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Review

A Review of the Physical and Chemical Characteristics and Energy-Recovery Potential of Municipal Solid Waste in China

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Abstract: The complexity and strong spatial and temporal characteristics of municipal solid waste (MSW) have made resource utilization a major challenge in establishing the life-cycle model of MSW. Based on the planning of the domestic "dual-carbon" target and the current status of the structural transformation of resource utilization, this paper summarizes the physicochemical properties of MSW in China by component, species, and region. The aim is to identify the physicochemical components of MSW in different regions of China, drawing on the research findings of various scholars. A total of 159 sets of MSW data were collected, including 90 sets of physical composition and 69 sets of elemental composition. These data were used to calculate the calorific value of MSW and determine the energy-recovery and power-generation potentials before and after MSW classification. The analysis estimates the volume of MSW requiring removal in different regions of China in 2021 and assesses the effectiveness of the energy-recovery potential (ERP) and power-generation potential (PGP) before and after MSW classification in these regions. The aim is to offer insightful guidance and recommendations for municipal waste-treatment strategies tailored to the diverse regions of China.

Keywords: MSW; physicochemical properties; calorific value; energy-recovery potential; power-generation potential

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1. Introduction

At present, the world's energy pattern is still dominated by fossil fuels. However, with the changing international situation and political landscape, the world's energy price fluctuates unpredictably. Additionally, as global environmental and climate problems worsen, all countries have started investing in energy transition. Yuan Hu et al. [1] classified 144 countries, including China, into four categories based on the per capita GDP and economic structure data of the world's countries. They conducted normalization research on the energy consumption structure of these four categories of countries. The study highlighted that China's main energy source is coal, followed by oil, while renewable energy accounts for only 16%. From the above, it can be seen that China urgently needs to carry out a structural transformation of energy consumption. The "double carbon target" proposed by China at the 75th United Nations General Assembly in 2020 refers to the targets of carbon peaking by 2030 and carbon neutrality by 2060. This demonstrates China's determination and implementation of the transformation of its energy-consumption structure.

In recent years, there has been an increase in the production of MSW due to population growth and urbanization [2] The World Bank predicts that the annual global production of MSW is expected to reach 3.4 billion tons by 2050. This highlights the importance of managing MSW as a valuable resource and a crucial aspect of transforming the energy-consumption structure. China, as a typical developing country, recognizes that implementing complete life-cycle tracking of MSW is an effective measure to enhance the resource recycling rate and address the growing issue of "garbage surrounding the city" [3].

According to 《*China's National Statistical Yearbook 2022*》 [4], the domestic waste removal volume in China in 2021 is projected to reach 248,692,000 tons. The daily capacity for waste treatment is expected to be 1,057,064 tons, with an incineration treatment rate of 68.01% and a sanitary landfill treatment rate of 24.74%. From the above, it can be seen that the mainstream treatment of MSW in China is incineration and landfill. Scholars from various countries have conducted extensive research on these two treatment methods. MSWI primarily involves the combustion of a variety of combustible materials, such as dried food waste, paper, wood chips, textiles, leather, Ref. [5], and rubber. The chemical composition of these materials, including C, H, O, N, S, and Cl, Ref. [6], plays a key role in determining the calorific value of MSW. However, the release of pollutants and greenhouse gases (GHC) from the incineration of N, S, and Cl cannot be overlooked. Ioan [7], Han [8], Chen [9], and Liu et al. [10] conducted in-depth research on energy recovery and pollutant emissions during MSWI using plant-specific data. In particular, Chen et al. highlighted the relationship between the physical composition of MSW and its influence on energy recovery and GHG emissions. The previous studies mentioned in the instructions focus on improving the efficiency of waste-incineration power generation and reducing pollutant emissions based on the physical and chemical properties of MSW in a specific location. However, there is a lack of research on the variation in energy-recovery efficiency due to the differences in MSW and limited studies on the properties and treatment of MSW in a regional area.

Another common method for treating MSW is landfilling. Research in this area focuses on the biogas production capacity and pollutant emission level associated with landfilling. Liu et al. [11] conducted an analysis of the effect of different component contents and concentrations of various MSW, particularly kitchen waste, on the fermentation process in Xi'an, China. They determined the carbon-to-nitrogen ratio of the waste components at the optimal gas production rate. Di et al. [12] analyzed the physical composition of MSW in the study area and constructed an anaerobic kinetic model to investigate the relationship between the components of domestic waste, leachate, and methane gas production rate. The treatment measures of the landfill can produce clean methane, but the damage of fermented liquid and residue to the environmental soil cannot be ignored. The study of Kristin et al. [13] reveals the direct influence of the pretreatment process and waste components on the heavy-metal content of digestate, which points out the direction for the subsequent fermentation of digestate with low environmental damage. It can be observed that utilizing MSW directly for fermentation biogas production can lead to significant environmental pollution and impact the gas production rate. Current research by scholars focuses on the classification of MSW and the utilization of kitchen waste with high water content and easy fermentation for fermentation biogas production. This also provides ideas for the following research on MSW classification and treatment.

In summary, based on China's national conditions, this paper will focus on two treatment methods of MSW: incineration and landfill fermentation. The incineration efficiency of MSW is positively correlated with its calorific value, which is closely related to its composition. Similarly, the gas production rate of landfill fermentation of MSW is also closely linked to its composition. As far as China is concerned, there is a significant potential for MSW resource recovery. However, there is a lack of research on the compositional data of MSW in different regions of China, and there is insufficient research on the differences in MSW composition among different regions. In this paper, we have conducted a comprehensive review of the relevant literature published since 2000 using the literature reading method. Each piece of data pertaining to the physical or chemical composition of municipal solid waste (MSW) was treated as a distinct data point. In total, we gathered 159 data points, with 90 related to physical composition and 69 related to chemical composition. Furthermore, we took care to normalize these data points for the purpose of our analysis. The physical and chemical compositions of municipal domestic wastes in various regions of China have been summarized in recent years. Meanwhile, it is known from the literature [14] that kitchen waste in MSW has a high moisture content and is difficult to incinerate, but it is easy to ferment to produce biogas [15]. Therefore, this paper proposes a classification strategy for MSW, specifically focusing on the fermentation of kitchen waste and the incineration of the remaining waste. It analyzes the elemental compositions and calorific values of the classified MSW and evaluates the potential of power generation from MSW before and after the classification. The objective of this paper is to characterize the physicochemical composition of MSW in various regions of China, taking into account China's unique national conditions. By doing so, we aim to provide valuable insights for the development of effective MSW treatment methods and strategies tailored to specific regions.

2. Current Status of MSW Treatment and Data Collection in China

Statistics from the 《*China Statistical Yearbook 2022*》 show that, in 2021, China's national MSW removal volume was 249.682 million tons, and the nonhazardous waste-treatment volume was 248.393 million tons, resulting in a high nonhazardous treatment rate of 99.5%. From the above statistics, it is evident that China has a significant amount of domestic waste production (referred to as MSW removal volume), indicating a substantial potential for resource recovery and energy development. Therefore, this section will analyze the recent situation of MSW removal in China. It will also provide a brief introduction to the data-collection methods and approaches used in the following studies on the physical and chemical properties of MSW. This will help pave the way for subsequent studies.

This paper provides a count of China's MSW removal, nonhazardous treatment, landfill treatment, and incineration treatment over the ten-year period from 2012 to 2021. The rates of nonhazardous treatment, landfill treatment, and incineration are also calculated, as shown in Figure 1. As can be seen from Figure 1, China's MSW production has continued to rise since 2012, with a small drop in MSW production from 2019 to 2020 due to Coronavirus disease (COVID-19). However, the overall increase in MSW production in the past ten years has been significant, with a year-on-year growth rate of approximately 46.2%. The rate of nonhazardous treatment of MSW has also consistently risen, starting from an initial rate of 84.8% and reaching 99.5%. This demonstrates the increasing efforts in reducing and treating China's municipal solid waste. Municipal solid waste reduction and resource utilization level saw an overall improvement [16]. The garbage incineration disposal rate and landfill disposal rate show a negative correlation. Over the past ten years, the MSW incineration disposal rate has consistently shown an upward trend, with the rate of increase accelerating each year. This trend is closely related to China's 13th Five-Year Plan and 14th Five-Year Plan, which have policies promoting the incineration of domestic waste [17]. The number of waste-incineration plants in China will reach 852 by 2022. It can be seen that MWSI power generation has become one of the important pillars of China's power industry [18]. While, by 2022, the landfill rate of MSW in China will still be as high as 21.0%, so research on landfill treatment is also necessary.

To summarize, the MSW treatment initiatives in China mainly involve incineration for power generation and landfill biogas as the two treatment methods [19]. The energy-recovery efficiency and pollutant emissions of these methods are dependent on the components of MSW. Therefore, data on the MSW components will be collected and studied in different regions of China to identify the physicochemical characteristics of MSW that align with China's national conditions. Based on this, corresponding recommendations for the development of MSW treatment strategies in different regions will be provided.

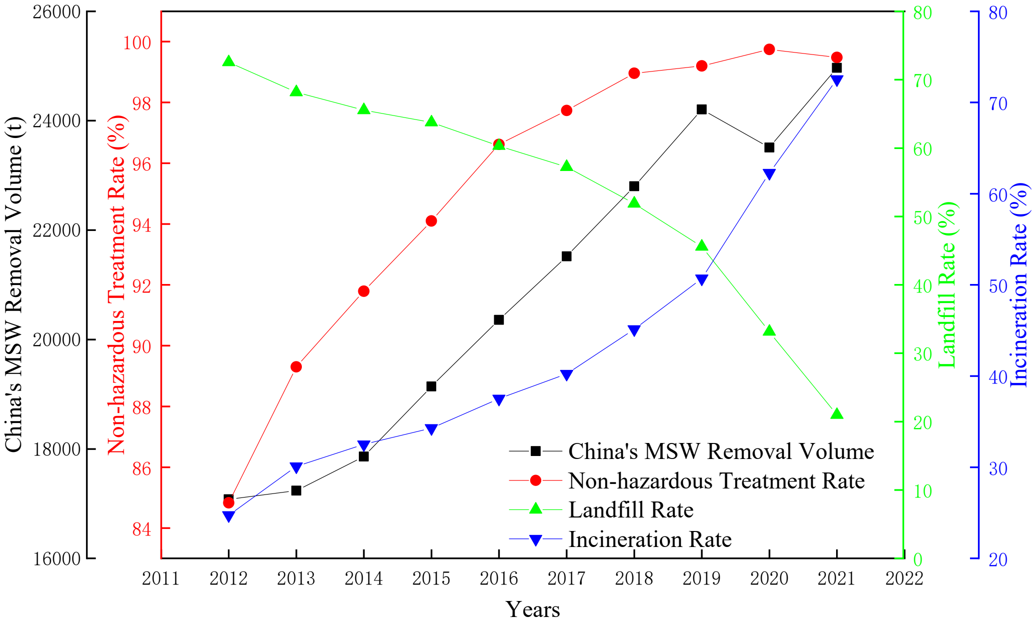

Figure 1. Production and disposal of MSW in China.

3. Physical and Chemical Properties of MSW in China

The physicochemical properties of MSW are severely constrained by geographic location, weather factors, cultural differences, etc. For instance, shellfish waste makes up a larger portion of MSW in seaside cities compared to inland areas. As a result, the physical composition of MSW exhibits a wide range of categories and noticeable differences. Additionally, China, with its three major geographic gradients, five climate types, and long history, experiences high spatial and temporal variations in the physicochemical composition of MSW.

3.1. Physical Properties of MSW in China

The physical properties of MSW can be summarized as follows: (1) the complexity and high regionality of the physical composition; and (2) the high moisture content [20]. The following section will focus on these two aspects.

3.1.1. Physical Composition of MSW in China

The physical composition of MSW varies greatly from region to region. A wide variety of different types of domestic waste are combined to form the domestic waste samples needed for the study. As a result, the physical composition of MSW is classified differently in the literature from different sources. This classification facilitates the analysis of the collected data. To analyze the data, the raw data on the physical composition of MSW obtained from various sources [21–66] need to be normalized and a reasonable classification needs to be developed. In this paper, we refer to the “Sampling and Analytical Methods for Domestic Waste” (2009) [67] to classify the physical components of domestic waste. These components are divided into the following eight categories based on their physical and chemical properties: kitchen waste, paper, plastic and rubber, textiles, wood and bamboo, glass, metal, and others. The “others” category includes mixtures such as gray clay, ceramic tiles, and other materials that are more difficult to categorize using the aforementioned criteria.

A total of 90 data points were collected for the physical composition of this paper, with 6 data points being national data. The data were collected from various locations, including Jinan, Qingdao, Beijing, Tianjin, and Shanghai, and then summarized and generalized based on the regions where these cities are located. The data points are distributed across seven regions in China: EC (East China), NC (North China), NEC (Northeast China), CC

(Central China), SC (South China), SWC (Southwest China), and NWC (Northwest China). Due to the variation in the number of domestic and foreign scholars studying domestic waste in different cities, the distribution of data points across the seven regions is uneven. Therefore, the study of the physical composition of domestic waste in different regions may have corresponding errors. However, the specific distribution of the collected data points falls within a reasonable range, as shown in Figure 2.

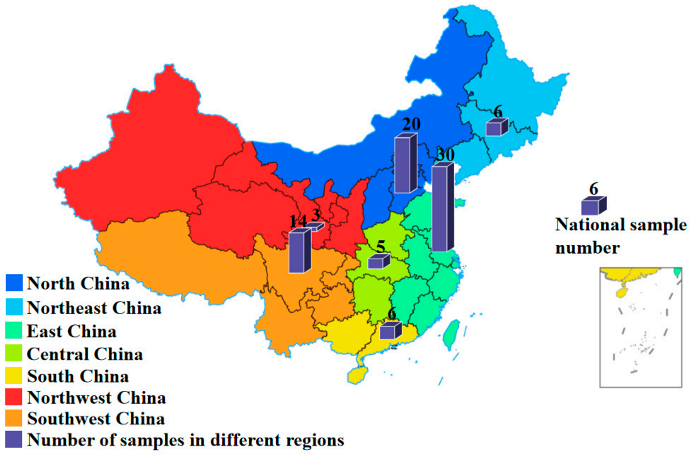

Figure 2. Distribution of data points on the physical composition of domestic waste.

As shown in Figure 2, the data points collected on the physical composition of MSW are primarily concentrated in the NC and EC regions. These two regions, compared to the rest of China, exhibit clear seasonality and have a higher economic level. As a result, the MSW components in these regions are more complex and volatile. Additionally, a larger number of data points are available, making it easier to determine the representative physical composition of MSW in these regions. The collected data from different regions were processed using MATLAB (https://www.mathworks.com/products/matlab.html, accessed on 5 December 2023) in combination with box-plot data processing. This involved eliminating outliers and calculating averages. The resulting data represent the modified region universally, and the specific physical composition of different regions is shown in Table 1 below.

Table 1. Mean values of physical composition of MSW in different regions.

Regions Component	EC	NC	NEC	CC	SC	SWC	NWC	Nationwide
Paper, %	8.93	13.73	6.99	6.62	10.15	9.12	7.13	9.76
Plastic, rubber, %	11.75	15.74	10.40	12.09	20.92	13.66	8.95	13.13
Textile, %	2.47	1.83	2.94	2.00	6.40	3.57	2.57	2.65
Wood, %	1.47	3.19	1.36	5.24	4.00	1.77	3.75	2.40
Kitchen waste, %	60.15	58.03	57.73	57.72	51.72	58.72	50.33	58.31
Glass, %	1.80	1.49	4.45	3.07	1.93	1.18	3.28	1.87
Metal, %	0.54	0.50	1.69	0.76	0.63	1.04	1.48	0.70
Other waste, %	10.16	5.97	13.64	16.25	4.24	9.10	22.50	10.44

The table reveals a close connection between the physical composition of MSW in China and the geographic location and climate of each region. For example, in SC, the proportion of plastic and rubber in domestic waste is as high as 20.20%, while in NWC, the proportion of other materials like gray soil, brick, and stone reaches 22.50%. This demonstrates that the physical composition of domestic waste is significantly influenced by the region's geography and climate. The data presented in the table align with China's national conditions and regional characteristics, confirming the accuracy of the data collection. With the exception of the physical composition of domestic waste in SC and NWC, which differ more from the summarized data, the remaining data are relatively consistent.

Therefore, it can be concluded that this study provides a certain level of universality in summarizing the physical compositions of domestic waste in different regions and across the entire country.

The above section provides a summary of the physical compositions of MSW in different regions and across the entire country of China. The data presented in this paper appears to be relatively accurate for the physical composition of waste in each region. However, it should be noted that the data for the physical composition of MSW across the country may contain some errors due to variations in climate, environment, and other regional characteristics.

To address this, the paper utilizes box plots to analyze the collected data points. The aim is to identify the most densely distributed intervals of data points and summarize the physical-composition intervals of MSW in China. This information can assist in the subsequent treatment of MSW throughout its life cycle in China and provide valuable insights for researchers studying MSW in the country.

A box-and-line diagram, depicted in Figure 3 below, was constructed using the mass percentage (wet basis) of different types of MSW reported in the related literature.

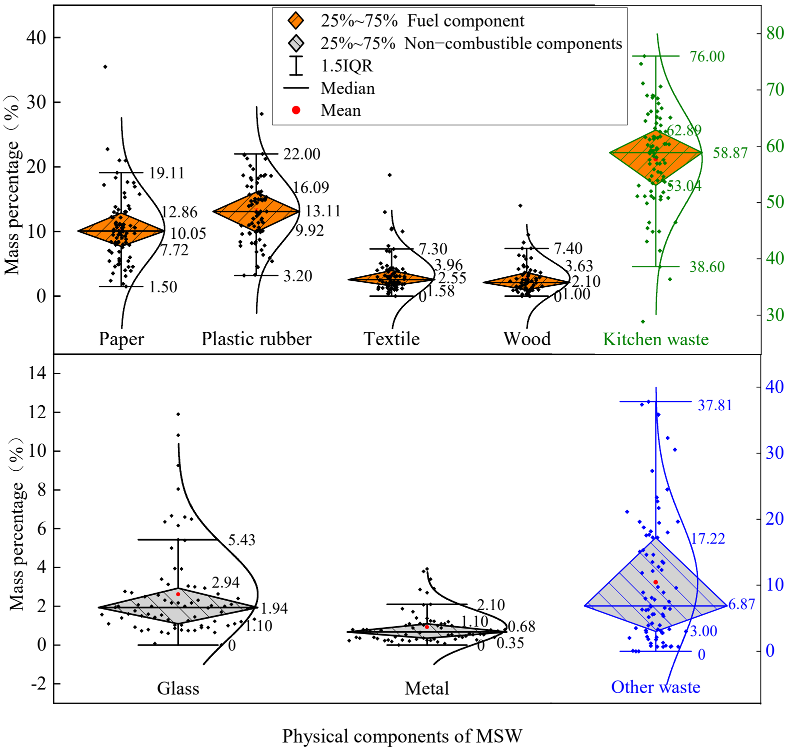

Figure 3. Interval diagram of the physical components of domestic waste.

The mass percentage of combustible components (paper, plastic, rubber, textiles, wood, and kitchen waste) in domestic waste is shown in Figure 3. By combining the scatter plot with the box line graph, we can visualize the distribution of the data. Comparing the mass percentages, it is evident that the mass share of kitchen waste is significantly higher than that of the other components. Most of the mass share of kitchen waste falls within the range of 53.04% to 62.89%. Similarly, the percentage of paper ranges from 7.72% to 12.86%, the mass percentage of plastic and rubber ranges from 9.92% to 16.09%, the mass percentage of textiles ranges from 1.58% to 3.96%, and the mass percentage of wood waste ranges from 1.00% to 3.60%.

Daily life inevitably generates a significant amount of noncombustible material in domestic waste. Although this type of waste accounts for a relatively small percentage of the total domestic waste, it is an important component, with physical and chemical properties that cannot be ignored. By collecting data, we can determine the mass-percentage range of this type of noncombustible household waste, as shown in Figure 3.

From the figure, it can be observed that the mass percentage of discarded glass products in domestic waste ranges from 1.10% to 2.94%. The proportion of metal waste ranges from 0.35% to 1.10%, and the mass percentage of other waste ranges from 3.00% to 17.22%.

3.1.2. Moisture Content of MSW

Moisture content is an important physical characteristic of MSW. The level of moisture content in domestic waste significantly affects its physical and chemical properties, as well as its calorific value. Therefore, studying the water content of domestic waste is necessary.

This paper focuses on collecting the physical and chemical composition of domestic waste, specifically the moisture content. The collected moisture data of domestic waste from different regions are summarized and unified to provide insights into the water content of domestic waste.

Additionally, the water content of kitchen waste is explored. However, due to the limited amount of data and its consistently high moisture content across the country, a multiregional comparison of the water content of kitchen waste is not conducted.

By combining data on the moisture content of seven different regions in China and applying the aforementioned data-processing methods, outliers can be eliminated, and the average moisture content of domestic waste in each region can be calculated. It is important to note that variations in the object of study among different scholars may introduce a certain degree of uncertainty in the statistics of water content. To address this, subsequent studies aim to use national data on domestic waste's moisture content to reduce uncertainty by utilizing a larger and more uniform dataset. Therefore, the following study will use national data as the basis and strive to minimize uncertainty. Table 2 presents the moisture content of MSW in different regions.

Table 2. Table of average values of the moisture content of MSW in different regions.

Regions	EC	NC	NEC	CC	SC	SWC	NWC	Nationwide
Moisture, %	53.30	52.68	55.07	45.77	52.06	53.43	40.58	51.62

As shown in Table 2, the moisture content in the southern and eastern coastal regions of China is higher compared to the central and northwestern regions. This can be attributed to the geographic location and climate. The northwest region of China falls within the arid and semiarid zone, as well as the alpine zone. These regions are also categorized under the temperate continental climate and temperate monsoon climate, which have relatively low water content. On the other hand, EC, NC, and CC exhibit moisture content that is relatively close to each other. The moisture content of the MSW is 51.62%, which is also similar to the moisture content of the research location. Therefore, it can be concluded that the MSW is suitable for the study.

Many scholars have studied the moisture content of domestic waste. This paper collects data on the moisture content of the domestic waste and kitchen waste separately. The data is then combined to obtain their respective mass-percentage range intervals, as shown in Figure 4.

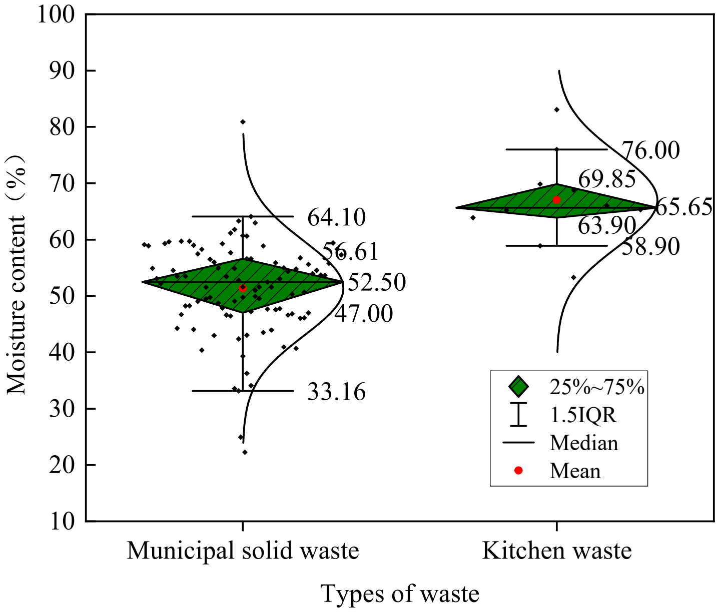

Figure 4. MSW and Kitchen-Waste Moisture Content Map.

From the figure, it is evident that the water content of domestic waste ranges from 47.00% to 56.61%, while the water content of kitchen waste is relatively high, ranging from 63.90% to 69.85%. Combining this with the previous study, it can be concluded that the water percentage of kitchen waste in domestic waste falls within the range of 26.61% to 44.63%. In other words, the water contained in kitchen waste accounts for 41.64% to 94.97% of the total moisture in domestic waste.

3.2. *Chemical Characterization of MSW in China*

Domestic waste is used as fuel in incineration boilers, and its constituent elements need to be analyzed to determine its calorific value and incineration flue-gas products. This paper collects data on the elemental composition of domestic waste by reviewing the literature [36,39,49,51,53,68–79]. Box line plots are then used to summarize the mass-percentage intervals of the major elemental components.

The data on the physical composition of domestic waste indicates that kitchen waste accounts for a high percentage, ranging from 53.04% to 62.89%. Therefore, it is also necessary to summarize the elemental components of kitchen waste. This paper will explore the overall elemental composition of domestic waste and the elemental composition of kitchen waste separately. Additionally, due to variations in sampling, preparation, drying, and processing methods used by different scholars, the collected data needs to be standardized.

3.2.1. Elemental Composition of MSW

The calorific value of domestic waste has a significant impact on its characteristics. Since this paper aims to use domestic waste as fuel, it is necessary to analyze its chemical composition. Therefore, this study will investigate the physical composition of domestic waste using the aforementioned method, focusing on the elemental composition. First, the chemical composition of domestic waste in different regions will be explored, followed by an analysis of national characteristics and a comparative study. Additionally, this paper includes the classification of domestic waste-treatment strategies, such as kitchen-waste fermentation and incineration power generation for the rest of the waste (mainly dry waste). Therefore, it is also important to study the chemical composition of kitchen waste. However, the research on the chemical composition of kitchen waste is limited, and the variation in chemical compositions among different regions is minimal. As a result, a comparative study of different regions is not conducted.

Chemical Composition of Domestic Waste in Different Regions

This paper collects a total of 69 data points on the chemical composition of domestic waste. These include two nationwide data points. Throughout the collection process, there has been more research conducted by scholars, both domestic and international, on the chemical composition of domestic waste in the southern region of China and the eastern seaboard region of China. As a result, the collected data are concentrated in these regions. The specific distribution of the data points is illustrated in Figure 5.

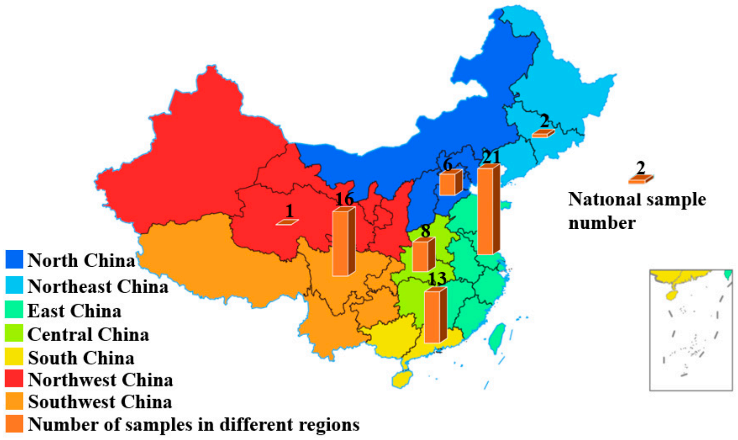

Figure 5. Distribution of chemical-composition data points of MSW.

As shown in the figure above, the collected data points for chemical composition are distributed across seven regions in China. There are more data points scattered in the southern and eastern coastal provinces. By processing the collected data and eliminating anomalies, the mean values can be calculated. The mean-value table, shown in Table 3 (moisture refers to the moisture data contained in the collected chemical-composition data points), can be obtained.

Table 3. Mean values of the chemical composition of MSW in different regions.

Regions Elements	EC	NC	NEC	CC	SC	SWC	NWC	Nationwide
C, %	15.99	14.89	16.44	15.06	17.47	15.26	9.63	15.80
H, %	2.24	1.64	2.30	1.99	2.35	2.01	1.47	2.13
O, %	8.70	13.07	10.17	9.42	11.00	12.06	6.02	10.70
N, %	0.42	0.40	0.58	0.43	0.43	0.63	0.22	0.46
S, %	0.09	0.12	0.11	2.30	0.09	0.13	0.09	0.09
Cl, %	0.69	0.46	0.26	-	0.76	0.47	-	0.55
Moisture, %	51.87	46.04	49.53	47.32	49.78	52.85	24.95	51.12
Ash, %	24.90	22.82	13.86	28.27	20.39	10.91	59.52	23.000

From the table, it can be observed that the main chemical elements in domestic waste are C, H, O, N, S, and Cl. The elements C and O account for the majority of the mass percentage, while the remaining four elements account for a relatively small percentage. The chemical composition of national domestic waste, as shown in the table, is consistent with that of domestic waste in the EC region, except for a slight difference in the O element. The elemental composition, moisture, and ash are relatively consistent.

In conclusion, the chemical composition of national domestic waste is applicable to the region where the research object of this paper is located and exhibits a certain degree of universality. The collected data have a certain degree of credibility.

Ranges of Chemical Composition of MSW in China

Same as above, for the research and analysis of the physical composition of MSW in China, this section also needs to investigate the chemical composition of domestic waste in the country. All the collected chemical-composition data are summarized and presented in a box-and-line diagram, as depicted in Figure 6. The figure illustrates the specific intervals of mass percentages for several different chemical elements present in domestic waste. It is worth noting that the elemental analysis of domestic waste in the literature is primarily based on a wet basis; hence, the data shown in the figure represent the elemental mass percentages of MSW (wet basis).

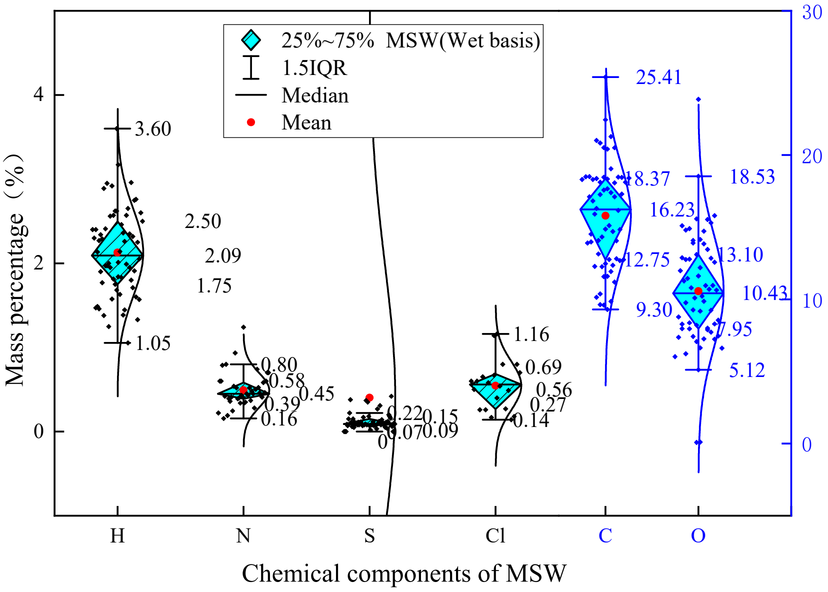

Figure 6. Chemical-element composition of MSW.

3.2.2. Elemental Composition of Kitchen Waste

Kitchen waste refers to the leftover food from various sources, including animal and vegetable products and fruits. It contains a high amount of moisture and organic matter. Through treatment and processing, it can be utilized for composting, biogas production, and biofuel preparation, and transformed into a valuable resource. Given its significant presence in domestic waste, it is essential to analyze its physicochemical properties.

To analyze the properties of kitchen waste, it is necessary to refer to the existing literature [80–102]. By collecting data from these sources, the mass percentage of six different elements in kitchen waste can be obtained, as shown in Figure 7. Since kitchen waste has a high moisture content, researchers often prioritize drying the samples before analysis. Therefore, the collected data represents the mass percentage of the elemental components of dried kitchen waste.

The figure shows the fluctuation range of elemental composition (dry basis) in kitchen waste in China. The C element ranges from 46.86% to 43.42%, the H element ranges from 5.04% to 7.09%, the N element ranges from 2.15% to 3.69%, the O element ranges from 32.98% to 41.15%, the S element ranges from 0.30% to 0.75%, and the Cl element ranges from 0.01% to 0.42%.

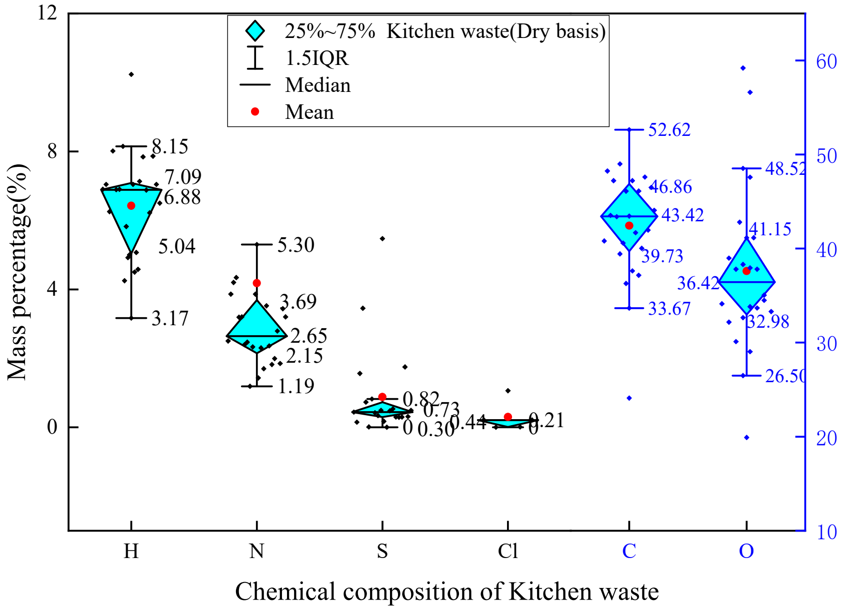

Figure 7. Elemental composition of kitchen waste (dry basis).

3.2.3. Elemental Composition of Sorted Waste

This paper aims to compare and analyze the energy-recovery potential and power-generation potential of MSW from different regions, both before and after classification. To achieve this, it is necessary to study the chemical compositions of the classified waste from different regions. However, due to the limited data available for kitchen waste and for the sake of simplicity in the calculations, this paper assumes that the elemental composition of kitchen waste is the same across all regions. Additionally, it is assumed that the remaining domestic waste, excluding kitchen waste, has the same moisture content. The elemental composition of kitchen waste is provided in Table 4.

Table 4. Mean chemical composition of kitchen waste.

Elements	**C**	**H**	**N**	**O**	**S**	**Cl**	**Moisture (M)**
Kitchen-waste composition (dry basis), %	43.23	6.26	2.84	36.53	0.37	0.37	66.743

The chemical composition of domestic waste and kitchen waste can be deduced after classification, using the known chemical composition. This can be done using Equations (1)–(4).

$$e_o = [e_w - e_{kd} \times (1 - M_k) \times a] \times (1 - a) \tag{1}$$

$$e_c = e_o \times \left(1 - \frac{b}{1 - a}\right) \tag{2}$$

$$M_c = (M_w - a \times M_k)/(1 - a) \tag{3}$$

$$A_c = 1 - M_c - e_c \tag{4}$$

e_o: Elemental composition of the remaining waste after removal of kitchen waste, %;
$e_o{}'$: Corrected elemental composition of the remaining waste after removal of f kitchen waste, %;
e_w: Elemental composition of domestic waste wet base, %;
e_{kd}: Elemental composition of dry kitchen waste base, %;
M_k: Moisture in kitchen waste, %;
a: Percentage of kitchen waste, %;

e_c: Elemental composition of sorted waste (excluding kitchen waste, metals, glass and ash bricks, etc.), %;
b: Percentage of noncombustible waste such as glass, metal, and ash bricks and blocks, %;
M_c: Sorted waste moisture, %;
A_c: Ash content of sorted waste, %.

The data in the Table 5 are calculated by using Equations (1)–(4) along with the findings from the previous study. These calculations determine the chemical composition of the remaining waste after the classification of MSW in various regions of China and the entire country. The table offers data support for the calculation of the energy-recovery rate and power-generation potential of MSW classified in different regions, as discussed later in the paper.

Table 5. Mean chemical composition of the remaining waste after sorting in different regions.

Elementals **Regions**	**C**	**H**	**N**	**O**	**S**	**Cl**	**Moisture (M)**
EC	26.87	3.61	-	5.10	0.06	2.46	29.43
NC	19.24	1.28	-	17.71	0.15	1.28	17.41
NEC	36.19	4.88	0.14	14.01	0.15	1.06	26.02
CC	30.45	3.55	-	10.86	10.04	0.00	20.81
SC	24.20	3.07	-	11.37	0.06	1.79	31.60
SWC	22.77	2.63	0.25	16.45	0.21	1.51	33.08
NWC	10.68	1.88	-	-	0.13	-	-
Nationwide	25.86	3.18	-	12.61	0.07	1.83	29.26

4. Calculations of MSW Calorific Value, ERP, and PGP

When using MSW as fuel for incineration power generation, it is necessary to study its calorific value. Currently, the calculation method for the calorific value of domestic waste mainly relies on two approaches. The first approach involves calculating the calorific value based on the physical composition of the waste, while the second approach involves calculating the calorific value based on the elemental composition. By combining these two methods with the aforementioned research on calorific value calculation, a comprehensive understanding can be gained.

4.1. Calculation of Physical-Composition Calorific Value

Since the physical components of MSW are greatly influenced by climate, geography, dietary habits, and other factors, the physical composition of domestic waste fluctuates significantly. Therefore, Li et al. [46] conducted research on MSW in certain Chinese cities to propose a formula for calculating the calorific value of MSW applicable to Chinese cities. This formula, shown in Equation (5), considers the physical grouping of MSW based on dry basis components. However, the above-mentioned studies were conducted based on wet-based components, so the collected data needs to be processed. It is assumed that the moisture content of all the waste components is the same.

$$Q = 41.1 \times Ru_d + 22.9 \times K_d + 20.7 \times Pa_d - 4.5 \times W_m \tag{5}$$

Q: Calorific value, kJ/kg;
Ru_d: Components of plastic–rubber MSW on a dry basis, %;
K: Percentage of kitchen waste on a dry basis, %;
Pa_d: Components of paper household waste on a dry basis, %;
W_m: Moisture content of MSW, %;

Using Equation (5) in conjunction with the physical components of MSW summarized above, the ratio of different physical components within the interval is divided into 10 intervals. By performing calculations in MATLAB, we can obtain 1,000,000 sets of data that allow us to determine the minimum and maximum values of the calorific value of domestic waste's physical components, which are 3148.171 kJ/kg and 5208.922 kJ/kg, respectively [103]. These results fall within a reasonable range, confirming the validity of the interval summarization of the physical components.

4.2. Calculation of Calorific Value of Chemical-Element Composition

Currently, there are numerous studies that utilize elemental analysis to calculate the calorific value of MSW. The most commonly used formulas for calorific value calculation in these studies are the Dulong formula, Steuer formula, and Scheurer–Kestner formula [77], as shown in Equations (6)–(8). By combining the elemental composition intervals mentioned above and applying these three formulas, an approximate interval for the calorific value of MSW can be obtained.

$$Q_D = [81 \times C + 342.5 \times (H - O/8) + 225 \times S - 6 \times (9 \times H + W_m)] \times 4.19 \tag{6}$$

$$Q_S = \left[\begin{array}{c} 81 \times \left(C - \frac{3}{8} \times O\right) + 57 \times \frac{3}{8} \times O + 345 \times \left(H - \frac{O}{16}\right) \\ +25 \times S - 6 \times (W_m + 9 \times H) \end{array} \right] \times 4.19 \tag{7}$$

$$\begin{array}{c} Q_{SK} = [81 \times (C - 3/4 \times O) + 57 \times 3/4 \times O + 345.2 \times H + 22.5 \times S \\ -6 \times (W_m + 9 \times H)] \times 4.19 \end{array} \tag{8}$$

Q_D, Q_S, and Q_{SK} are the calorific values, calculated by the above three equations, respectively, kJ/kg;
C, H, O, and S are the percentage of elemental mass in MSW, %.

Figure 6 above presents the data on the chemical composition of domestic waste. The three equations mentioned above can be combined to calculate the calorific value intervals of domestic waste as follows: (2672.5~6587.7) kJ/kg, (3363.3~7093.1) kJ/kg, and (4052.9~7511.7) kJ/kg. All of these intervals fall within reasonable ranges, confirming the reasonableness of the elemental composition interval summary. Table 6 provides a summary of the specific distribution intervals of the chemical elemental composition of domestic waste and its calorific value. The calorific value of domestic MSW in China is relatively low compared to the EU and other countries, with a range of 7–15 MJ/kg [104]. This suggests that there is a need for improvement in China's technology for the classification, collection, and efficient utilization of MSW.

Table 6. Elemental composition and calorific value range of domestic waste.

Elemental range, %	C 12.75~18.37	H 1.75~2.50	O 7.95~13.10	N 0.39~0.59
Elemental range, %	S 0.07~0.15	Cl 0.27~0.69	Ash 16.01~30.00	Moisture 46.96~56.65
Calorific value, kJ/kg	2674.50~7511.70			

4.3. Analysis of ERP and PGP in Different Regions

The treatment of domestic waste is the most crucial aspect of LCA for MSW. Implementing efficient treatment initiatives can greatly enhance the resource utilization of MSW. Therefore, this paper uses ERP and PGP as the evaluation criteria. The study above focuses on the physicochemical composition of MSW in various regions of China. It identifies the fluctuation intervals and mean values of the MSW's physicochemical composition in different regions. The following section will investigate the energy recovery and utilization rate, as well as the power-generation potential of MSW in these regions based on the aforementioned study. Additionally, it will compare the characteristics of changes in the energy-recovery and utilization rate and power-generation potential of MSW before and after classification in different regions. This analysis will provide valuable insights for implementing effective treatment measures for MSW in different regions. The empirical formulas in Sections 4.1 and 4.2 are used to verify the accuracy of the collected data. Additionally, a study by [77] demonstrates that the calculation of the calorific value using Dulong's elemental formula is relatively more accurate. Therefore, in the following section, we will utilize Dulong's formula to calculate the calorific value of the MSW. This calculation will be crucial for determining the energy-recovery rate and power-generation potential.

4.3.1. Analysis of the ERP and PGP of Unclassified Waste

Currently, the classification and transportation of MSW in China (except for some big cities) is still in the initial stage [105]. As a result, all MSW in China is currently transported to waste-incineration power plants and then reclassified to remove noncombustible materials. In this paper, the total amount of MSW removed from different regions of China in 2021 is used as the basis for calculation. The chemical composition of MSW in different regions is considered to calculate its calorific value, which is then used to determine the energy-recovery rate.

The ERP and PGP of incineration are calculated as follows:

$$ERP_I = Q_D \times M \times 10^7 / (24 \times 365) \tag{9}$$

$$PGP_I = 0.25 \times 41.67 \times Q_D \times M \times 10^5 \tag{10}$$

$$ERP = ERP_I \tag{11}$$

$$PGP = PGP_I \tag{12}$$

ERP_I: MSW incineration energy-recovery potential (kWh);
Q_D: The calculation of the calorific value of MSW is determined in accordance with Section 3 using Equation (6) (kJ/kg);
M: Annual clearing volume of MSW (kt); calculation of the mass in the required unit hours therefore requires division by the factors 365 and 24;
PGP_I: Net electricity-generation potential from incineration (kW); the conversion efficiency is 0.25 [106].

Using the formula mentioned above, along with the chemical-element composition summarized in the previous section on China's MSW, the energy-recovery potential of China's MSW in 2020 can be calculated to be 1273 billion kWh. This value has an error of 4% compared to the statistical data of 1326 billion kWh in 2020 from the China Business Intelligence website "https://www.askci.com/ (accessed on 10 December 2023)" [107]. The accuracy of the MSW component data mentioned above has been verified side by side. Based on the research conducted on the chemical compositions of MSW in different regions, combined with the waste removal volume of those regions in 2021, the values of ERP and PGP were calculated for various regions in China. The results, shown in Table 7, indicate that the SC region has the highest potential for energy recovery from MSW, while the NWC region has the lowest potential. The coastal region shows relatively high values of both ERP and GRP. This conclusion aligns with the regional differences and national conditions of China.

Table 7. ERP and GRP calculation form for unsegregated garbage.

Parameters	MSW Removal in Different Regions	ERP	PGP
Regions	kt	GWh	GW
EC	43,898	264,897.70	2759.57
NC	45,310	183,349.06	1910.04
NEC	20,208	122,436.12	1275.48
CC	43,344	240,400.32	2504.37
SC	50,427	320,017.95	3333.79
SWC	29,476	139,028.14	1448.33
NWC	16,029	61,324.23	638.85
Nationwide	248,692	1,272,724.55	13,258.61

4.3.2. Analysis of Energy-Recovery Rate and Power-Generation Potential of Waste Separation

China's abundant population leads to the significant issue of kitchen waste as part of MSW. It is characterized by high moisture content and low calorific value, which would result in a significant waste of energy if directly incinerated. However, these characteristics are advantageous for fermentation and biogas production. Therefore, the classification strategy proposed in this paper involves fermenting kitchen waste to produce biogas, while incinerating the remaining waste. The aim is to compare the energy-recovery potential and net power-generation potential of MSW before and after classification. The energy-recovery potential and net power-generation potential of MSW landfill fermentation and the total ERP and PGP after categorization are calculated as follows:

$$ERP_L = NCV \times M \times \eta \times P_f \times 10^4/0.042 \tag{13}$$

$$PGP_L = 0.3 \times ERP_L/24 \tag{14}$$

$$ERP = ERP_I \times \left(1 - P_f\right) + ERP_L \tag{15}$$

$$PGP = PGP_I \times \left(1 - P_f\right) + PGP_L \tag{16}$$

ERP_L: Energy-recovery potential of MSW fermentation for biogas production (kWh) [106];
NCV: Net calorific value, MSW biomass process normally takes the value 0.218 (kW·m^{-3}) [108];
η: The gas production rate for 1 t of kitchen waste is usually taken as 115.73 (m^3) [109];
P_f: Percentage of kitchen waste in different regions (%);
PGP_L: Net power-generation potential from fermentation (kW); the conversion efficiency is 0.3 [106].

The calculation of ERP and PGP after categorization utilizes the chemical element composition data of various regions from the previous study, along with the percentage of kitchen waste and MSW removal volume data from different regions in 2021. These input data are used to calculate the ERP and PGP data after categorization for different regions in China, as presented in Table 8. Furthermore, a comparison and an analysis are conducted with the unclassified regions.

Table 8. ERP and GRP calculation tables for sorted waste.

Parameters Regions	MSW Removal in Different Regions	ERP	PGP
	kt	GWh	GW
EC	43,898	384,077.53	4331.42
NC	45,310	239,209.81	2820.86
NEC	20,208	211,079.75	2344.86
CC	43,344	410,664.17	4591.03
SC	50,427	396,976.57	4461.79
SWC	29,476	196,264.97	2261.09
NWC	16,029	96,669.42	1107.97
Nationwide	248,692	1,841,267.39	20,896.42

As shown in Tables 7 and 8, the ERP and PGP are relatively high in the CC, SC, and EC regions of China, which is in positive feedback with factors such as economic level, geographic location, and environment. The ERP of sorted treatment for MSW is generally higher than that of unsegregated treatment. However, the net PGP is lower in regions with a higher percentage of kitchen waste. This can be attributed to the inefficiency of fermentation for biogas production and the immaturity of biogas power-generation technology in China.

A comparison of Tables 7 and 8 reveals a significant increase in the ERP and PGP of MSW following its classification. Nationally, the ERP and PGP of MSW after classification increased by 44.67% and 57.61%, respectively, compared to unclassified waste. The increase in ERP and PGP following the classification of MSW in NEC, CC, and NWC is substantial. Upon analyzing the composition of MSW in these three regions, it is evident that they have a higher proportion of other waste types, leading to a significant increase in the calorific value of MSW after sorting. Additionally, the water content of MSW in CC and NWC is lower, while the water content of kitchen waste is higher, making fermentation easier after sorting. As a result, the increase in ERP and PGP is more pronounced in these regions compared to others.

The PGP calculated in this study represents the net PGP. Equations (10) and (14) were computed without taking into account the conversion coefficients of 0.25 and 0.3 and then divided by the amount of garbage removed to yield power-generation values before and after classification of 213.25 kWh/t and 308.51 kWh/t, respectively. This result is supported by the power-generation potential of incoming garbage, which is approximately 300 kWh/t, as outlined in the domestic waste-incineration treatment engineering technology. However, when compared to the power-generation potential of 460–476 kWh/t in European countries [7], the power-generation potential of waste in our country is lower. Several factors may explain this disparity. (1) Our calculations assume that all garbage is used for power generation, which may result in a relatively conservative estimate of the power-generation capacity of incoming garbage. (2) When compared to the NCV of MSW in European countries, such as the UK where the average calorific value of MSW is 10.6 MJ/t [110], the range of values calculated in this study fluctuates between 2 and 7 MJ/t, indicating a relatively lower calorific value in our waste, leading to a lower power-generation potential. (3) European countries have relatively mature classification technology, as supported by the technology of classification. This technology results in a relatively higher proportion of combustible materials in the physical composition of MSW. For instance, in the UK, combustibles account for as much as 46.9% (excluding 24.0% of kitchen waste) [110], supporting the conclusion of the larger calorific value mentioned earlier.

Above all, it is undeniable that the ERP and PGP of separated treatment is significantly higher than that of unsegregated treatment, especially in regions with a large amount of MSW removal. The successful implementation of energy recovery and the reuse of MSW will directly impact the transformation of China's energy-consumption structure in the future.

5. Conclusions

The research in this paper is based on the collection, summarization, and analysis of data on the physicochemical composition of MSW in China published in recent years. By summarizing a large amount of data, the most suitable embodiment of MSW data for China's national conditions is identified. The above work leads to the following four conclusions.

(1) With the development of society and advancements in incineration and power-generation technology, the predominant treatment method for MSW in China has shifted from landfill to incineration and power generation. By 2021, the proportion of MSWs being treated through incineration and power generation has reached a high of 72.55%. (2) This paper adopts the data-processing method of box plot to summarize the universal physical-composition interval and chemical composition interval of MSW in China. Two methods were used to calculate the calorific value based on physical composition and elemental composition. The obtained fluctuation interval of the calorific value of the waste was in the range of 2672.5–7511.7 kJ/kg. The results fell within a reasonable range, which verified the accuracy of the data. (3) This paper offers a comprehensive review of the physicochemical composition of MSW in different regions of China. It provides references for the disposal of MSW to the specific characteristics of each region, such as geographic location and climate. (4) The volume of MSW removed from various regions of China in 2021, along with the chemical composition and percentage of kitchen waste in each region, as well as the moisture content, were used as input data. The ERP and PGP of MSW in different regions of China were calculated before and after classification. The results indicated that the ERP

of MSW in the country increased by 44.67% after classification. This finding provides a valuable reference for determining the next MSW treatment method in China.

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Data Availability Statement: The preceding studies on MSW in China have been limited to the physical and chemical characteristics of a certain place. In this paper, we collect data from journals in recent years and study and analyze the physical and chemical properties of MSW in China and different regions. Then, the ERP and PGP of MSW before and after classification are compared and analyzed to provide some guidance for MSW treatment measures in different regions of China.

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Abbreviations

MSW	municipal solid waste
MSWI	municipal solid waste incineration
ERP	energy-recovery potential
PGP	power-generation potential
EC	East China
NC	North China
NEC	Northeast China
CC	Central China
SC	South China
SWC	Southwest China
NWC	Northwest China
GHG	Greenhouse Gas
LCA	Life-Cycle Assessment

References

1. Hu, Y.; Peng, L.; Li, X.; Yao, X.; Lin, H.; Chi, T. A novel evolution tree for analyzing the global energy consumption structure. *Energy* **2018**, *147*, 1177–1187. [CrossRef]
2. Kaza, S.; Yao, L.C.; Bhadatata, P.; Van Woerden, F. *What a Waste 2.0*; World Bank Publications: Washington, DC, USA, 2018.
3. Wang, Z.; Teng, Y.; Hui, X.; Chen, Z. A Sustainable Development Multi-energy System Planning Method Incorporating the Demand of Waste Disposal and Peak Shaving. *Proc. CSEE* **2021**, *41*, 16.
4. Statistics, N.B.O. *China Statistical Yearbook*; National Bureau of Statistics: Beijing, China, 2022.
5. Haque, N.; Azad, A.K. Comparative Study of Hydrogen Production from Organic Fraction of Municipal Solid Waste and Its Challenges: A Review. *Energies* **2023**, *16*, 7853. [CrossRef]
6. Arruda Ferraz de Campos, V.; Carmo-Calado, L.; Mota-Panizio, R.; Matos, V.; Silva, V.B.; Brito, P.S.; Eusébio, D.F.L.; Tuna, C.E.; Silveira, J.L. A Waste-to-Energy Technical Approach: Syngas–Biodiesel Blend for Power Generation. *Energies* **2023**, *16*, 7384. [CrossRef]
7. Istrate, I.-R.; Galvez-Martos, J.-L.; Vázquez, D.; Guillén-Gosálbez, G.; Dufour, J. Prospective analysis of the optimal capacity, economics and carbon footprint of energy recovery from municipal solid waste incineration. *Resour. Conserv. Recycl.* **2023**, *193*, 106943. [CrossRef]
8. Han, X.; Chang, H.; Wang, C.; Tai, J.; Karellas, S.; Yan, J.; Song, L.; Bi, Z. Tracking the life-cycle greenhouse gas emissions of municipal solid waste incineration power plant: A case study in Shanghai. *J. Clean. Prod.* **2023**, *398*, 136635. [CrossRef]
9. Chen, Y.C. Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology. *J. Clean. Prod.* **2018**, *192*, 262–269. [CrossRef]
10. Liu, B.; Han, Z.; Liang, X. Dioxin emissions from municipal solid waste incineration in the context of waste classification policy. *Atmos. Pollut. Res.* **2023**, *14*, 101842. [CrossRef]

11. Liu, Y.; Li, X.; Chen, Q.; Tan, P.; Qiu, L.; Deng, Y.; Wang, F.; Jiang, N. Analysis of Composition of Municipal Solid Wastes in Xi'an and Anaerobic Fermentation Performance with Different Solid Concentrations. *China Biogas* **2019**, *37*, 37–43.
12. Abedi, S.; Nozarpour, A.; Tavakoli, O. Evaluation of biogas production rate and leachate treatment in Landfill through a water-energy nexus framework for integrated waste management. *Energy Nexus* **2023**, *11*, 100218. [CrossRef]
13. Knoop, C.; Dornack, C.; Raab, T. Nutrient and heavy metal accumulation in municipal organic waste from separate collection during anaerobic digestion in a two-stage laboratory biogas plant. *Bioresour. Technol.* **2017**, *239*, 437–446. [CrossRef] [PubMed]
14. Zhao, W.; Sun, X.; Wang, Q.; Ma, H.; Teng, Y. Lactic acid recovery from fermentation broth of kitchen garbage by esterification and hydrolysis method. *Biomass Bioenergy* **2009**, *33*, 21–25. [CrossRef]
15. Huang, N. Application of dry anaerobic fermentation technology in municipal domestic waste treatment. *Sichuan Archit.* **2019**, *39*, 4.
16. Liu, S.; Dai, S. Research on Driving Factors of Improving Urban Solid Waste Disposal Capacity: Based on the Empirical Analysis of 30 Provinces from 2004 to 2020. *Chin. J. Environ. Manag.* **2023**, *15*, 109–117. [CrossRef]
17. Sun, H.; Xie, Z.; Liang, Y.; Zhang, J. The current situation and development of domestic domestic waste incineration power generation under the background of "dual-carbon". In Proceedings of the Jilin Electrical Engineering Society 2022 Annual Academic Conference, Jilin, China, 2022; pp. 226–229.
18. Sun, X. Research on the current situation and development trend of waste incineration power generation in China. *Telecom World* **2020**, *27*, 137–138.
19. Li, W.; Ma, Z.; Yang, E.; Cai, Y.; Chen, Z.; Gao, R.; Yan, J.; Cao, X.; Pan, E. Characteristics of Electrostatic Precipitator Ash and Bag Filter Ash From a Circulating Fluidized Bed Municipal Solid Waste Incinerator. *Proc. CSEE* **2019**, *39*, 1397–1405. [CrossRef]
20. Chen, C.; Jin, Y.; Chi, Y. Effects of moisture content and CaO on municipal solid waste pyrolysis in a fixed bed reactor. *J. Anal. Appl. Pyrolysis* **2014**, *110*, 108–112.
21. Gu, B.; Jiang, S.; Wang, H.; Wang, Z.; Jia, R.; Yang, J.; He, S.; Cheng, R. Characterization, quantification and management of China's municipal solid waste in spatiotemporal distributions: A review. *Waste Manag.* **2017**, *61*, 67–77. [CrossRef]
22. Huang, Q.; Wang, Q.; Dong, L.; Xi, B.; Zhou, B. The current situation of solid waste management in China. *J. Mater. Cycles Waste Manag.* **2006**, *8*, 63–69. [CrossRef]
23. Ji, L.D. The current municipal solid waste management situation in Tibet. *Waste Manag.* **2009**, *29*, 1186–1191.
24. Li, X.; Bi, F.; Han, Z.; Qin, Y.; Wang, H.; Wu, W. Garbage source classification performance, impact factor, and management strategy in rural areas of China: A case study in Hangzhou. *Waste Manag.* **2019**, *89*, 313–321. [CrossRef] [PubMed]
25. Tai, J.; Zhang, W.; Che, Y.; Feng, D. Municipal solid waste source-separated collection in China: A comparative analysis. *Waste Manag.* **2011**, *31*, 1673–1682. [CrossRef]
26. Wang, C.M. Municipal solid waste management in Beijing: Characteristics and challenges. *Waste Manag. Res.* **2013**, *31*, 67–72. [CrossRef] [PubMed]
27. Wang, Y.; Zhang, X.; Liao, W.; Wu, J.; Yang, X.; Shui, W.; Deng, S.; Zhang, Y.; Lin, L.; Xiao, Y.; et al. Investigating impact of waste reuse on the sustainability of municipal solid waste (MSW) incineration industry using emergy approach: A case study from Sichuan province, China. *Waste Manag.* **2018**, *77*, 252–267. [CrossRef] [PubMed]
28. Zhou, C.; Ma, S.; Yu, X.; Chen, Z.; Yan, L. A comparison study of bottom-up and top-down methods for analyzing the physical composition of municipal solid waste. *J. Ind. Ecol.* **2021**, *26*, 240–251. [CrossRef]
29. Zhou, H.; Meng, A.H.; Long, Y.Q.; Li, Q.H.; Zhang, Y.G. An overview of characteristics of municipal solid waste fuel in China: Physical, chemical composition and heating value. *ChemInform* **2015**, *46*. [CrossRef]
30. Zhuang, Y.; Wu, S.-W.; Wang, Y.-L.; Wu, W.-X.; Chen, Y.-X. Source separation of household waste: A case study in China. *Waste Manag.* **2008**, *28*, 2022–2030. [CrossRef]
31. Chen, G. The Prediction of the Status about the Municipal Solid Waste in Beijing and the Evaluation of the Effectiveness. Master's Thesis, North China University of Technology, Beijing, China, 2009.
32. Chen, R. Analysis of Municipal Solid Disposal Status and Process Scheme of Resource Utilization in a City of Northeast China. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2014.
33. Chen, W. Comparative analysis of physical composition and characteristics of domestic waste in urban and rural areas of Beijing. *Recycl. Resour. Circ. Econ.* **2020**, *13*, 17–22.
34. Dong, X.; Xia, S.; Li, X. Physical Component Characteristics of Domestic Waste in Songjiang District, Shanghai. *Environ. Sanit. Eng.* **2015**, *23*, 26–28.
35. Dong, X.; Zhang, Y. Investigation and Analysis of Physicochemical Characteristics of Municipal Solid Waste in Shanghai. *Environ. Sanit. Eng.* **2016**, *24*, 18–21.
36. Du, C. Survey and Analysis of Municipal Domestic Waste in Dujiangyan. *Environ. Sanit. Eng.* **2016**, *24*, 8–9.
37. Du, W.; Gao, Q.; Zhang, E.; Miu, Q.; Wu, J. The Emission Status and Composition Analysis of Municipal Solid Waste in China. *Res. Environ. Sci.* **2006**, *19*, 85–90.
38. Huang, C. The Statistical Analysis of Characteristics of Municipal Solid Waste for Shenzhen. Master's Thesis, Huazhong University of Science & Technology, Wuhan, China, 2012.
39. Huang, H. Characteristic Analysis of Domestic Waste in Yanshan Area. *Environ. Sanit. Eng.* **2003**, 150–151.
40. Jiang, J.; Xiao, B.; Yang, J.; Li, J.; Shi, X. Pyrolysis Gas Characteristics of Municipal Solid Waste. *Environ. Sci. Technol.* **2006**, 79–81+120.

41. Jiang, Z.; Zhang, W.; Qi, W. Physical Properties and Change Regularity of Domestic Waste in Qingdao City. *Environ. Sanit. Eng.* **2011**, *19*, 36–37+41.
42. Li, C.; Li, G.; Jiang, J.; Pan, L.; Xu, D. Contributions of Different Components of Domestic Waste for Compost Putrescibility. *Environ. Sanit. Eng.* **2009**, *17*, 1–4.
43. Li, C. Beijing Urban Areas MSW Physical and Chemical Properties Investigation. Master's Thesis, Beijing University of Technology, Beijing, China, 2015.
44. Li, D. Inquiry and Characteristics Study on Biological Pretreatment of Municipal Solid Waste in Dalian. Master's Thesis, Dalian University of Technology, Dalian, China, 2008.
45. Li, M.; Zheng, Z. Property Change of Domestic Waste and Diversified Transition of Treatment Technologies in Jinan. *Environ. Sanit. Eng.* **2014**, *22*, 62–64.
46. Li, X.; Lu, S.; Xu, X.; Yan, J.; Chi, Y. Analysis on caloric value of Chinese cities' municipal solid waste. *China Environ. Sci.* **2001**, 61–65.
47. Li, Y. Study on Refuse Derived Fuel Product from Waste and Energy Utilization. Ph.D. Thesis, Zhejiang University, Hangzhou, China, 2018.
48. Liu, D.; Huang, M.; Ren, Y.; Ren, X. Basic Characteristics of Municipal Domestic Waste and Its Availability in Sichuan Province. In Proceedings of the Sichuan Society of Environmental Science 2011 Academic Annual Meeting, Chengdu, China, 14 December 2011; pp. 379–385.
49. Lu, X.; Yang, D.; Yao, J. Study on Influencing Factors of Municipal Solid Waste Heating Value in Taiyuan. *Environ. Sanit. Eng.* **2018**, *26*, 29–32.
50. Lv, Y. Analysis on Models to Evaluate the Lower Heating Value of Municipal Solid Waste in South China City. *China Resour. Compr. Util.* **2020**, *38*, 82–85.
51. Qu, X. Study on Life Cycle Assessment of Urban Solid waste Processing Systems in Qingdao. Master's Thesis, Qingdao University of Technology, Qingdao, China, 2011.
52. Song, H.; Wang, T. Status and Countermeasures of Domestic Waste Treatment in Zhengzhou City. *Environ. Sanit. Eng.* **2012**, *20*, 28–29+32.
53. Song, Q. Research on Hydrogen Production of Food Waste and Sewage Sludge by Anaerobic Fermentation. Master's Thesis, Dalian University of Technology, Dalian, China, 2008.
54. Tang, Y. Measurement of Heat Value for Municipal Domestic Waste in Tianjin. *Environ. Sanit. Eng.* **2013**, *21*, 26–27.
55. Tao, X.; Huang, T.; Yang, H.; Tang, X. Survey and analysis of municipal domestic waste in the urban zone of Chengdu city. *Guangdong Agric. Sci.* **2009**, 94–96.
56. Wang, G.; Zhang, H.; Wang, D.; Zhang, L.; Sun, W. Physical Composition and Characteristics Analysis of the Municipal Solid Waste (MSW) in Beijing. *Environ. Eng.* **2018**, *36*, 132–136.
57. Wang, Z.; Zhou, Y. The significance of domestic waste composition, physical and chemical properties for incineration for power generation. *Clean. World* **2020**, *36*, 51–53.
58. Wei, X.; Wang, X.; Li, L.; Liu, C.; Stanisavljevic, N.; Peng, X. Temporal and spatial characteristics of municipal solid waste generation and treatment in China from 1979 to 2016. *China Environ. Sci.* **2018**, *38*, 3833–3843.
59. Xiao, M.; Zhou, J. Investigation and Analysis on the Municipal Waste Situation of Jiujiang City. *Jiangxi Energy* **2008**, 51–53.
60. Xin, M.; Dong, Y.; Cai, Y.; Chen, L.; Xu, L.; Cheng, L. Study on thermolysis and burning of the main combustible components of city refuse. *Cem. Eng.* **2010**, 66–71.
61. Xu, Y.; Guo, D. Present status and Countermeasure of Domestic Waste in Jinan. *Environ. Sanit. Eng.* **2005**, 46–48.
62. Yang, G.; Ma, Z. Feasibility study of municipal solid waste incineration power generation in Jinhua. *Energy Eng.* **2005**, 10–13.
63. Yang, N.; Shao, L.; He, P. Study on the moisture content and its features for municipal solid waste fractions in China. *China Environ. Sci.* **2018**, *38*, 1033–1038.
64. Zhang, B. Study on Prediction Model of Municipal Solid Waste Transportation Amount and Composition. Master's Thesis, Huazhong University of Science and Technology, Wuhan, China, 2008.
65. Zhao, W. Study on Pyrolytic Combustion Characteristics of MSW and Incineration Experiment with Co-Current Shaft Furnace. Ph.D. Thesis, Northeastern University, Boston, MA, USA, 2012.
66. Wang, X.Y.; Shen, G.X.; Wang, l.; Qi, Z.F.; Dong, X.D. *Physical and Chemical Characteristics of Domestic Waste in Shanghai and Production Analysis*; Shanghai Environmental Sanitation Engineering Design Institute: Shanghai, China, 2005. Available online: https://kns.cnki.net/kcms2/article/abstract?v=0qMDjMp0v1mm0s_kT87l6ev9179YuIhHI8RM3O6ZhBFdYlqcU1le9xfJsWFN_uxF6Q8DuzreaVvWZ-SzkuE54ss9VnRZWSLN5G4zIbjk44J63R2-yDeQeZTxF8N33cNAzk7KMVDbJX0sJ_wjbCtORfkXw_5HX9_3&uniplatform=NZKPT&language=CHS (accessed on 5 December 2023).
67. *CJT313-2009*; Sampling and Analytical Methods for Domestic Waste. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2009.
68. Jia-Wei, L.; Sukun, Z.; Jing, H.; Ming, L. Status and perspectives of municipal solid waste incineration in China: A comparison with developed regions. *Waste Manag.* **2017**, *69*, 170–186.
69. Liu, X.; Wang, W.; Gao, X.; Zhou, Y.; Shen, R. Effect of thermal pretreatment on the physical and chemical properties of municipal biomass waste. *Waste Manag.* **2012**, *32*, 249–255. [CrossRef] [PubMed]

70. Chi, Y.; Yan, J.; Li, X.; Jiang, X.; Yang, J.; Ma, Z.; Ni, M.; Cen, K. Characteristics of typical municipal solid waste and heterogeneous circulating fluidized bed incineration technology. *Proc. Munic. Waste Inciner.* **2005**.
71. Li, D.; Gu, H. Investigation and Analysis of Municipal Solid Waste Status Quo in Chongqing. *Chongqing Environ. Sci.* **2001**, *23*, 3.
72. Wang, Y.; Yuan, H.; Lu, T.; Xiong, Z. Municipal solid waste heat value analysis and prediction based on level of economic development. *Eng. J. Wuhan Univ.* **2012**, *45*, 3.
73. Wang, Z. An analysis of the correlation between physical classification, elemental analysis and calorific value of domestic waste. In Proceedings of the 2017 East China Area Academic Exchange Conference of the China Coal Society, Fuzhou, China, 18 October 2017.
74. Xi, Y.; Li, H.; Fan, W. Analysis of dynamic characteristics of physical and chemical properties of municipal domestic waste. *Shanghai Environ. Sci.* **2002**, *21*, 4.
75. Xiong, C. Research on the Pyrolysis Characteristic of MSW in Nanchuan and Cold Flow Field Analysis in Circulating Fluidized Bed. Master's Thesis, Chongqing University, Chongqing, China, 2005.
76. Xiong, Q. Calculation and Comparison of Calorific Value of Domestic Waste in Selected Municipalities. *Theor. Res. Urban Constr.* **2018**, 191.
77. Zhang, X. Determination and Evaluation on Calculation Model of Calorific Value of Municipal Solid Waste in Beijing. In Proceedings of the Environmental Engineering 2018 National Academic Conference, Beijing, China, 20 August 2018.
78. Huang, B.; Li, X.; Wang, L.; Cui, Z. Analysis of Physicochemical Property and Discussion of Disposal of MSW in the Urban Zone of Chongqing City. *J. Chongqing Univ.* **2003**, *26*, 5.
79. Huang, M.; Liu, D. Characteristic and Composition of Municipal Solid Waste in Sichuan Province. *Environ. Monit. China* **2012**, *28*, 3.
80. De Clercq, D.; Wen, Z.; Fan, F.; Caicedo, L. Biomethane production potential from restaurant food waste in megacities and project level-bottlenecks: A case study in Beijing. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1676–1685.
81. Hongcai, S.; Xuanyou, Z.; Rendong, Z.; Zhihao, Z.; Yan, Z.; Gaojun, Z.; Caimeng, Y.; Dwi, H.; Mi, Y. Hydrothermal carbonization of food waste after oil extraction pre-treatment: Study on hydrochar fuel characteristics, combustion behavior, and removal behavior of sodium and potassium-ScienceDirect. *Sci. Total Environ.* **2020**, *754*, 142192. [CrossRef]
82. Jin, C.; Sun, S.; Yang, D.; Sheng, W.; Ma, Y.; He, W.; Li, G. Anaerobic digestion: An alternative resource treatment option for food waste in China. *Sci. Total Environ.* **2021**, *779*, 146397. [CrossRef] [PubMed]
83. Li, H.; Li, T.; Wei, X. Main performance analysis of kitchen waste gasification in a small-power horizontal plasma jet reactor. *J. Energy Inst.* **2019**, *93*, 367–376. [CrossRef]
84. Li, Y.; Jin, Y.; Li, J. Enhanced split-phase resource utilization of kitchen waste by thermal pre-treatment. *Energy* **2016**, *98*, 155–167. [CrossRef]
85. Li, Y.; Jin, Y.; Li, J.; Chen, Y.; Gong, Y.; Li, Y.; Zhang, J. Current Situation and Development of Kitchen Waste Treatment in China. *Procedia Environ. Sci.* **2016**, *31*, 40–49. [CrossRef]
86. Zhang, W.; Chen, B.; Li, A.; Zhang, L.; Li, R.; Yang, T.; Xing, W. Mechanism of process imbalance of long-term anaerobic digestion of food waste and role of trace elements in maintaining anaerobic process stability-ScienceDirect. *Bioresour. Technol.* **2019**, *275*, 172–182. [CrossRef]
87. Yuan, J.; Li, Y.; Wang, G.; Zhang, D.; Shen, Y.; Ma, R.; Li, D.; Li, S.; Li, G. Biodrying performance and combustion characteristics related to bulking agent amendments during kitchen waste biodrying. *Bioresour. Technol.* **2019**, *284*, 56–64. [CrossRef]
88. Zhang, W.; Wu, S.; Guo, J.; Zhou, J.; Dong, R. Performance and kinetic evaluation of semi-continuously fed anaerobic digesters treating food waste: Role of trace elements. *Bioresour. Technol.* **2015**, *178*, 297–305. [CrossRef]
89. Chen, J.; Huang, M. Pollutants emission and calorific value effect during kitchen waste co-combustion with different combustible fuel. *Environ. Prot. Technol.* **2017**, *23*, 6.
90. Guo, J. Research on the Combustion Characteristic of Municipal Solid Waste. Master's Thesis, North China Electric Power University, Hebei, China, 2008.
91. Hong, N.; Yu, H.; Xue, X.; Wang, P.; Zhan, S. Study on pyrolysis liquefaction characteristics of typical components of kitchen trash. *Chin. J. Environ. Eng.* **2010**, *6*.
92. Jin, T.; Yan, J.; Michael, B.; Moritz, M.; Cao, X.; Lu, H. Experimental study on making bio-coal from food waste by hydrothermal carbonization. *Renew. Energy Resour.* **2014**, *32*, 7.
93. Liu, L.; Li, H.; Chen, M.; Wu, H.; Ou, F. Study on combustion characteristics and kinetics of kitchen waste for degreased under different oxygen concentrations. *Chin. J. Environ. Eng.* **2015**, *9*, 929–933.
94. Qu, Z.; Liu, Z.; Zhu, Z.; Li, B.; Zhang, Y. Bio-crude Production from Kitchen Waste through Hydrothermal Liquefaction. *Acta Energiae Solaris Sin.* **2016**, *37*, 7.
95. Wang, T. Study of Mechanism for Hydrothermal Carbonization of Food Waste and the Clean and Enhanced Pelletization Properties of Hydrochar. Ph.D. Thesis, Hunan University, Changsha, China, 2019.
96. Xia, M. Physical and Chemical Characteristics Analysis of the Kitchen Waste in Shanghai. *J. Anhui Agric. Sci.* **2015**, *43*, 3.
97. Yi, R. An Experimental Research on Catalytic Pyrolysis of Municipal Solid Waste. Master's Thesis, Huazhong University of Science and Technology, Wuhan, China, 2007.
98. Zhang, J.; Wang, D.; Jiang, B.; Wei, Y. Hydrothermal liquefaction of kitchen waste for bio-oil production. *CIESC J.* **2016**, *67*, 8.

99. Zhang, X.; Xing, X.; Mi, M.; Li, Y.; Ma, P. Study on Combustion Characteristics and Kinetics of Food Waste and Its Hydrochars. *Acta Energiae Solaris Sin.* **2020**, *41*, 8.
100. Zhang, Z.; Yuan, J.; Wang, G.; Zhang, D.; Li, B.; Li, G. Effects of bulking agent amendments on the combustion properties of biological drying products of kitchen waste. *Chin. J. Environ. Eng.* **2020**, *14*, 11.
101. Zhao, X.; He, D.; Wang, L. Study on Combustion Characteristics of Kitchen Waste. *Sichuan Environ.* **2019**, *38*, 4.
102. Zhao, Y.; Liu, J.; Li, R.; Nie, Y. De-volatilization kinetics of the combustible components in municipal solid waste. *J. Tsinghua Univ. (Sci. Technol.)* **2007**, *47*, 5.
103. Wang, K. Study on Models for Predicting Heat Value of Municipal Solid Waste. Master's Thesis, Huazhong University of Science and Technology, Wuhan, China, 2007.
104. EuropeDay. Available online: https://europeday.europa.eu/index_en (accessed on 15 December 2023).
105. Zhao, S.; Li, X.; Cai, Z.; Zhao, Z. Study on the status quo and countermeasures of urban and rural living garbage classification and treatment in China. *Resour. Econ. Environ. Prot.* **2022**, 118–121.
106. Chakraborty, M.; Sharma, C.; Pandey, J.; Gupta, P.K. Assessment of Energy Generation Potentials of MSW in Delhi under Different Technological Options. *Energy Convers. Manag.* **2013**, *75*, 249–255. [CrossRef]
107. 2021 China Refuse Incineration Power Generation Market Status and Development Prospect Forecast Analysis. 2021. Available online: www.askci.com (accessed on 10 December 2023).
108. Ma, T.; Wang, X.; Hong, T.; Chen, D.; Zhang, W. Temporal and Spatial Variation & Influence Factors Analysis of Waste–to–energy Utilization Potential for Municipal Solid Waste in China. *Energy Conserv. Technol.* **2021**, *039*, 99–106.
109. Pramanik, S.K.; Suja, F.B.; Zain, S.M.; Pramanik, B.K. The Anaerobic Digestion Process of Biogas Production from Food Waste: Prospects and Constraints. *Bioresour. Technol. Rep.* **2019**, *8*, 100310. [CrossRef]
110. Porteous, A. Why energy from waste incineration is an essential component of environmentally responsible waste management. *Waste Manag.* **2005**, *25*, 459.