The Spatial Distribution and Potential for Energy Recovery of Urban-Rural Wastes in Guangdong Province, Southern China

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Abstract. Wastes-to-energy (WTE) has been widely recognized as an effective way to save resources while minimizing environmental pollution, which has become the key issue for a sustainable society. Urban-rural wastes include all kinds of waste generated during human activities, which have a wide range from municipal solid waste (MSW) to agricultural residues and animal excrement, etc. In order to evaluate their potential for energy recovery and greenhouse gas (GHG) mitigation in Guangdong province, the generation, spatial distribution and energy potential of three typical waste streams (i.e. MSW, agricultural residues and animal excrement) were investigated using statistical and estimation methods. Results showed that: (1) MSW was mainly concentrated in the Pearl River Delta, but agricultural residues and animal excrement mainly distributed in the East Wing, West Wing and Mountainous Areas; (2) energy potential of studied wastes at least can reach 15.661 million tons of coal-equivalent and corresponding GHG mitigation is 41.720 million tons CO₂ equivalent. The pattern of distributed utilization may be appropriate for rural wastes, such as agricultural residues and animal excrement, because recycling is difficult due to they are dispersed distribution. Results of this study may help decision-makers to evaluate the proper management of urban-rural wastes and can be a reference for other developing countries.

Keywords. Urban-rural wastes; wastes-to-energy; spatial distribution; Guangdong Province.

1. Introduction
In recent decades, China has experienced a rapid industrialization and urbanization development. Guangdong is a typical representative province of industrialization and urbanization with fast development of social economy. As the process of industrialization and urbanization accelerating, cities are facing the predicament of been surrounded by wastes and the restriction brought by energy consumption to economic development becomes increasingly obvious. The generation of MSW for Guangdong was 23.3 million tons in 2015, and total energy consumption was 301.45 million tons coal-equivalent [1]. Traditional MSW disposal patterns, such as the over dependency on sanitary landfill has to be converted as landfills continue to run out of space and move farther from cities [2]. The per capita emissions of GHG for the world, China and Guangdong were 4510 kg, 6093 kg and 5224 kg CO₂-equivalent, respectively in 2012 [3]. The per capita emissions for Guangdong was higher than that for the world but lower than that for China, which suggests that there is still great potential in realizing energy-saving and emission reduction. In addition, the gap between the urban and rural areas is still obvious due to regional development differentiation. In the context of rural area, a huge portion of...
agricultural residues was used as traditional biomass by rural house-holds due to energy poverty and a large amount of animal excrement were discharged into the environment without proper treatment, which have been identified as one of the main reasons for the soil, water and air pollution [4]. The WTE approaches not only can solve problems of energy shortage and environmental pollution in urban-rural areas, but also have significant socio-economic benefits.

WTE is the international research hotspot and plenty of research achievements generated on energy potential evaluation, energy conversion technologies, and associated environmental, political and financial problems [5-17]. WTE utilizes three main pathways: thermochemical, physicochemical and biochemical processes, such as incineration, gasification, anaerobic fermentation technologies and so on. The incineration and refuse derived fuel (RDF) technology for MSW proves to be efficient solutions with a relatively higher efficiency and lower operational cost [18, 19], but toxic substances produced by incineration have negative effects on the environment [16]. Bio methanation technology can prove to be the most suitable WTE technology for animal excrement [2, 20-23]. Gasification and direct combustion of agricultural residues to generate power are two main approaches for energy recovery [10, 21, 24-30]. To some extent, above studies have been analyzed the WTE potential from aspects of technology, economy, ecological environment and policy. However, most of researches have only focused on single kind of waste or energy recovery in single region (urban or rural areas). In developing countries, wastes generation and disposal approaches are obviously different between the urban area and rural area, and studies for energy recovery by various solid waste in the context of urban-rural areas are insufficient.

The objectives of this article were: (1) to identify the quantities and spatial distribution characteristics of MSW, agricultural residues and animal excrement in Guangdong Province; (2) to assess the energy recovery potential of these wastes base on three technical scenarios: incineration of MSW, direct combustion of agricultural residues to generate power and anaerobic fermentation of animal excrement to generate biogas.

2. Materials and Methods

2.1. Study Area

Guangdong province, with longitude and latitude ranging from 111°59'E to 112°2'E and 22°56'N to 22°60'N, respectively, is located in the southern of China (figure 1a). It is one of the major provinces of economy and population in China. The permanent population was 10.849 million and per capita GDP was 67,503 Yuan in 2015 [1]. Guangdong Province has 21 cities that have subdivided into four geographic regions: the Pearl River Delta, East Wing, West Wing and Mountainous Areas. The region of Pearl River Delta includes 9 cities (Guangzhou, Foshan, Zhaoping, Zhongshan, Zhuhai, Jiangmen, Huizhou, Dongguan and Shenzhen) and it was the most developed region with dense population and developed economy (figures 1b and 1c). There were a large number of industrial enterprises distributed in this region. The East Wing includes 6 cities (Shantou, Chaoshou, Jieyang, Shanwei, Meizhou and Heyuan); the West Wing includes 4 cities (Yunfu, Yangjiang, Maoming and Zhanjiang) and the Mountainous Areas includes 2 cities (Qingyuan and Shaoguan).

2.2. The Current Status of Energy Recovery

At present, energy utilization for wastes mainly focused on MSW and Sanitary landfill was the main disposal way [31]. The delivering quantity and disposed volume of MSW in Guangdong in 2015 were 23.2 and 21.2 million tons, respectively. Treatment rate of delivering quantity was 91.6%. Quantity of sanitary landfill, incineration and other disposal were 11.38, 7.08 and 0.28 million tons, respectively [32]. Incineration accounts for 30% of total amount at present. Figure 2 illustrated the percentage of sanitary landfill, incineration and other disposal for 21 cities of Guangdong Province and figure 3 mapped the geographic location and processing capacity of landfills and incineration plants (Data from Guangdong Construction Yearbook [33]).

Figures 2 and 3b showed that sanitary landfill adopted by almost all of cities but incineration for power generation only concentrated in the Pearl River Delta region (figure 2 and 3a). Except Jiangmen
and Zhaoqing, all of cities in this region have established incineration plant, and the percentage of incineration for Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Zhongshan, Huizhou, Shantou and Maoming were 22%, 48%, 26%, 28%, 77%, 98%, 25 %, 18 % and 30%, respectively. In the region of West Wing, only Maoming established an incineration plant. In the regions of East Wing and Mountainous Areas, there were no incineration plants. Therefore, potential for energy recovery of MSW is still very large in Guangdong.

Figure 1. Map of study area with distribution of population and per capita GDP, (a) location of Guangdong Province in China map, (b) population distribution of 21 municipalities in Guangdong Province in 2015, (c) per capita GDP of 21 municipalities in Guangdong Province in 2015.

As regards the main organic wastes, animal excrement and agricultural residues have not have not been formed large-scale utilization. Domestic biogas constructions in Guangdong rural area have reached 325,000 households and the generation of biogas was about $1.48 \times 10^9$ m$^3$ [34]. About 20% agricultural residues been burned in agricultural field without proper treatment and large portion of the rest was used for traditional biomass energy or discarded [35].

Figure 2. Disposal approaches for MSW in 21 cities of Guangdong in 2015.
2.3. Wastes Generation Calculations

Three kinds of waste were investigated in this study, but only MSW have complete statistics data in Guangdong statistical yearbook. Although animal excrement and agricultural residues did not have published data, they can be calculated on the basis of statistics data and estimation formula. The estimation methods for animal excrement and agricultural residues were listed in table 1.

The growth period of livestock commonly taken as being over one year and that of poultry is calculated according to actual breeding days, which totals about 55 days and 210 days for broilers, ducks and geese, respectively. The annual emissions of Cattle ($A_1$), goats ($A_2$), hogs ($A_3$) and poultry ($A_4$) are about 7300, 474, 1367.6 and 32.03 kg/head, respectively [4].

The generation of agricultural residues calculated using the ratios of agricultural residue to agricultural product in china (table 2).

Using above estimation method and combine with statistical data, the wastes generation of each city has figured out, and then their spatial distribution were mapped using ArcGIS 10.2 software.

| Waste categories                  | Estimation formula | Parameters implication                                                                 |
|-----------------------------------|--------------------|--------------------------------------------------------------------------------------------|
| Animal excrement [4]              | $P = \sum A_i \times X_i$ | Where $P$ denotes the annual production of livestock and poultry excrement; $A_i$ is the annual emission of type $i$ animal or poultry; $X_i$ is the number of type $i$ animal or poultry stock on hand at the end of year; $n=4$; 1-Cattle; 2-Goats; 3-Hogs; 4-Poultry. |
| Agricultural residues [26, 30]    | $P = \sum R_i \times T_i$ | Where $P$ denotes the annual production of agricultural residues; $R_i$ is grain-straw ratio of crop $i$; $T_i$ is yield of crop $i$; $n=7$; 1-Rice; 2-Potato; 3-Soybeans; 4-Sugarcane; 5-Peanut; 6-Tobacco; 7-Vegetables. |

2.4. Energy Potential and GHG Emissions Mitigation Calculations

According to the calorific values (CV) of standard coal (29.26 GJ/t), potential for energy recovery can be expressed with standard coal based on CV equivalent because coal is the mainstay of fossil energy in China. The WTE opportunities in this study have undertaken in the context of three scenarios: (1) incineration, (2) direct combustion and (3) anaerobic fermentation. Energy potential for the first two scenarios can calculate directly base on CV of wastes but the last scenario have to be first calculated the generation of biogas and then convert to standard coal according CV of biogas (20.89 KJ/m$^3$).
Table 2. Estimated ratios of agricultural residue to agricultural product.

| Type of crop     | Type of residue | Ratio of residue to product [30, 36] | Total ratio (R) |
|------------------|-----------------|-------------------------------------|-----------------|
| Rice             | Straws          | 0.94                                | 0.94            |
| Potato           | Stem and leaves | 0.96                                | 0.96            |
| Soy beans        | Straws stalk    | 1.6                                 | 1.6             |
|                  | Bagasse         | 0.24                                | 0.34            |
| Sugarcane        | Cane stalk sheath | 0.1                              | 0.1             |
|                  | Stalks          | 1.5                                 | 1.78            |
| Peanut           | Peanut hull     | 0.28                                |                 |
| Tobacco          | Stems leaves    | 1.6                                 | 1.6             |
| Vegetables       | Vine stems shell | 0.1                             | 0.1             |

MSW can be further categorized into food waste, paper, textile, plastics, metals, and glasses. The moisture content and CV of each constituent were listed in table 3. The percentages of each constituent to total amount in Guangdong were 53% (food waste), 8% (paper), 5% (textile), 33% (plastic), <1% (Glass & metal), respectively [37]. Energy recovery from glass and metal can neglected due to their low energy content [16, 38].

The potential of biogas generation in Guangdong can be estimated on amount of COD by animal excrement. The coefficients of COD emission from cattle, hogs, goats and poultry were 848.2, 36, 4.4 and 1.765 kg/head×annum, respectively [4, 39]. Biogas obtained from animal excrement calculated by the following equation:

\[ PE = Q_{COD} \times D \times C_b \] (1)

where PE indicates biogas potential by wastes from animal excrement; \( Q_{COD} \) is the amount of COD produced. By calculating, the total amount of COD emission from cattle, hogs, goats and poultry were 2055, 769, 2 and 572 thousand tons, respectively; D denotes the available percentage of COD disposed, taken as 80%, and \( C_b \) is the coefficient of biogas production, taken as 0.538 m³ according to local climate (The mean annual temperature is 15-25 ℃) [4, 22].

As biomass can sustainable supply, the net CO₂ emissions from agricultural residues and animal excrement during the consumption process are considered to be equal to zero [15, 40], therefore, a large amount of GHG emissions can be avoided due to the saved fossil energy to produce equal amount of heat or electricity produced by biomass energy. The GHG emissions from MSW incineration are mainly determined by carbon content in the MSW [41]. The C concentration in MSW positively related to the generated volumes of organic materials, such as food waste and paper, but had a relatively lower relationship to textiles, metals and glasses [16]. Therefore, the net CO₂ emissions from MSW incineration also can be neglect from a lifecycle perspective. Previous study showed that the mitigation of GHG emissions for saving a ton of standard coal is about 2.664 t CO₂-equivalent [42], so the total amount of GHG reduction was calculated according saving amount of standard coal.

3. Results and Discussion

3.1. Wastes Generation from 2011 to 2015

The generation trends of MSW, animal excrement and agricultural residues from 2010 to 2014 illustrated in figure 4 in the form of histogram.

Figures 4a and 4c showed that the rising trends for generation of MSW and agricultural residues in the recent 5 years and total amount of them had exceeded 23 and 21 million tons in 2015, respectively. The rising trends of MSW maybe owe to the sustainable increasing population. The permanent population of Guangdong has increased from 105.05 million to 108.49 million in five years due to rapid industrialization and urbanization [43]. The amount of agricultural residues mainly dominated by the
sown area of major crops, which have been increased from 141.6 million acres to 143.9 million acres in recent 5 years [43]. That may be the main reason for continuous increasing generation of agricultural residues. As the main source of organic contamination, disposal approaches for animal excrement have aroused wide concern. There are about 25,000 pig farms have being forced to closed by the local government in recent years according to official documents, that is why the amount of animal excrement sustainable decreasing from 2011 to 2015.

![Image](image_url)

**Figure 4.** The generation trends of wastes from 2011 to 2015, (a) MSW, (b) animal excrement, and (c) agricultural residues.

### 3.2. Spatial Distribution Characteristics

The spatial distributions of MSW, agricultural residues and animal excrement mapped using ArcGIS illustrated in figure 5. There only displayed the spatial distribution of 2015 because spatial evolution is a slow process and the overall trends of spatial distributions have not significantly changed in the recent five years.

Figure 5 showed that the spatial distribution of wastes have obvious regional characteristics. As the most developed region in Guangdong Province, the Pearl River Delta was abundant in MSW, but amounts of agricultural residues and animal excrement were very little (figure 5a). There is no doubt that is because the Pearl River Delta is the core region of modern manufacturing with very little agricultural land. Regions of East Wing, West Wing and Mountainous Areas were rich in agricultural residues and animal excrement, but quantity of MSW was very little (figures 5b and 5c). These regions are less developed areas with sparse population and lagging economy and they take agriculture as their dominant industry, So agricultural residues and animal excrement were rich in these regions.

### 3.3. Energy Potential and GHG Emissions Mitigation

Results of Energy potential and GHG emissions mitigation of MSW and agricultural residues listed in table 3; Potential for energy recovery and environment benefit of animal excrement were displayed in table 4.

As shown in table 3, if all of MSW was incinerated, potential for energy recovery will reach 10.14 million tons coal-equivalent and GHG emissions reduction will reach 27.01 million tons CO$_2$-equivalent. Actually, as mentioned above, the utilized portion already accounts for 30% of total amount at present and this portion should subtracted when calculating developing potential. So energy developing potential of MSW is 7.01 million tons coal-equivalent and corresponding GHG emissions reduction is 18.91 million tons CO$_2$-equivalent. However, energy potential of food waste is very low due to its low net CV and high moisture content (85%), which is an obstruction for energy recovery. Previous studies
also indicate that waste incineration is only suitable for combustible MSW with non-biodegradable matter and low moisture content [38, 44]. Therefore, making biogas using food waste may be better than direct incineration. Food waste is a highly desirable substrate for making biogas due to its high biodegradability and methane yield [12, 45, 46].

If all of agricultural residues energy utilized by direct combustion to generate power, the potential for energy recovery could reach 7.71 million tons coal-equivalent and GHG mitigation will reach 20.57 million tons CO₂-equivalent. The collectable coefficient and moisture content of agricultural residues have taken into consideration when estimating the maximum available supply of dry material. However, only several main agricultural crops were involved in this study and many subtropical fruits, such as banana, pineapple and mangoes, and garden waste did not include due to incomplete statistic data. It will be a tremendous number for energy recovery if all of these wastes have taken into account, because these wastes were abundant in Guangdong, such as garden waste [47]. In addition, agricultural residues can be energy utilized by multiple approaches but this study only considered the method of direct combustion to generate power, which is suitable for China’s situations because many cogeneration energy plants already went into production [48]. Energy recovery for agricultural residues using gasification and RDF technology also have a broad prospect in China, but they were not taken into account in this study due to data missing.

The potential of biogas generation for animal excrement, in theory, is $1.462 \times 10^9$ m$^3$ (table 4). Converting biogas to standard coal, potential for energy recovery is 1.045 million tons coal-equivalent and GHG mitigation is 2.782 million tons CO₂-equivalent (table 4). As mentioned before, the amount of actually developed was about 10% of theoretical value. Conversion of animal wastes to biogas using distributed plants has become one of the most attractive technologies for energy recovery in Europe and Germany [49], but in China, biogas development and utilization mainly based on single small-scale

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**Figure 5.** Spatial distribution of wastes. (a) MSW, (b) animal excrement, and (c) agricultural residues.
In sum up, energy recovery potential for MSW, agricultural residues and animal excrement is at least 18.895 million tons coal-equivalent and GHG mitigation potential is 50.336 million tons CO₂-equivalent in theory. Subtracting the portion of already energy utilized, the developing potential of these wastes is 15.661 million tons of coal-equivalent and corresponding GHG emissions reduction is 41.720 CO₂ million tons CO₂-equivalent. Despite the developing potential is prospective, waste recycling is very difficult, especially for rural wastes, due to they are dispersed distribution. Therefore, distributed utilization based on local scenarios should be appropriate for rural areas [48].

### Table 3. Energy potential and GHG mitigation estimation for MSW and agricultural residues.

| Category of wastes     | Generation (10⁴t) | Collectable coefficient (%) | Moisture content (%) | Calorific value (GJa) | Energy recovery (coal-eq 10⁴t) | GHG reduction (CO₂-eq 10⁴t) |
|------------------------|-------------------|-----------------------------|---------------------|-----------------------|-------------------------------|-----------------------------|
| Food waste             | 1230              | -                           | 85 [50]             | 4 [51]                | 25                            | 67                          |
| Paper                  | 186               | -                           | 5 [50]              | 16 [51]               | 96                            | 257                         |
| Textile                | 116               | -                           | 0.5 [50]            | 18 [51]               | 71                            | 189                         |
| Plastic                | 765               | -                           | 10 [50]             | 35 [51]               | 822                           | 2190                        |
| Glass & metal          | 23                | -                           | 5-10 [50] ≤1 [51]   | -                     | -                             | -                           |
| Rice                   | 1023              | 0.83<sup>30</sup>           | 6 [30]              | 14 [30]               | 381                           | 1016                        |
| Soy beans              | 161               | 0.73<sup>30</sup>           | 11 [30]             | 13 [30]               | 46                            | 124                         |
| Sugarcane              | 27                | 0.56<sup>30</sup>           | 10 [30]             | 15 [30]               | 7                             | 19                          |
| Peanut                 | 370               | 0.97<sup>30</sup>           | Drie [30]           | 15 [30]               | 184                           | 489                         |
| Peanut                 | 194               | 0.83<sup>30</sup>           | 10 [30]             | 15 [30]               | 74                            | 198                         |
| Tobacco                | 9                 | 0.95<sup>30</sup>           | 4 [30]              | 11 [30]               | 3                             | 8                           |
| Vegetables             | 344               | 0.50<sup>30</sup>           | Drie [30]           | 13 [30]               | 76                            | 203                         |
| Total amount           | 1014              |                             |                     |                       |                              | 2701                        |

### Table 4. Energy potential and GHG mitigation estimation for animal excrement.

| Animal excrement COD (10⁴t) | Biogas generation (10⁴m³) | Energy recovery (coal-eq 10⁴t) | GHG reduction (10⁴t) |
|-----------------------------|---------------------------|--------------------------------|---------------------|
| Cattle                      | 2055                      | 88400                          | 63.2                | 168.2                           |
| Goats                       | 2                         | 100                            | 0.1                 | 0.2                              |
| Hogs                        | 769                       | 33100                          | 23.6                | 63.0                             |
| Poultry                     | 572                       | 24600                          | 17.6                | 46.8                             |
| Total amount                | 3398                      | 146200                         | 104.5               | 278.2                            |

### 4. Conclusion

The generation trends of MSW and agricultural residues have been rising from 2011 to 2015, but generation trends of animal excrement has been decreasing in the recent 5 years. The spatial distribution of waste has distinctive regional characteristics. MSW was mainly concentrated in the Pearl River Delta, but agricultural residues and animal excrement mainly distributed in the East Wing, West Wing and Mountainous Areas. The developing potential of urban-rural wastes in Guangdong is about 15.661 million tons of coal-equivalent and corresponding GHG mitigation is 41.720 CO₂ million tons CO₂-equivalent. If take all kinds of organic wastes into account, such as garden waste, energy potential of urban-rural wastes will be much larger. The distributed utilization pattern may be appropriate for rural wastes because waste recycling is difficult due to they are dispersed distribution. Results of this study may help decision-makers to evaluate the proper management of urban-rural wastes and can be a
reference for other developing countries.

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