categories, whose environmental impact is far less than the other three processes.

Flue gas purification leads to the largest environmental impact during the entire life cycle, which plays a leading role for eight environmental impact categories, such as ionizing radiation (99.27 %), terrestrial ecotoxicity (88.80 %), mineral resource scarcity (97.97 %), and marine eutrophication (73.07 %). In general, flue gas purification (65.61 %), waste incineration (18.50 %), and transportation (11.93 %) contribute more than 96 % of the total environmental impact. They are recognized as the key processes in the whole life cycle.

### 3.4. Determination of key factors

The proportion of key factors of key processes has been recognized, as illustrated in Fig. 5. The environmental impact of urea accounts for 34 % of the total environmental load, which is the denitration substance required in flue gas purification. Activated carbon used to adsorb heavy metals and dioxins accounts for 22 % of the entire environmental impact of flue gas purification. EDTA used to stabilize fly ash accounts for 19 % of the total environmental impact of flue gas purification. Carbon dioxides and nitrogen oxides emitted during waste incineration, as well as diesel fuel used for boiler startup and auxiliary combustion, are the key substances that cause environmental pollution, accounting for 56.45 %, 21.90 % and 19.21 % of the total environmental impact in waste incineration

**Table 2**
Cost information of MSW incineration for power generation.

| Items | Unit | Amount |
| --- | --- | --- |
| Initial capital cost | Million RMB | 400 |
| Raw material & fuel cost | Million RMB | 8.91 |
| Labour cost | Million RMB | 6.22 |
| Operation & maintenance cost | Million RMB | 5.32 |
| MSW treated | Thousand Tonne/a | 255.5 |

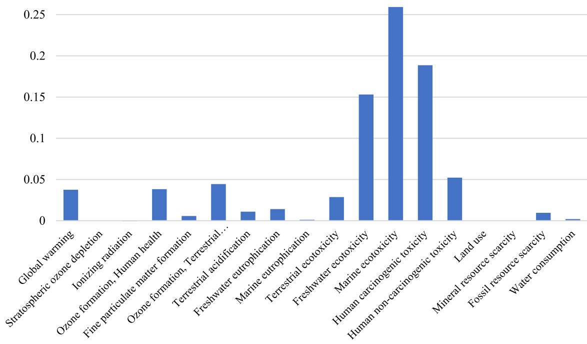


**Fig. 2.** Normalized environmental impact of the MSW incineration without the environmental benefits of on-grid electricity.

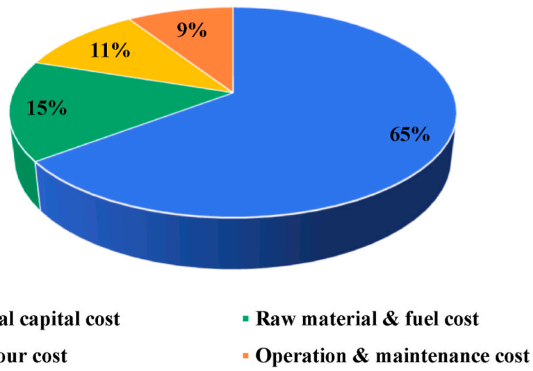


**Fig. 3.** The LCC compositions of MSW incineration power generation.

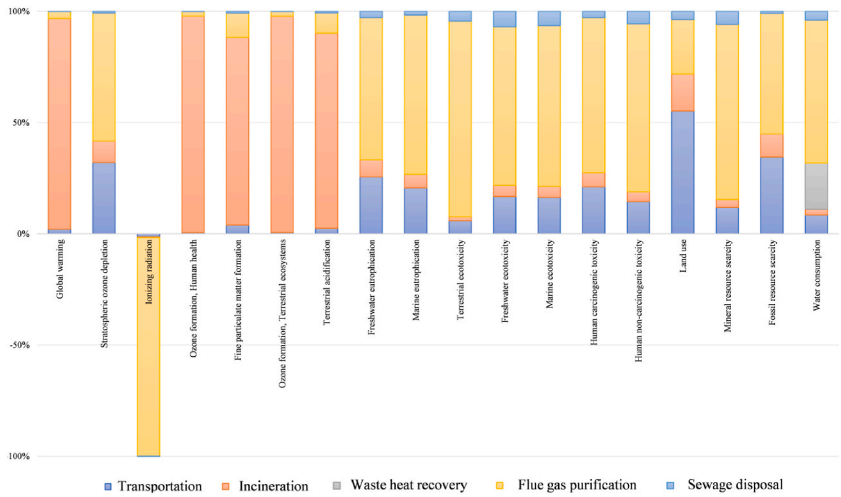


**Fig. 4.** Percentage of environmental impact of key processes.

process, respectively. Diesel fuel has an environmental impact of up to 99 % of the total impact on transportation, thus being the key substance in this process. At the sewage treatment stage, sulfuric acid and sodium hydroxide regulating the pH of sewage tanks, have environmental impact ratios of 66.37 % and 22.77 %, respectively; ammonium polyacrylate used for cleaning filter membrane accounts for 10.85 % of the entire environmental impact of sewage treatment process.

Urea, activated carbon, EDTA and diesel fuel for transportation are the main factors to the overall load, with environmental impact ratios of 27.54 %, 17.95 %, 15.25 % and 11.85 % respectively (see Table 3). They are the key factors that cause the environmental impact across the whole process.

The environmental impact load of urea, activated carbon, EDTA and diesel fuel for transportation accounts for a high proportion in

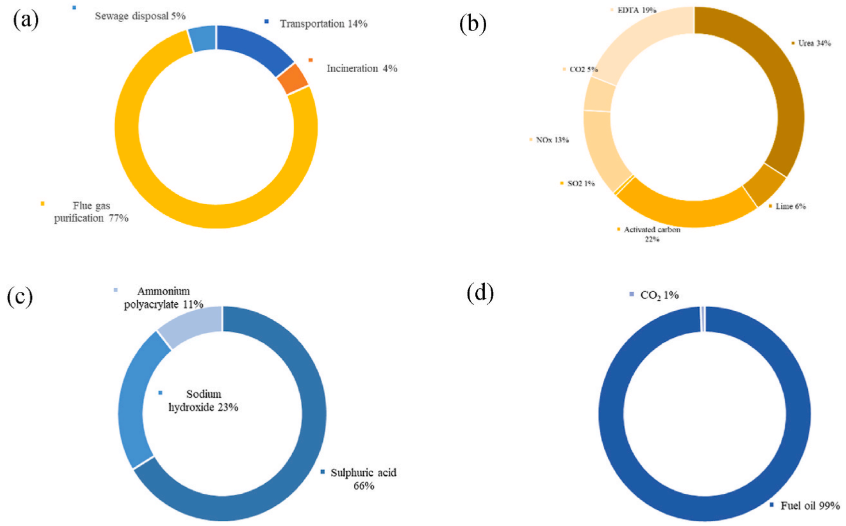


**Fig. 5.** Percentages of key factors in (a) entire life cycle process, (b) flue gas purification process, (c) sewage disposal process, (d) transportation process.

the four key categories, as shown in Table 3. Urea, activated carbon, EDTA and diesel fuel for transportation are the key substances that bring about environmental pollution.

Fig. 6 shows the share of environmental impact of different factors in the seven primary categories, which are disintegrated to investigate the key factors. It can be seen that environmental impacts of urea, activated carbon, EDTA and diesel fuel for transportation are largely focused on marine ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity; the proportion of urea is 41.70 %, 35.88 %, 11.40 % and 42.74 % of the four environmental impact categories respectively; the share of activated carbon is 21.82 %, 20.71 %, 23.32 % and 21.82 % respectively; and that of diesel fuel used for transportation is 15.92 %, 14.90 %, 11.95 % and 13.34 % respectively. The primary environmental impacts of $NO_X$ are concentrated in ozone formation (terrestrial ecosystems) and ozone formation (human health), accounting for 95.03 % and 95.19 % of the two categories, respectively. Meanwhile, lime contributes 4.86 % of the total environmental load. Carbon dioxides generated by the incineration process accounts for 4.06 % of the overall environmental impact load, and its environmental impact is focused on global warming, accounting for 91.24 %.

## 4. Discussion

### *4.1. Differences of environmental impacts in each month*

According to the data lists collected in each month, the change trend of environmental impacts throughout one year can be found, as shown in Fig. 7. For the detailed monthly inventory of MSW incineration, see Supplementary Table 1. In January, March, and December, the boilers are shut down for maintenance, thus the data could not accurately reflect the environmental impact. It can be found that the environmental impact value of the non-heating months is directly lower than that of the heating months, which is due to residential heating. The power plant is located in the suburbs, so the waste mostly comes from surrounding residents. During heating months, loose coal is burnt by residents in non-central heating areas, resulting in a large amount of non-combustible components such as slag from incineration waste, which reduces the calorific value of waste. Low temperatures not only reduce the fermentation efficiency of stacked garbage, but also increases the heat required for moisture evaporation of waste; the calorific value of waste incineration in heating months is significantly lower than that in other months. More fuel is required to maintain the stability of the furnace temperature, to increase the content of $NO_x$ in the furnace; and more urea needs to be used at the flue gas purification stage. The increase of non-combustible substances will promote flue gas dust, which further enhances the amount of activated carbon in the flue gas purification system and the power consumption of the electrostatic precipitator.

**Table 3**
The share of key inputs in primary impact categories of MSW incineration power generation.

| Category | Materials |
|---|---|
| Marine ecotoxicity | Urea 41.70 %+Activated carbon 21.82 %+Fuel oil (transportation) 15.92 % |
| Freshwater ecotoxicity | Urea 35.88 %+Activated carbon 20.71 %+Fuel oil (transportation) 14.90 % |
| Human carcinogenic toxicity | EDTA 43.44 %+Activated carbon 23.32 %+Fuel oil (transportation) 11.95 % |
| Human non-carcinogenic toxicity | Urea 42.74 %+Activated carbon 21.82 %+Fuel oil (transportation) 13.34 % |
| Normalized impact | Urea 27.54 %+Activated carbon 17.95 %+EDTA 15.25 % |

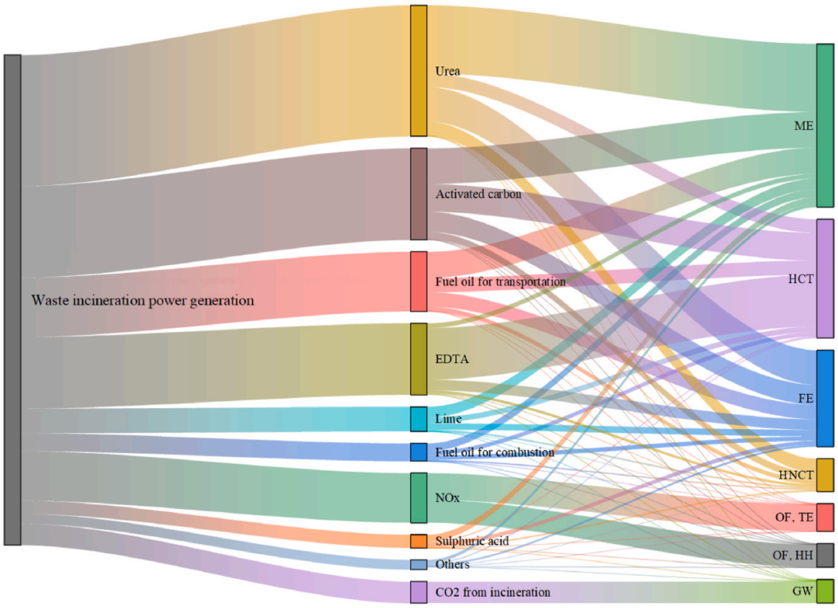


**Fig. 6.** Percentage of key substances in the impact categories. (ME: marine toxicity; HCT: human carcinogenic toxicity; FE: freshwater ecotoxicity; HNCT: human non-carcinogenic toxicity; OF, TE: ozone formation (terrestrial ecosystems); OF, HH: ozone formation (human health); GW: global warming).

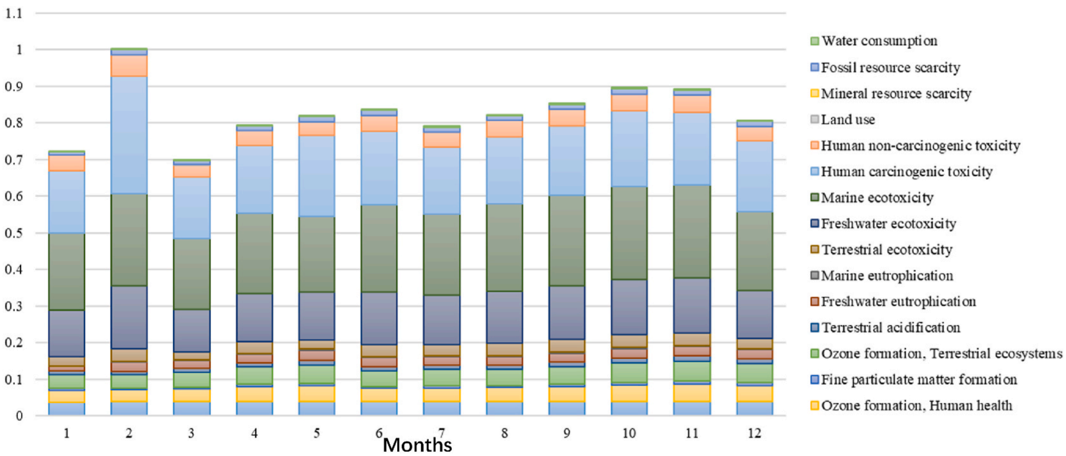


**Fig. 7.** Difference in monthly environmental impact of each MSW incineration process.

Urea, activated carbon, EDTA and diesel fuel for transportation are key factors, accounting for 27.54 %, 17.95 %, 15.25 % and 11.85 % of the overall environmental impact load, respectively. The amount of these four substances determines the entire environmental impact of the technology. Two representative months, November and July, are selected to compare the differences in consumption of key substances. In November, 1.28 kg urea, 0.49 kg activated carbon, 4.82 kg EDTA and 0.96 kg fuel, are required to deal with one tonne of waste; in July, 1.09 kg urea, 0.48 kg activated carbon, 4.77 kg EDTA and 0.04 kg fuel, are required for one tonne of waste, which was a decrease of 14.84 %, 2.04 %, 1.04 % and 95.83 %, respectively compared with November. The overall environmental impact value in July is 0.79, which decrease 11.38 % compared with November.

## 4.2. Environmental benefits of MSW incineration

Reducing the space that waste occupies, and eliminating pathogenic microorganisms are the main benefits of MSW incineration. Secondly, a large amount of heat generated can be converted into electrical energy, decreasing the demand for fossil fuels. Fig. 8 shows the normalized results of the environmental impacts with the consideration of the environmental benefits of MSW incineration replacing the equivalent electricity from a local power company. In this study, 271 kWh of on-grid electricity can be produced by one tonne of waste, so the environmental benefits can be defined as offsetting the environmental impact of the equivalent electricity produced by the local power plant. In terms of marine ecotoxicity, freshwater ecotoxicity and human carcinogenic toxicity, which have the greatest environmental impacts, the normalized values have decreased from 0.26, 0.15 and 0.19 to −5.86, −3.81 and −1.83, respectively; other categories such as human non-carcinogenic toxicity and terrestrial ecotoxicity have also declined so that the total environmental impact load decreased from 0.85 to −12.19. MSW incineration is conducive to promoting environmental quality.

### *4.3. Sensitive analysis and optimization suggestion*

Although the proportion of waste treated by incineration increased from 19.15 % in 2010 to 62.29 % in 2020, the amount of waste disposed by landfill increased from 158.05 million tonnes in 2010 to 120.38 million tonnes in 2017, and then decreased to 77.72 million tonnes in 2020 [3,4]. Landfill is still significant for waste treatment in China, which is due to its mature technology and simple operation and management, as well as the large initial investment and long cost recovery period of waste incineration. According to this study, the LCC of MSW incineration per functional unit is 132.26 RMB, while the income from one tonne of waste is 212.43 RMB when considering the benefits of by-products and government subsidies. The initial capital accounts for 65 % of the LCC. Therefore, to promote the development of waste incineration technology in China, it is recommended to reduce initial investment costs and greatly improve the efficiency of power generation. At national level, it is necessary to change the industrial environment and promote garbage classification; at industrial level, more durable and cheaper industrial materials should be manufactured with higher efficiency and wider applicability; and at individual level, incineration plants need to strengthen management, reduce the duration of incinerators' shutdown and maintenance, and increase the waste sorting process.

As shown in Fig. 9, urea plays a key role in human non-carcinogenic toxicity, marine ecotoxicity, freshwater ecotoxicity, and total load. The 10 % reduction in urea will also result in a decrease of 4.64 %, 4.17 %, 3.66 % and 2.75 % in the four abovementioned categories, respectively. The change in the activated carbon input has the most significant impact on human carcinogenic toxicity, marine ecotoxicity, freshwater ecotoxicity and total environmental impact load. A 10 % reduction in the activated carbon input provides benefits of 3.23 %, 2.18 %, 2.11 % and 1.80 %, respectively. Transportation fuel accounts for a large proportion of the five environmental impacts and the economic cost, especially the latter. When the consumption is reduced by 10 %, the cost will be reduced by 1.57 %. EDTA has the most significant impact on human carcinogenic toxicity and cost. A 10 % reduction in the EDTA input provides benefits of 2.17 % and 1.61 %, respectively. Sensitivity analysis reveals that urea, activated carbon, fuel for transportation and EDTA have a great impact on the environment, and carbon tax, lime, and waste fly ash, requiring a special disposal account for a large proportion of the LCC. In order to reduce environmental pollution and economic cost, the amount or output of key substances should be reduced as a priority.

The GW results of MSW incineration for power generation are compared with other existing studies, which includes the cases of Shanghai City and Hangzhou City in China, Malaysia, and France. It should be noted that carbon emission of each case varies significantly due to the difference of auxiliary fuels. In this study, diesel is consumed as auxiliary fuel, the GW value is 320 kg $CO_2$ eq, which is similar as the results of Han et al. [48] and Beylot and Villeneuve [26]. However, in the case of Hangzhou City and Malaysia, the GW value is 620 kg $CO_2$ eq and 646 kg $CO_2$ eq due to the massive combustion of coal Malakahmad et al., [49]; [50]. Besides, different incineration processes and different MSW compositions can contribute different air pollutant emissions as well. Optimization suggestions are proposed from the three respects: (1) Electric or hybrid vehicles are encouraged to reduce fuel consumption during transportation. (2) Combustion technology needs to be improved to reduce the output of thermal NOX in furnaces and further reduce the use of urea. (3) Waste classification should be promoted to reduce various pollutants generated during combustion.

## 5. Conclusion

An integrated evaluation of environmental impact and economic cost is performed for MSW incineration for power generation from "cradle to grave". The LCA results show that flue gas purification, waste incineration and transportation are the key processes, while urea, activated carbon, fuel for transportation and $NO_X$ emissions are key factors. The LCC is 132.26 RMB/t of waste, of which initial capital cost has the most cost burden and raw materials and fuels are the second largest cost factor. Sensitivity analysis reveals that urea and fuel for transportation are the primary factors to be optimized as a priority. Environmental impacts in non-heating months are evidently lower than in heating months because of residents' daily heating requirements.

The total normalized environmental impact value of waste incineration is 0.85 without environmental benefits from power generation; after considering the environmental benefits, the value decreases to −12.19. This shows that MSW incineration is effective in promoting over all environmental quality. Based on the findings from this study, suggestions are made for promoting power generation efficiency, decreasing $NO_x$ emissions, and controlling input materials required for pollutants disposal, all of which provide valuable references for those responsible for optimizing MSW incineration technology and processes. However, the current study has limitations. The levelized cost of MSW incineration power generation is not calculated due to data availability, which will be addressed in future research.

## CRediT authorship contribution statement

**Hongtao Sun:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Wen Li:** Writing – review & editing, Visualization. **Jing Wang:** Writing – review & editing, Visualization. **Xiaopeng Qin:** Writing – review & editing, Visualization. **Lijian Jin:** Investigation. **Fei Tian:** Investigation. **Tongsuo Yang:** Investigation. **Feng Zhang:**

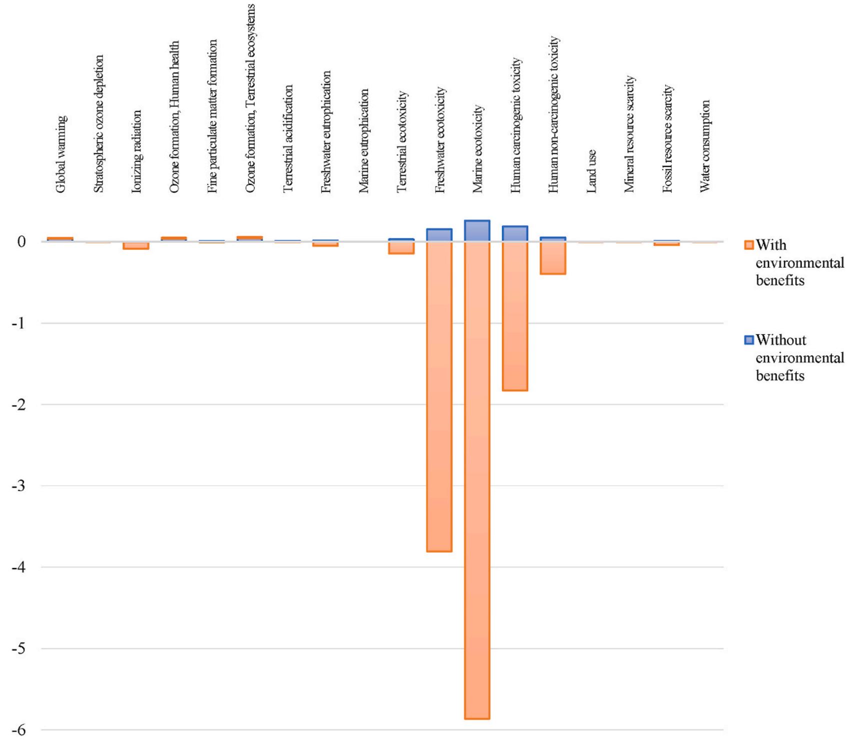


**Fig. 8.** Comparison of environmental impact with or without environmental benefits from power generation.

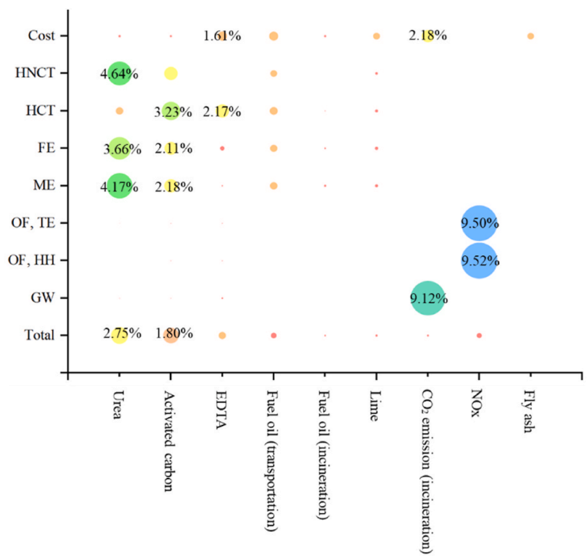


**Fig. 9.** Results of sensitivity analysis in the impact categories of a 10 % change in key factors.

Visualization, Data curation. **Leping Chen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Yifei Shi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Xueliang Yuan:** Writing – review & editing, Methodology, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declared that they have no conflicts of interest to this work.

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## Appendix A. Supplementary data

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## References

[1] World Bank, Solid aste Management, 2022. https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management. (Accessed 14 February 2023).
[2] S. Kaza, L. Yao, P. Bhada-Tata, F. Van Woerden, What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050, World Bank Publications, 2018.
[3] NBS (National Bureau of Statistic), China Statistical Yearbook, National Bureau of Statistics of China, 2011. http://www.stats.gov.cn/tjsj/ndsj/2011/indexch.htm. (Accessed 14 February 2023).
[4] NBS (National Bureau of Statistic), China Statistical Yearbook, National Bureau of Statistics of China, 2021. http://www.stats.gov.cn/tjsj/ndsj/2021/indexch.htm. (Accessed 14 February 2023).
[5] X. Liang, T.A. Kurniawan, H.H. Goh, D. Zhang, W. Dai, H. Liu, K.C. Goh, M.H.D. Othman, Conversion of landfilled waste-to-electricity (WTE) for energy efficiency improvement in Shenzhen (China): a strategy to contribute to resource recovery of unused methane for generating renewable energy on-site, J. Clean. Prod. 369 (2022) 133078.
[6] A. Damgaard, C. Riber, T. Fruergaard, T. Hulgaard, T.H. Christensen, Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration, Waste Manag. 30 (7) (2010) 1244–1250.
[7] R. Zhao, L. Sun, X. Zou, M. Fujii, L. Dong, Y. Dou, Y. Geng, F. Wang, Towards a Zero Waste city- an analysis from the perspective of energy recovery and landfill reduction in Beijing, Energy 223 (2021) 120055.
[8] L.F. Rodrigues, I.F.S.d. Santos, T.I.S.d. Santos, R.M. Barros, G.L. Tiago Filho, Energy and economic evaluation of MSW incineration and gasification in Brazil, Renew. Energy 188 (2022) 933–944.
[9] Ç. Iris, J.S.L. Lam, A review of energy efficiency in ports: operational strategies, technologies and energy management systems, Renew. Sustain. Energy Rev. 112 (2019) 170–182.
[10] B. Zhao, R. Xu, F. Ma, Y. Li, L. Wang, Effects of biochars derived from chicken manure and rape straw on speciation and phytoavailability of Cd to maize in artificially contaminated loess soil, J. Environ. Manag. 184 (15) (2016) 569–574. Pt3.
[11] S.A.S. Abd Kadir, C.-Y. Yin, M. Rosli Sulaiman, X. Chen, M. El-Harbawi, Incineration of municipal solid waste in Malaysia: salient issues, policies and waste-to-energy initiatives, Renew. Sustain. Energy Rev. 24 (2013) 181–186.
[12] N.D. Couto, V.B. Silva, A. Rouboa, Assessment on steam gasification of municipal solid waste against biomass substrates, Energy Convers. Manag. 124 (2016) 92–103.
[13] S. Wang, Z. Han, J. Wang, X. He, Z. Zhou, X. Hu, Environmental risk assessment and factors influencing heavy metal concentrations in the soil of municipal solid waste landfills, Waste Manag. 139 (2022) 330–340.
[14] R. Bian, J. Chen, T. Zhang, C. Gao, Y. Niu, Y. Sun, M. Zhan, F. Zhao, G. Zhang, Influence of the classification of municipal solid wastes on the reduction of greenhouse gas emissions: a case study of Qingdao City, China, J. Clean. Prod. 376 (2022) 134275.
[15] M. Allsopp, P. Costner, P. Johnston, Incineration and human health. State of knowledge of the impacts of waste incinerators on human health, Environ. Sci. Pollut. Res. Int. 8 (2) (2001) 141–145.
[16] F. Zuliani, A. Manzardo, A. Marson, A. Fedele, A life cycle assessment approach for nitrogen footprint quantification: the reactive nitrogen indicator, Sci. Total Environ. 882 (2023) 163578.
[17] ISO (International Organization for Standardization), ISO 14040:2006/AMD 1:2020: environmental management - life cycle assessment - principles and framework - amendment 1. https://www.iso.org/standard/76121.html, 2020. (Accessed 10 October 2023).
[18] Y. Li, X. Yuan, Y. Tang, Q. Wang, Q. Ma, R. Mu, J. Kellett, J. Zuo, Integrated assessment of the environmental and economic effects of "coal-to-gas conversion" project in rural areas of northern China, Environ. Sci. Pollut. Res. 27 (2020) 14503–14514.
[19] M. Tao, D. Lu, Y. Shi, C. Wu, Utilization and life cycle assessment of low activity solid waste as cementitious materials: a case study of titanium slag and granulated blast furnace slag, Sci. Total Environ. 849 (2022) 157797.
[20] T.H. Christensen, A. Damgaard, J. Levis, Y. Zhao, A. Bjorklund, U. Arena, M.A. Barlaz, V. Starostina, A. Boldrin, T.F. Astrup, V. Bisinella, Application of LCA modelling in integrated waste management, Waste Manag. 118 (2020) 313–322.
[21] I.R. Istrate, J.L. Galvez-Martos, J. Dufour, The impact of incineration phase-out on municipal solid waste landfilling and life cycle environmental performance: case study of Madrid, Spain, Sci. Total Environ. 755 (Pt1) (2021) 142537.
[22] K.A. Clavier, J.M. Paris, C.C. Ferraro, T.G. Townsend, Opportunities and challenges associated with using municipal waste incineration ash as a raw ingredient in cement production - a review, Resour. Conserv. Recycl. 160 (2020) 104888.
[23] M. Liikanen, J. Havukainen, M. Hupponen, M. Horttanainen, Influence of different factors in the life cycle assessment of mixed municipal solid waste management systems – a comparison of case studies in Finland and China, J. Clean. Prod. 154 (2017) 389–400.
[24] Y. Guo, T. Glad, Z. Zhong, R. He, J. Tian, L. Chen, Environmental life-cycle assessment of municipal solid waste incineration stocks in Chinese industrial parks, Resour. Conserv. Recycl. 139 (2018) 387–395.
[25] S. Chang, Life Cycle Assessment of the High Parameter Rubbish Incineration Power System, Tsinghua University, Dissertation, 2014.
[26] A. Beylot, J. Villeneuve, Environmental impacts of residual municipal solid waste incineration: a comparison of 110 French incinerators using a life cycle approach, Waste Manag. 33 (12) (2013) 2781–2788.
[27] H. Zhen, K. Yuan, Y. Qiao, J. Li, M.A. Waqas, G. Tian, T. Dorca-Preda, M.T. Knudsen, Eco-compensation quantification of sustainable food waste management alternatives based on economic and environmental life cycle cost-benefit assessment, J. Clean. Prod. 382 (2023) 135289.
[28] V. Martinez-Sanchez, M.A. Kromann, T.F. Astrup, Life cycle costing of waste management systems: overview, calculation principles and case studies, Waste Manag. 36 (2015) 343–355.
[29] V. Milić, K. Ekelöw, B. Moshfegh, On the performance of LCC optimization software OPERA-MILP by comparison with building energy simulation software IDA ICE, Build. Environ. 128 (2018) 305–319.
[30] X. Li, R. Bai, J. McKechnie, Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes, J. Clean. Prod. 127 (2016) 451–460.

[31] E. Lee, D. Oliveira, L. Oliveira, E. Jimenez, Y. Kim, M. Wang, S.J. Ergas, Q. Zhang, Comparative environmental and economic life cycle assessment of high solids anaerobic co-digestion for biosolids and organic waste management, Water Res. 171 (2020) 115443.
[32] M. Mohsenizadeh, M.K. Tural, E. Kentel, Municipal solid waste management with cost minimization and emission control objectives: a case study of Ankara, Sustain. Cities Soc. 52 (2020) 101807.
[34] R. Bian, T. Zhang, F. Zhao, J. Chen, C. Liang, W. Li, Y. Sun, X. Chai, X. Fang, L. Yuan, Greenhouse gas emissions from waste sectors in China during 2006–2019: implications for carbon mitigation, Process Saf. Environ. Protect. 161 (2022) 488–497.
[35] L. Gu, Studies on the Environmental Impact of the Building Industry in China Based on the Life Cycle Assessment, Tsinghua University, 2009.
[36] K. He, Technical manual for the preparation of urban air pollutants emission inventory. https://www.mayiwenku.com/p-13074793.html/, 2015. (Accessed 14 February 2023).
[37] SAC (Standardization Administration of China), General rules for calculation of the comprehensive energy consumption. https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=53D1440B68E6D50B8BA0CCAB619B6B3E, 2020. (Accessed 14 February 2023).
[38] NDRC (National Development and Reform Committee), Guidelines for the Compilation of Provincial Greenhouse Gas Inventories, 2011. https://wenku.baidu.com/view/8c3abc0bff0a79563c1ec5da50e2524de418d0f8.html. (Accessed 14 February 2023).
[39] R.K. Samal, M. Tripathy, Cost and emission additionality of wind energy in power systems, Sustain. Energy Grids 17 (2019) 100179.
[40] K. Kaku, Global warming and climate change of asian countries including Japanese domestic greenhouse gas (GHG) reduction in the filed of poultry and swine industries, Procedia Eng. 8 (2011) 511–514.
[41] H. Wang, X.e. Wang, J. Song, S. Wang, X. Liu, Uncovering regional energy and environmental benefits of urban waste utilization: a physical input-output analysis for a city case, J. Clean. Prod. 189 (2018) 922–932.
[42] M. Goedkoop, R. Heijungs, M.A.J. Huijbregts, A. De Schryver, J. Struijs, R. Van Zelm, ReCiPe2008: A life cycle impact assessment method whichcomprises harmonised category indicators at the midpoint and the endpoint level 1 (2009) 1–126. https://web.universiteitleiden.nl/cml/ssp/publications/recipe_characterisation.pdf. (Accessed 14 February 2023).
[43] M. Liu, Y. Li, X. Yuan, Y. Xu, L. Qiao, Q. Wang, Q. Ma, Life cycle environmental impact assessment of sulfur-based compound fertilizers: a case study in China, ACS Sustain. Chem. Eng. 10 (7) (2022) 2308–2317.
[44] M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, R. van Zelm, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, Int. J. Life Cycle Assess. 22 (2) (2017) 138–147.
[45] R. Zhang, X. Ma, X. Shen, Y. Zhai, T. Zhang, C. Ji, J. Hong, Life cycle assessment of electrolytic manganese metal production, J. Clean. Prod. 253 (2020) 119951.
[46] RIVM (National Institute for Public Health and the Environment), LCIA:the ReCiPe model. https://www.rivm.nl/en/life-cycle-assessment-lca/recipe, 2020. (Accessed 14 February 2023).
[47] B. Obuobi, G. Adu-Gyamfi, M. Adjei, E. Nketiah, Technologies potential and economic viability analysis of deriving electricity from Municipal Solid Waste in Kumasi, Ghana, Energy Sustain. Dev. 68 (2022) 318–331.
[48] X. Han, H. Chang, C. Wang, J. Tai, S. Karellas, J. Yan, L. Song, Z. Bi, Tracking the life-cycle greenhouse gas emissions of municipal solid waste incineration power plant: a case study in Shanghai, J. Clean. Prod. 398 (2023) 136635.
[49] A. Malakahmad, M.S. Abualqumboz, S.R.M. Kutty, T.J. Abunama, Assessment of carbon footprint emissions and environmental concerns of solid waste treatment and disposal techniques: case study of Malaysia, Waste Manage. (Tucson, Ariz.) 70 (2017) 282–292.
[50] Z. Zhou, Y. Tang, J. Dong, Y. Chi, M. Ni, N. Li, Y. Zhang, Environmental performance evolution of municipal solid waste management by life cycle assessment in Hangzhou, China, J. Environ. Manag. 227 (2018) 23–33.
[51] W. Chaya, S. Gheewala, Life cycle assessment of MSW-to-energy schemes in Thailand, J. Clean. Prod. 15 (2007) 1463–1468.
[52] Ecoinvent Database. https://v31.ecoquery.ecoinvent.org/Details/UPR/c367e1b8-fee8-4bba-8fb7-e1cf7cabc3c6/8b738ea0-f89e-4627-8679-433616064e82. (Accessed 14 February 2023).