Report

Bridging the Energy Benefit and POPs Emission Risk from Waste Incineration

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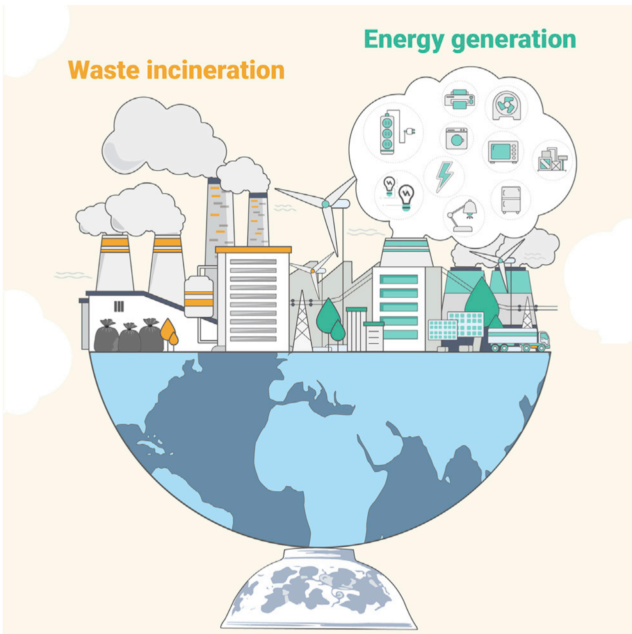
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Emission of trace organic pollutants from solid waste incineration in China was comprehensively evaluated
- The energy benefit-to-emission index for organic pollutants ($EBEI_{OP}$) for evaluation of solid waste management on a local or regional scale was proposed
- Production of medical and industrial waste was smaller than that of municipal waste but yielded comparable or even higher emission of dioxins
- Higher $EBEI_{OP}$ values were associated with economic factors, while lower values were influenced by emissions from incineration of medical and industrial waste
- An $EBEI_{OP}$ value of ≥ 60 can serve as a reference for "profitable" solid waste management, assisting decision making during energy benefit and environmental risk assessment

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Incineration has been the globally controversial and concerned method of solid waste disposal. Energy recovery and volume reduction are the benefits from waste incineration, but risk due to release of persistent organic pollutants is the major public concern in the world. In this study, the emission of organic pollutants including dioxins and polychlorinated naphthalenes from solid waste incineration in China was comprehensively evaluated, and a relationship between energy benefit and pollutant emission was firstly established. The results show that production of medical and industrial waste was smaller than that of municipal waste but yielded comparable or even higher emission of dioxins. The energy benefit-to-emission index for organic pollutants ($EBEI_{OP}$) for evaluation of solid waste management on a local or regional scale was proposed. Significant correlations between net energy benefit and pollutant emission for provinces with higher $EBEI_{OP}$ values were found. Furthermore, higher $EBEI_{OP}$ values were associated with economic factors while lower values were influenced by emission from incineration of medical and industrial waste. We suggest that an $EBEI_{OP}$ value of ≥ 60 can serve as a reference for "profitable" solid waste management, assisting decision making during energy benefit and environmental risk assessment.

KEYWORDS: solid waste incineration; energy benefit; persistent organic pollutant emission

INTRODUCTION

Large quantities of solid waste are produced each year worldwide, causing worldwide concern to its green and sustainable management, especially in developing countries. From a global point of view, municipal solid waste generation levels stand at approximately 1.3 billion tons per year in 2018 and is anticipated to increase to around 2.2 billion tons per year by 2025,[1] indicating a global challenge of green and sustainable development. East Asia and the Pacific region produce approximately 270 million tons of waste per year, and China contributes approximately 70% of the total solid waste generated in the region.[1] This infers that China was the second largest generator of solid waste in the year 2016, behind only the United States.[2] Therefore, a risk-and-benefit assessment of solid waste management in China, as a typical developing country generating large quantities of solid waste, is of great significance for guiding global solid waste management.

Incineration and landfill are the major pathways of solid waste disposal. Waste incineration is widely used to recover the energy content of solid waste.[3–5] During the process of waste incineration, solid wastes are combusted and converted to residues, and gaseous products and energy is simultaneously generated. Incineration reduces the amount and weight of solid waste by up to 90% and 70%, respectively.[6–8] Approximately 20% of the municipal solid waste is incinerated annually in Europe.[9] Some countries such as Switzerland, Japan, and Denmark incinerate more than 65% of the municipal solid wastes produced. Others such as the United Kingdom and the United States, who used to disregard waste incineration in decisions on waste management systems, have also changed their approach in recent years with a number of incineration plants under construction or being planned.[10] Thus, waste disposal by adopting incineration techniques has been increasing worldwide. In the past decades, incineration has become an increasingly important component of solid waste management in China. According to the Chinese national "13th Five-Year Plan" (2016–2020) of the Facilities Construction Plan on Harmless Disposal of National Municipal Waste,[11] by the end of 2020 municipal solid waste incineration facilities might account for more than 50% of the total capacity and should exceed 60% in eastern China. This governmental emphasis on disposal of solid waste by incineration indicates the need to evaluate the energy benefit and environmental risk of waste incineration in China.

Incineration of solid waste is a controversial technology, the main concern of which is the emission of toxic pollutants, but the energy recovery aspect also carries large importance.[4,5,10] Incineration generates ash and releases particulate and gaseous pollutants such as heavy metals, CO_2, N_2O, and persistent organic pollutants (POPs).[1] Waste incineration is considered as an important source of toxic POPs[12–16] such as the notorious polychlorinated dibenzo-*p*-dioxins, dibenzofurans, and the emerging polychlorinated naphthalenes (PCNs). These pollutants are bio-accumulative in biota and in the human body.[17,18] The Stockholm Convention on Persistent Organic Pollutants[19] and the European Protocol to the regional UNECE Convention on Long-Range Transboundary Air Pollution on Persistent Organic Pollutants[20] both call for efforts to eliminate or reduce the emission of these pollutants. Emission control during waste incineration activities has gained much attention, but the energy benefit of these processes should also be considered. However, to our knowledge, the relationships and balance between emission of these POPs and energy benefits have not been quantitatively assessed.

Energy recovery is the major point besides material recovery and reduction in waste volume. In some European countries, the main targets of waste incineration are the recovery of energy and materials, followed by the disposal of residues. If the energy recovery efficiency of incineration is higher than a designated threshold, it can be considered as a recovery operation rather than a disposal operation.[3] This indicates the importance of energy recovery in waste management. Life-cycle assessment (LCA) has been widely used for the evaluation of solid waste management systems and technology.[10,21–27] LCA can evaluate different patterns of waste management technologies for case studies taking environmental and economic impacts into consideration. It is a good decision-making tool but with little emphasis on the relationships between environmental impact and energy benefit. Moreover, for the environmental impact assessment, it usually focuses on traditional air pollutants while emissions of toxic POPs are rarely included. Therefore, studies on relationships between energy recovery and emission of POPs are required. The major contributors to municipal solid waste generation are the United States, China, Brazil, Japan, India, Germany, Russia, and the United Kingdom.[2] Among these countries, the United States has the largest electricity generation capacity, followed by Germany and Japan.[2] To the best of our knowledge, the capacity for generating electricity from solid waste

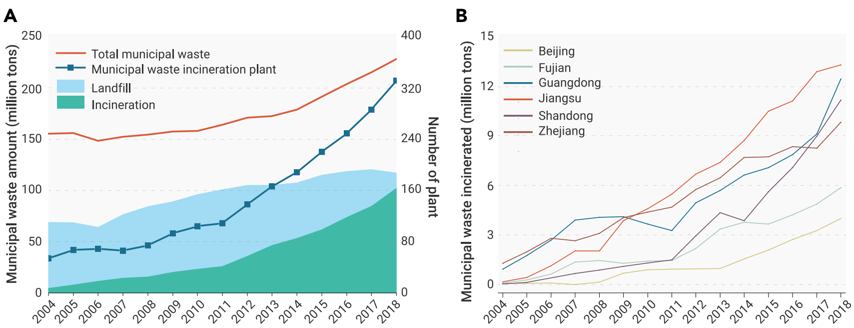

Figure 1. Status of Municipal Waste Production and Disposal (A) Time trend of municipal waste production, number of municipal waste incineration plants, and amount of landfilled and incinerated waste in China between 2004 and 2018.

(B) Time trend of municipal waste incinerated by province/municipality.

incineration in China has never been reported on the national level; such data could guide sound management and disposal of solid waste worldwide.

In this study, the status of solid waste incineration in China was comprehensively analyzed. Solid wastes were classified as municipal, medical, and industrial. Emissions of two toxic organic pollutants from these three categories were evaluated. Dioxins as the notorious POPs, and PCNs as the emerging POPs, listed in the Stockholm Convention were selected to be representative toxic compounds with the aim of evaluating their emissions resulting from waste incineration. The energy benefit and environmental risk of waste incineration in China were assessed, and an index of energy benefit-to-emission of organic pollutants for use in evaluating solid waste management was proposed. This study may be helpful in comprehensively assessing organic contamination from solid waste incineration and in characterizing the relationship between energy benefit and environmental risk, to benefit emission control and energy recovery.

RESULTS AND DISCUSSION

Solid Waste Generation and Disposal in China

Large quantities of solid waste are produced in China each year, and their disposal poses a challenge. Previous studies on solid waste management were mainly focused on municipal waste, which accounts for the largest proportion of the total amount of solid wastes, while a few investigated medical and industrial wastes. To comprehensively evaluate the state of solid waste production and disposal in China, we classified solid wastes into municipal, medical, and diverse industrial solid waste. Industrial solid waste includes waste from industrial activities such as hazardous chemical production, printing and dyeing, waste metal recycling, and electronics.

Figure 1 shows the time trend of municipal waste production, number of municipal waste incineration plants, and amount of landfilled and incinerated waste in China between 2004 and 2018 and the time trend of municipal waste incinerated by province/municipality. The total amount of municipal waste produced annually in China increased from 155 million to 228 million tons and the number of waste incineration plants increased from 54 to 331 during the study period. Municipal waste production is expected to increase in the future with population and economic growth. The municipal waste produced was mainly disposed of by incineration (102 million tons in 2018) or landfill (117 million tons in 2018). However, the average annual increase in landfilled waste was 4.4% and 28.3% in incinerated waste during the study period, demonstrating a growing role for waste incineration. Figure S1 compares the amount of incinerated and landfilled municipal solid wastes by province/municipality in 2018; in Jiangsu, Zhejiang, Shandong, and Fujian, more waste was disposed of by incineration than landfill. Furthermore, these four provinces and Guangdong exhibited a rapid growth in municipal waste incineration between 2004 and 2018. Other provinces/municipalities also exhibited an increasing trend in incinerating waste, indicating the need for characterizing emissions from waste incineration.

Emission of Persistent Organic Pollutants

Figure 2 shows the annual dioxin emission from solid waste incineration and annual solid waste yield and disposal capacity of incinerators in China in 2014 and dioxin emissions by province/municipality. Figure S2 shows PCN emissions from waste incineration in 2014. Dioxin and PCN emissions are presented as toxic equivalent quantity (TEQ), calculated from toxic equivalency factors (WHO-2005 TEFs). The World Health Organization (WHO) proposed the concept of TEFs to compare the toxicities of individual dioxin and dioxin-like compounds relative to the most toxic 2,3,7,8-tetrachlorodibenzo-*p*-dioxin, which is used as a reference and given a TEF of 1.[28] The WHO recommends that the upper range of the tolerable daily intake (TDI) of 4 pg TEQ/kg body weight should be considered as the maximal tolerable intake on a provisional basis and that the ultimate goal is to reduce human intake levels to below 1 pg TEQ/kg body weight per day.[29]

Total dioxin emission from solid waste incineration in 2014 was 592 g TEQ, and municipal, medical, and industrial waste incineration yielded 217 g TEQ (36.6%), 103 g TEQ (17.5%), and 272 g TEQ (45.9%), respectively. Of note, it was found that annual medical waste disposal in 2014 contributed only 1.6% to the total yield, but that its dioxin emission accounted for 17.5% of the total dioxin emissions from solid waste incineration. For industrial waste, the disposal accounted for 13.3% but dioxin emission accounted for 45.9%. In other words, dioxin emission from incineration was 12.2 g TEQ (municipal waste), 302.5 g TEQ (medical waste), and 97.8 g TEQ (industrial waste) per million tons. This indicates that while production of medical and industrial wastes is smaller than that of municipal waste, dioxin emissions from incinerating these wastes are considerable and require control.

Dioxin and PCN emissions correlated with waste production by province/municipality. These emissions were highest in Zhejiang, Guangdong, and Jiangsu (Figures 2 and S2), which also accounted for the highest production of municipal waste (Figure S1). Dioxin emission from industrial waste incineration in Zhejiang was 105.2 g TEQ, accounting for 80% of the total dioxin emissions from solid waste incineration in the province. Zhejiang is a major region of electronic waste recycling in China,[30] and this activity may explain the high dioxin and PCN emissions. Electronic waste usually contains many valuable metals, especially copper and other precious metals from printed circuit boards and computer wiring, while also including chlorinated organic materials such as polyvinyl chloride.[31] Chlorinated materials are important dioxin precursors, and copper could act as a catalyst for the formation of dioxins, making electronic waste incineration an important contributor to dioxin emissions.[32] Regarding PCN emission, technical PCNs and polychlorinated biphenyls (PCBs) are extensively used as insulating oils in electrical components (cable, transformers, and capacitors), engine oil additives, and electroplating masking compounds.[33] Technical PCBs are also reported to contain varying amounts of PCNs as impurities.[34] Therefore, PCNs can be emitted or formed during the burning processes of wastes possibly including electronic waste recycling.[35] In summary, the high emission of dioxin and PCNs in the aforementioned provinces could be attributed to the following reasons: (1) their relatively higher solid waste generation and (2) the contribution of emissions possibly from electronic waste recycling processes.

Assessment of Energy Benefit and Environmental Risk

Figure 3A shows the electricity consumption in the waste disposal industry and annual electricity generation from municipal waste incineration in China between 2004 and 2017. Annual electricity generation increased concurrently with waste production and waste incineration, as did energy consumption.

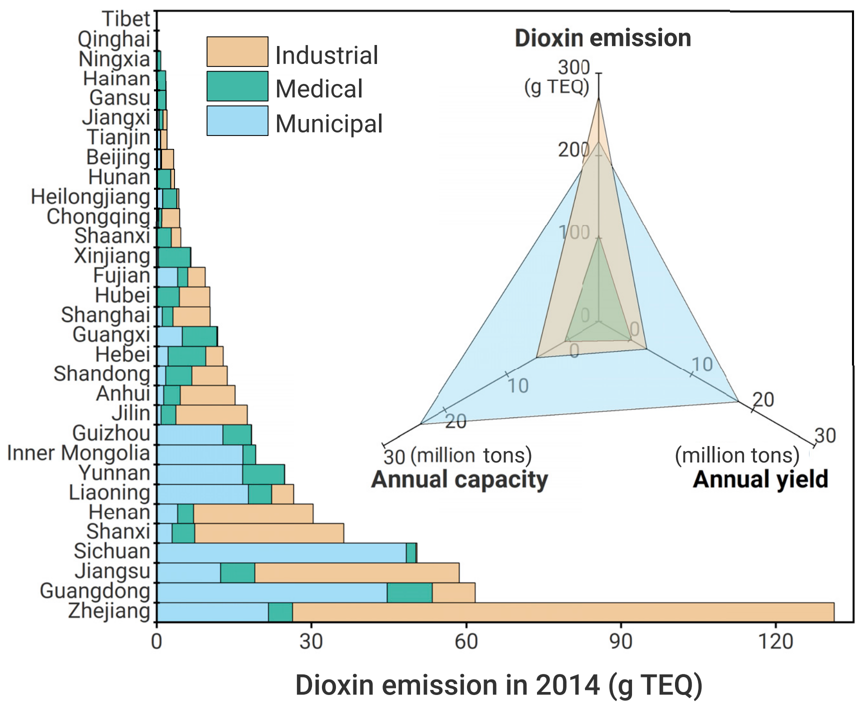

Figure 2. Annual Dioxin Emission from Solid Waste Incineration and Annual Solid Waste Yield and Disposal Capacity of Incinerators in China in 2014 and Dioxin Emissions by Province/Municipality

Figure 3B shows provincial electricity generation from waste incineration and total emission of dioxins and PCNs in 2014. Provinces with relatively higher emissions, such as Zhejiang, Jiangsu, and Guangdong, also generated more electricity from waste incineration. To gain a further understanding of the relationship between electricity generation and emission of organic pollutants, we plotted the electricity recovered against dioxin and PCN emissions (Figure S3) and found a good fit: R^2 for dioxin and PCN is 0.604 and 0.729, respectively.

To analyze the relationship between energy benefit and emission of organic pollutants, we estimated the net energy benefit from waste incineration activities using $EBEI_{OP}$. Figure 4A shows the $EBEI_{OP}$ values calculated for each province/municipality. We divided the provinces/municipalities by the index values: high, >30; medium, 10–30; low, <10. Figures 4B–4D show the relationship between net energy benefit and emissions by index value; the correlation increased as index values increased.

Boruta was used to identify possible factors influencing the $EBEI_{OP}$ (Figure 5). In provinces/municipalities with high index values, three attributes were confirmed as potentially important: gross domestic product (GDP), heating value, and number of incineration plants. In provinces/municipalities with low index values, industrial waste and medical waste were identified as potentially important attributes. These findings indicate that higher $EBEI_{OP}$ is associated with economic factors, while lower $EBEI_{OP}$ is more affected by the contribution of emissions from medical and industrial waste incineration, underscoring the need for better management of medical and industrial waste.

A higher $EBEI_{OP}$ value indicates more energy benefit and lower emissions of toxic organic pollutants. $EBEI_{OP}$ value may therefore be a useful metric for quantitatively evaluating the relationship between energy benefit and environmental risk of solid waste incineration. According to the present energy benefit-to-emission situation in China, we suggest using an $EBEI_{OP}$ value of ≥ 60 as a reference for "profitable" solid waste management. Under this standard, 25% of the provinces/municipalities in China could be considered as "profitable" managers of solid waste. Overall, our study indicates that lower emissions of trace organic pollutants with relatively higher energy benefits from solid waste incineration are feasible.

Perspectives on Emission Control and Energy Recovery

During the past decades, production of municipal waste has increased greatly and waste incineration has become an important method for solid waste disposal. Although production of medical and industrial waste is relatively smaller than that of municipal waste, emission of toxic pollutants from the incineration of these wastes is comparable or even higher. This indicates the need for policies, infrastructure, and technologies for emission control, especially in the industrial sector. Moreover, production of solid waste and emission of toxic organic pollutants in eastern China may increase trans-boundary pollution. The Chinese government has recently introduced and implemented stricter garbage classification policies, which may increase the heating values and reduce the total amount of municipal solid wastes. Of note, our findings suggest that better management of medical and industrial waste may increase the $EBEI_{OP}$.

Here, we suggested preliminary measures for a possibly better solid waste management: (1) for municipal solid wastes, implementing strict garbage classification policies is possibly the key point, but it still needs people to reuse, reduce, and recycle subjectively in the long term to control solid waste production; (2) for medical and industrial solid wastes, besides the systematic and comprehensive transportation and disposal policies to reduce their risk to the environment, technologies and equipment for simultaneous reduction in emission of dioxin-like compounds may be further developed and applied.

MATERIALS AND METHODS

Data Sources and Calculations

The following statistical data were used in this study: (1) generation of municipal solid waste in 31 provinces/municipalities in China between 2004 and 2018; (2) the amount of municipal waste disposed by incineration in 31 provinces/municipalities during that time; (3) the number of waste incineration plants constructed in China during that time; (4) annual energy consumption in the waste disposal industry during that time; (5) provincial investments in solid waste management; (6) gross regional products and per-capita gross regional products for 31 provinces/municipalities in 2014; and (7) resident consumption level for 31 provinces/municipalities in 2017. All information was obtained from the National Bureau of Statistics of China.[36] The calculation method of dioxins and PCN emissions were described in detail in our previous studies.[37,38] In brief, data from case studies of dioxins and PCNs from waste incinerations were used to compile a list of emission factors (μg/t), which were obtained by dividing the production rate (t/

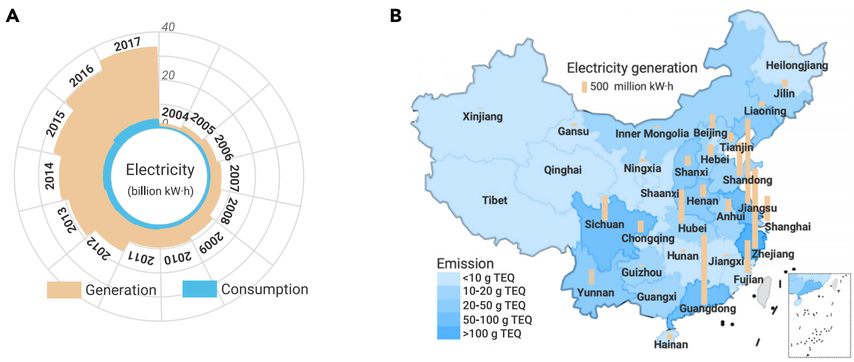

Figure 3. Electricity Generation and Dioxin Emissions (A) Electricity consumption in the waste disposal industry and electricity generated through municipal waste incineration in China between 2004 and 2017.
(B) Electricity generated by municipal waste incineration (yellow) and total emission of dioxins and polychlorinated naphthalenes (blue) in 2014 by province/municipality.

h) by the arithmetic product of the stack gas flow (m^3/h) and emission concentrations ($\mu g/m^3$), and using the average value. The emissions were then calculated by multiplying the amount of waste incinerated (million tons) by the known average emission factor.

Estimation of Energy Benefit

The annual electricity generation from solid waste incineration was estimated to assess the relationship between energy benefit and emission of organic pollutants. Energy generation from municipal waste incineration has been reported to be influenced by the heating value of solid waste and to differ between provinces/municipalities in China.[39,40] Therefore, prior to calculating how much electricity was generated by waste incineration, the heating values of waste in the studied areas were estimated. Data for several provinces were found in the literature, and some studies indicated that heating values of solid waste may be related to the economic development status of the locale.[40] In the present study, a good relationship between resident consumption level and heating value from reported heating values for ten provinces (Figure 6) was found. The correlation (R^2) was calculated as 0.603 ($p < 0.01$) by SPSS (IBM, Armonk, NY, USA). This model was then used to predict the heating values in other provinces/municipalities (Table 1).

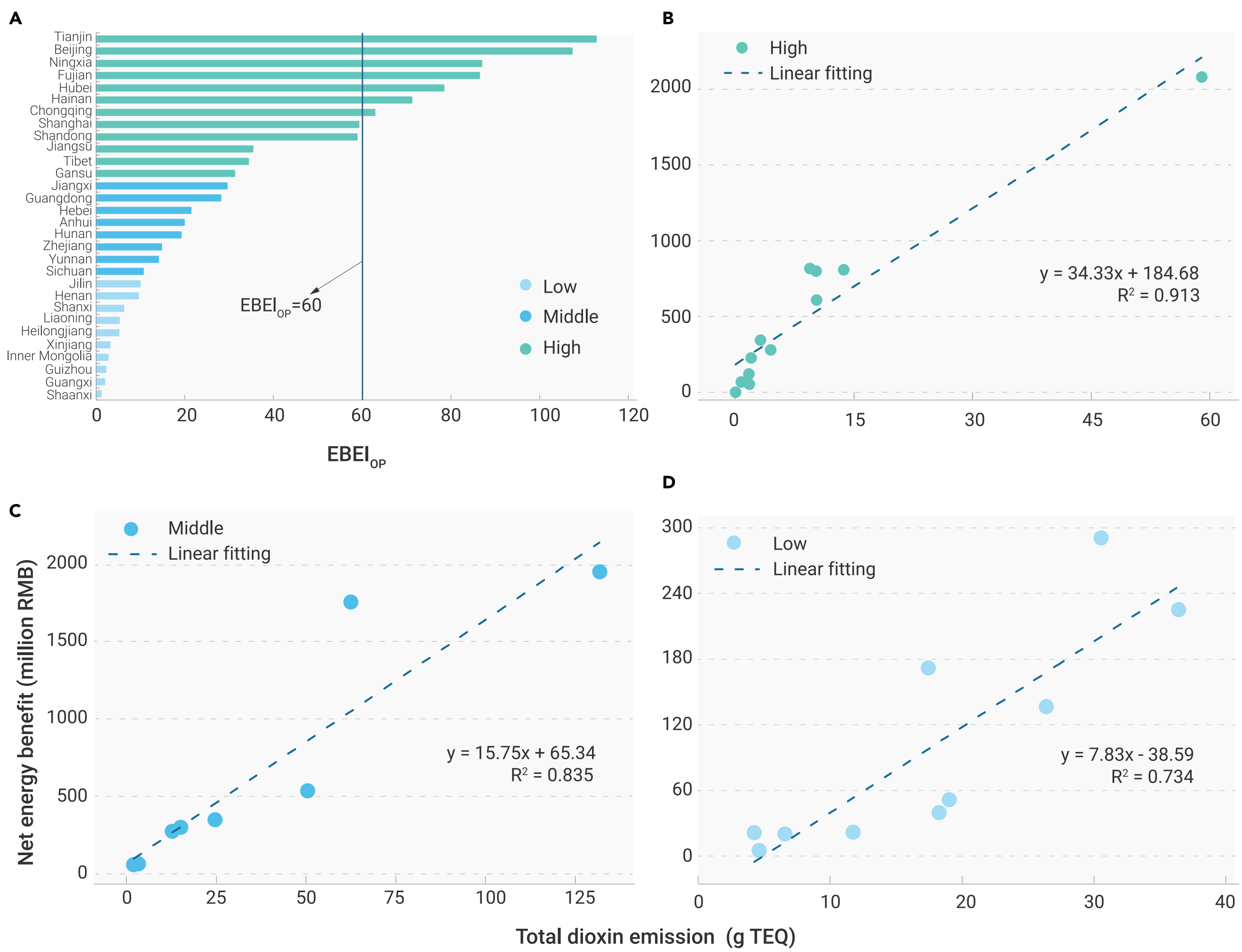

Figure 4. $EBEI_{OP}$ Values and Correlations with Emissions (A) $EBEI_{OP}$ values by province/municipality in China in 2014. (B–D) Relationship between pollutant emissions and net energy benefit of solid waste incineration in high (B), middle (C), and low (D) $EBEI_{OP}$ value provinces/municipalities in China in 2014. $EBEI_{OP}$, energy benefit-to-emission index for organic pollutants; TEQ, toxic equivalent quantity.

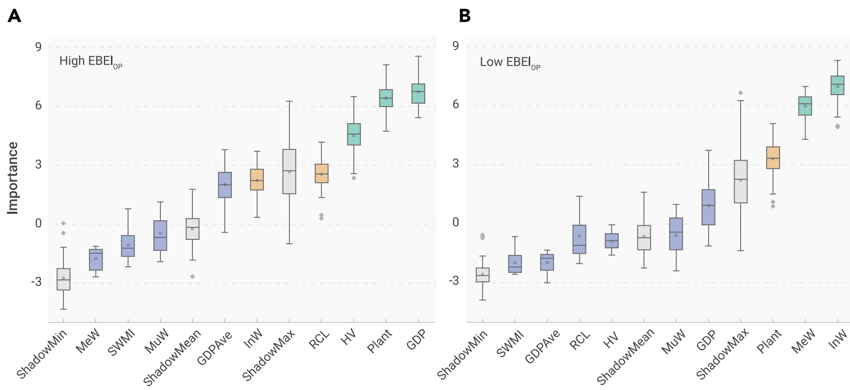

Figure 5. Results of Boruta Training Results of Boruta training for provinces/municipalities with high (A) and low (B) $EBEI_{OP}$ values in 2014. The outside lines represent the maximum and minimum; lines within the box represent the median value; top line of the box represents the first quartile; bottom line of the box represents the third quartile. Attributes deemed important by the algorithm are denoted in green; attributes deemed unimportant are denoted in purple. $EBEI_{OP}$, energy benefit-to-emission index for organic pollutants; ShadowMin, minimum importance of shadow attributes; ShadowMean, mean importance of shadow attributes; ShadowMax, maximum importance of shadow attributes; SWMI, solid waste management investment; MuW, municipal waste; MeW, medical waste; InW, industrial waste; GDPAve, per-capita gross regional products; RCL, resident consumption level; GDP, gross domestic product; HV, heating value; Plant, number of incineration plants.

Calculation of electricity generation was based on data from municipal solid waste incineration because data on provincial medical and industrial waste generation was not available. Besides, national medical and industrial waste accounted only 1.6% and 13.3% of the total national amount of solid waste, respectively, in 2014. Therefore, electricity generation was mainly from municipal waste incineration. After the heating values were obtained, the annual electricity generation was calculated using Equation 1. $\eta 1$ and $\eta 2$ values of 0.75 and 0.35, respectively, were used.[44,45]

$$EG = 0.2778 \times M \times HV \times \eta 1 \times \eta 2, \qquad \text{(Equation 1)}$$

where EG is electricity generation (million kW·h), M is the amount of incinerated waste in a given province/municipality (million tons), HV is the heating value of municipal solid waste for each province (kJ/kg), $\eta 1$ (0.75) is boiler thermal efficiency, and $\eta 2$ (0.35) is thermoelectric conversion efficiency.

As data on provincial energy consumption in 2014 were not available, it was estimated using Equation 2.

$$EC = \frac{NEC\ in\ 2014}{NM\ in\ 2014} \times M, \qquad \text{(Equation 2)}$$

where EC is energy consumption in a given province/municipality (tons of standard coal), NEC is the national energy consumption (tons of standard coal), NM is the amount of national incinerated waste (million tons), and M is the amount of incinerated waste in a given province/municipality (million tons).

The unit of electricity generation is in kW·h while energy consumption is in tons of standard coal equivalent. That 1 kW·h electricity costs 0.6 RMB was used for the calculation of energy benefit.[46] Assuming that a ton of raw coal equals 0.7 ton of standard coal[47] and that a ton of raw coal costs 650 RMB (an average of the market price), then 1 ton of standard coal costs 929 RMB. The net energy benefit was calculated using Equation 3.

$$NEB = EG \times p1 - EC \times \frac{p2}{0.7} \times \frac{1}{1,000,000}, \qquad \text{(Equation 3)}$$

where NEB is the net energy benefit (million RMB), EG is electricity generation (million kW·h), EC is energy consumption (tons of standard coal), $p1$ is the price of 1 kW·h of electricity (0.6 RMB), and $p2$ is the cost of 1 ton of raw coal (650 RMB).

To render the energy benefit/environmental risk assessment practicable, we proposed two assumptions. First, energy benefit is defined as generation of electricity after deduction of energy consumption. Second, the emission of trace organic pollutants is the dominant environmental concern. Unlike the LCA of solid waste management, which takes nearly all the input and output of waste incineration into consideration, our study focused more on correlations between energy benefits and organic pollutant emissions, which has never before been focused and clarified. Under these two assumptions, an energy benefit-to-emission index for organic pollutants ($EBEI_{OP}$), which is defined as energy benefit divided by emission of organic pollutants using Equation 4, was proposed to reflect the relationship between energy benefit and emission. The $EBEI_{OP}$ concept in this study is derived from the economic cost-benefit ratio, which has been used to analyze China's national air pollution control plan.[48] A higher cost-benefit ratio indicates higher return on investment. Similarly, in this study a higher $EBEI_{OP}$ indicates more energy benefit with less emission of toxic organic pollutants. This index may assist in evaluating energy and environmental risk in the management of solid waste incineration.

$$EBEI_{OP} = \frac{NEB}{EOP}, \qquad \text{(Equation 4)}$$

where $EBEI_{OP}$ is the energy benefit-to-emission index for organic pollutants, NEB is the net energy benefit (million RMB), and EOP is emission of organic pollutants (g TEQ).

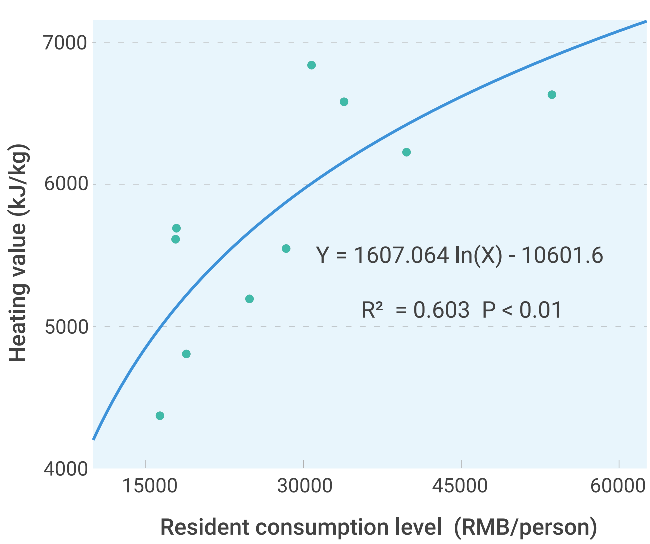

Figure 6. Model for Heating Value Prediction

Boruta Training

Boruta is a feature-selection algorithm that compares the importance of attributes with importance achievable at random.[49] By iteratively comparing the importance of attributes with the importance of shadow attributes, which are created by shuffling original ones, Boruta can consecutively drop attributes that have significantly worse importance than shadow ones and confirm attributes that are significantly better than shadows.[49] Boruta was used to identify possible contributors to the relationship between net energy benefit and pollutant emissions between provinces/municipalities with high and low $EBEI_{OP}$ values. Nine potential factors were used for training: the number of incineration plants (Plant), solid waste management investment (SWMI), GDP, per-capita gross regional products (GDPAve), resident consumption level (RCL), heating value for municipal solid waste (HV), and contribution of dioxin emissions from municipal (MuW), medical (MeW) and industrial (InW) waste incineration. The number of incineration plants was used to reflect the density of incineration activity. Contribution of dioxin emissions from municipal, medical, and industrial solid wastes were used to reflect the importance of waste category. Solid waste management investment was used to indicate the contribution of solid waste management investment. GDP, per-capita gross regional products, and resident consumption level were used to assess economic influences on the relationship between energy benefit and pollutant emissions. Heating value was used to reflect the influence of the properties of solid waste. R version 4.0.3 was used to perform the Boruta training using the package "Boruta" version 6.0.0. The "ggplot2" package, version 3.3.2, was used to obtain the related plots.

Table 1. Reported and Predicted Heating Values of Incinerated Municipal Solid Waste by Province/Municipality

Province/ municipality	Resident consumption level (RMB)	Heating value (kJ/kg)	Ref.
Shanghai	53,617	6,631	Yantao and Yang[39]
Shandong	28,353	5,548	Yantao and Yang[39]
Jiangsu	39,796	6,226	Yantao and Yang[39]
Guangdong	30,762	6,839	Yantao and Yang[39]
Zhejiang	33,851	6,581	Yantao and Yang[39]
Sichuan	17,920	5,691	Yantao and Yang[39]
Henan	17,842	5,613	Yantao and Yang[39]
Liaoning	24,866	5,194	Yantao and Yang[39]
Heilongjiang	18,859	4,806	Yantao and Yang[39]
Guizhou	16,349	4,371	Yazhuo et al.[40]
Tianjin	38,975	5,679	Ying[41]
Beijing	52,912	5,848	Jianying[42]
Ningxia	21,058	5,397	*
Fujian	25,969	5,734	*
Hubei	21,642	6,097	Yantao and Yang[39]
Hainan	20,939	5,388	*
Chongqing	22,927	5,533	*
Tibet	10,990	4,352	*
Gansu	14,203	4,764	*
Jiangxi	17,290	5,080	*
Hebei	15,893	4,945	*
Anhui	17,141	6,067	Yantao and Yang[39]
Hunan	19,418	5,630	Zhuangli[43]
Yunnan	15,831	4,938	*
Jilin	15,083	4,860	*
Shanxi	18,132	5,156	*
Xinjiang	16,736	5,028	*
Inner Mongolia	23,909	5,601	*
Guangxi	16,064	4,962	*
Shaanxi	18,485	5,187	*

*Predicted.

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AUTHOR CONTRIBUTIONS

G.L. designed the research. G.L. and C.L. conceived the paper; C.L., L.Y. and G.L. carried out the data collection with contributions from all the co-authors. C.L., L.Y., D.L. and G.L. performed the analysis and created the figures with contributions from all the co-authors; C.L. and G.L. co-wrote the paper. L.Y., X.L., Y.Y. and L.Q. edited the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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