Biomass Resource Utilization and Carbon Emission Reduction Potential in Municipal Solid Waste

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Abstract. Under the background of global warming, waste biomass is regarded as a resource that can be an alternative to fossil fuels. Many researchers have been taking the way of utilizing biomass resources and the carbon reduction it brings as a new research direction. Municipal domestic waste (MSW), as one of the biomass sources, has also been emphasized for its resource utilization. This paper illustrates the importance of biomass resource utilization in MSW and three newer ways of resource treatment in the last decade. Then the carbon reduction potential is estimated. The results indicate that biomass resource utilization is clearly related to the current situation of global warming control. The three types of resource utilization in MSW are hydrothermal treatment, pyrolysis and anaerobic treatment, of which hydrothermal and anaerobic treatment are suitable for the resource treatment of kitchen waste in MSW, while pyrolysis can be directly used for the treatment of MSW. It is also predicted that when all kitchen waste is treated by anaerobic digestion and the rest of the waste is incinerated or pyrolyzed in 2025, it can bring nearly 100 million tons of carbon dioxide equivalent emission reduction. The carbon reduction potential is huge. This study provides a reference for the subsequent treatment of MSW and the prediction of its carbon emission reduction.

Keywords: Municipal solid waste; carbon emission reduction; anaerobic digestion; pyrolysis; hydrothermal.

1. Introduction

From the 1997 Kyoto Protocol, the first document in human history to limit greenhouse gas emissions in the form of regulations, to the 2015 Paris Agreement, people around the globe are becoming increasingly aware of the importance of curbing global warming from controlling greenhouse gas emissions. The Paris Agreement has set as its main goal to limit the increase in global average temperature to 2 °C above pre-industrial levels. After studies have found that fossil energy sources contribute to huge carbon emissions, people have explored waste biomass as a resource that can replace fossil energy sources without contributing to excessive carbon emissions. Some scholars have analyzed the utilization of biomass from agricultural waste, and by quantifying the biomass energy potential and emission reduction effect of crop residues and livestock excreta in northern China, they found that under reasonable development and utilization, agricultural waste biomass can replace about 6.66 million tons of standard coal or 5.5 billion m^3 of natural gas, which has the emission reduction effect of reducing CO_2 emissions by about 17.01 million tons [1]. Some researchers have also studied the resource utilization of organic biomass wastewater. By analyzing and studying the anaerobic digestion project of a wastewater treatment in Jilin Province in China, the researcher found that the project could reduce greenhouse gas emissions by 9414 tCO_2e per year [2]. The carbon reduction potential of biomass resource treatment is huge.

Municipal domestic waste (MSW), as a kind of organic waste biomass, also has its own way of resource utilization. The main purpose of this paper is to explore the ways of converting biomass from MSW into usable resources and its contribution to carbon emission reduction under the background of controlling global warming. Firstly, the importance of biomass resource utilization in municipal domestic waste is explained from four aspects: the current situation of MSW in China, the harm brought by global warming, the relationship between global warming and carbon emission reduction, and the relationship between carbon emission reduction and biomass resource utilization. Then several newer ways of biomass resource utilization in the last decade are introduced respectively, and finally the contribution potential of carbon emission reduction from the methods therein is estimated.

2. Importance of Utilizing Biomass Resources from MSW

2.1. Current Situation of MSW in China

Relevant data have shown that in recent years, due to economic development and the improvement of people's living standards, the production of MSW in Chinese cities led by "Beijing, Shanghai and Guangzhou" has had a significant upward trend (Fig. 1). Annual report on the prevention and control of environmental pollution by solid waste in large and medium-sized cities posted by the Ministry of Ecology and Environment shows that as early as 2017, the total annual production of MSW in 202 large and medium-sized cities has exceeded 200 million tons [3]. The annual harmless disposal of MSW rose from 180.13 million tons in 2015 to 240.13 million tons in 2019 [4]. At present, the rate of harmless disposal of MSW (amount of harmless disposal of MSW/total production of MSW) is close to 100% in most cities in China, but the disposal method still needs to be improved. The demand of the relevant departments for waste treatment do not only remain in the harmless treatment rate, but also have higher standards for the utilization rate of waste resources, which attaches importance to green and sustainable development.

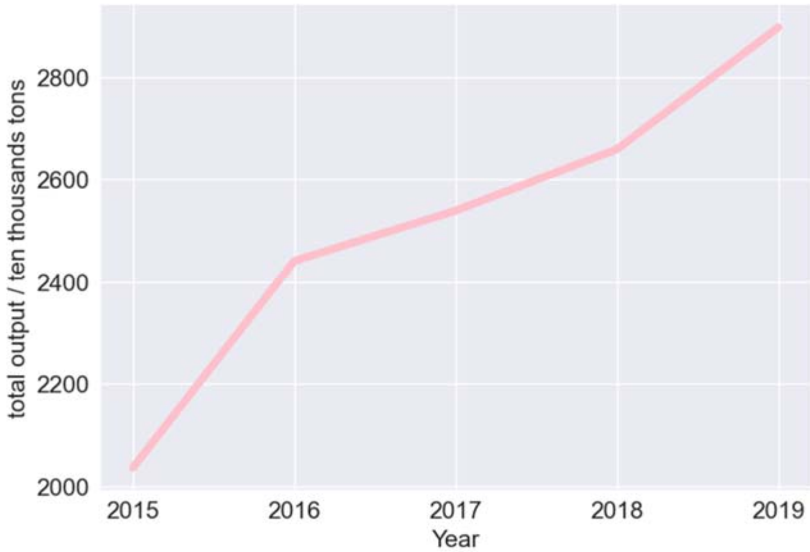

Fig 1. The trend of total MSW production in Beijing, Shanghai and Guangzhou (Photo/Picture credit: Original)

2.2. Necessity of Biomass Resource Utilization

In the context of sustainable development, "carbon emission reduction" is becoming a hot topic, as people around the world, especially in economically developed cities, are concerned about the threats of global warming. And global warming is related to the increase in the concentration of carbon dioxide (CO_2) in the atmosphere. Since the end of the twentieth century, the frequency of extreme weather events has caused economic losses and even threatened the lives of people around the world. The Intergovernmental Panel on Climate Change (IPCC) has attributed these widespread, intense, and catastrophic extreme weather events to global warming because it is global warming that increases the frequency of extreme weather events by increasing atmospheric instability. Unstable atmospheric conditions contribute to the occurrence of intense convective weather such as rain showers. In addition, warm air has a larger saturation mixing ratio than cold air, meaning that warm air can hold more water vapor when it is saturated. So as the globe warms, the likelihood of extreme heavy precipitation increases, while average precipitation is increasing. What's more, with the combined effects of urbanization and heat island effect, urban areas have a more prominent warming trend under the background of global warming, and they are also more vulnerable to extreme weather, especially extreme heat, extreme precipitation and flooding [5]. The increase in greenhouse gases such as carbon dioxide enhances the greenhouse effect thereby warming the earth. In the last century, scientists modeled that a doubling of carbon dioxide would result in a corresponding increase in global average temperature of approximately 2.93 °C, so it is urgent to work on reducing the increase in atmospheric carbon dioxide [6].

Chen et al. indicated through calculations that anthropogenic carbon dioxide emissions contribute more to the increasing trend of carbon dioxide concentration in the atmosphere, accounting for 48.4% [7]. Then, to reduce carbon emissions, human activities that emit too much carbon dioxide need to be controlled, one of which is the over-exploitation and over-use of fossil energy. Due to the urgent need for energy use but at the same time fossil energy stocks are running out, people are looking to biomass resources. Biomass is the most advantageous energy alternative because it contains similar chemical elements to fossil energy and is a renewable energy source. The extraction of fossil energy enables the carbon elements in the geological soil to return to the surface, and the burning of fossil fuels makes the carbon elements form carbon dioxide and emit into the atmosphere, while the utilization of biomass energy is artificially involved in the carbon cycle, reusing the carbon elements in nature without increasing the concentration of carbon dioxide in the atmosphere [8]. MSW is produced in large quantities and is rich in biomass, which can be used to reduce the use of fossil energy while consuming the excess amount of MSW and then to achieve carbon emission reduction.

3. Utilization of Biomass Resources from MSW

MSW refers to the solid waste generated in the daily life and activities of urban residents, which can be divided into four categories: recyclable waste, kitchen waste, hazardous waste and other waste, of which recyclable waste and kitchen waste account for the majority. Recyclable waste, such as paper and plastic, can be recycled and reused. Kitchen waste is a kind of biomass, including food scraps generated from daily household and food service. It has a high water content, and that is why it is also known as wet waste. It also has a high content of organic matter and fats.

3.1. Hydrothermal Technique

Biomass hydrothermal treatment technology is a thermochemical conversion process that thermally decomposes biomass in a high temperature and high pressure aqueous phase, including hydrothermal liquefaction, hydrothermal carbonization and hydrothermal gasification, and the type depends on the specific reaction temperature and pressure. Hydrothermal technique is suitable for organic solid wastes with high water content, i.e. kitchen waste as mentioned earlier. Subcritical water (200-374 °C) and supercritical water (374+ °C) in hydrothermal reactions are environmentally friendly solvents and catalysts that can reduce or replace the use of harmful solvents and catalysts.

Hydrothermal liquefaction (HTL) is a process in which biomass feedstock is converted to bio-oil in high-pressure subcritical water and produces aqueous phase products, solid residues and gaseous by-products. Fig. 2 presents the process of generating bio-oil from kitchen waste through HTL. The solid-liquid mixture formed after liquefaction in high pressure hot water is separated into solid phase and aqueous phase products by filtration. An organic solvent is added to the solid phase, and the solid residue, which is insoluble in the organic solvent, is separated out. And the product liquid bio-oil is extracted by the organic solvent. Govindasamy Gopalakrishnan stated that HTL is a process that artificially simulates the formation of fossil fuels by hydrothermal reactions in the natural deep earth and is the only thermochemical conversion method that has the ability to convert wet biomass into bio-oil [9]. Chen et al. pointed out that HTL can convert 30%-70% of organic biomass into bio-oil with a calorific value of 75%-90% of petroleum. They used the bio-oil produced by HTL, which was refined, in internal combustion engines, and found that all aspects of bio-oil met the current requirements of internal combustion engines [10]. Therefore, bio-oil is a renewable biomass fuel with great potential to replace fossil fuels. But it should be noted that the bio-crude oil produced by HTL cannot be used directly and needs to be refined. In addition, certain high-protein biomass feedstock components are converted into bio-oil with high nitrogen content, and the nitrogen oxides produced by its combustion can pollute the environment. Also, the aqueous phase produced has a large amount of toxic and hazardous substances, which will also cause environmental pollution if it is not treated effectively and discharged directly. But it is not a problem because the aqueous phase can be recycled as a reaction solvent for hydrothermal liquefaction, which can improve the yield and calorific value of bio-oil.

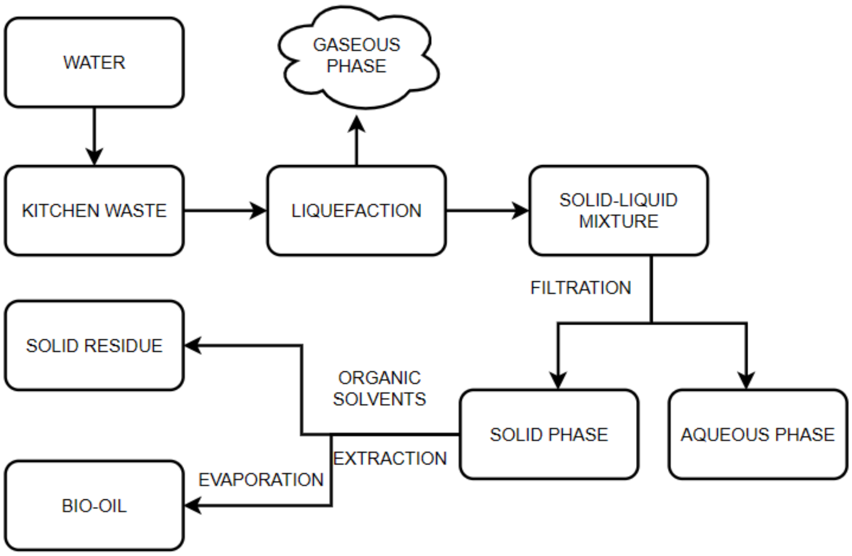

Fig 2. Hydrothermal liquefaction process of kitchen waste. (Photo/Picture credit: Original)

Hydrothermal carbonization (HTC) converts biomass feedstocks into coal-like biochar materials by enriching carbon through dehydration and decarboxylation reactions. HTC differs from HTL and HTG in that the HTC reaction requires lower temperatures (180-250 °C) and pressures (2-6 MPa). Hydrothermal chars are good solid fuels with a wide range of applications, and their calorific value is comparable to that of bituminous coal in fossil fuels. Moreover, hydrothermal char produced by higher temperature hydrothermal process has the property of high ignition point, which facilitates its transportation and storage and makes it easier to achieve marketable applications [11]. Compared to coal, hydrothermal charcoal also has lower CO_2 equivalent emissions of 0.45-0.70 kg/kWh (125-194.5 g/MJ) compared to 1.05-1.40 kg/kWh (291-389 g/MJ) for lignite in coal [12]. Of course, HTC also produces aqueous phase by-products, and similar to HTL, the aqueous phase can be recycled for hydrothermal reaction. It can improve both the hydrothermal char yield and the combustion performance of the produced hydrothermal char. Additionally, today's new direction in HTC technology, Co-Hydrothermal Carbonization (Co-HTC), literally, is the HTC of kitchen waste with other waste biomass, such as garden waste and sludge, which can produce high-quality biochar materials that are closer to the properties of coal.

Hydrothermal gasification (HTG) is a process of producing H_2, CH_4, CO and CO_2 based gases from wet biomass feedstock in supercritical water, and a small amount of liquid bio-oil is also produced (Fig. 3). Kitchen waste contains large amounts of C and H elements, which can easily be used to produce hydrogen through HTG. Both H_2 and CH_4 are clean energy sources. Synthetic natural gas (SNG), which is produced by combining H_2 and CH_4, is also a clean energy source. All of these can replace fossil energy to help reduce greenhouse gas emissions. Studies have shown that HTG of low concentration or single component in kitchen waste is more effective. An important reason is that the components of kitchen waste interact with each other during the gasification process, inhibiting the gasification and reducing the efficiency of gasification [13].

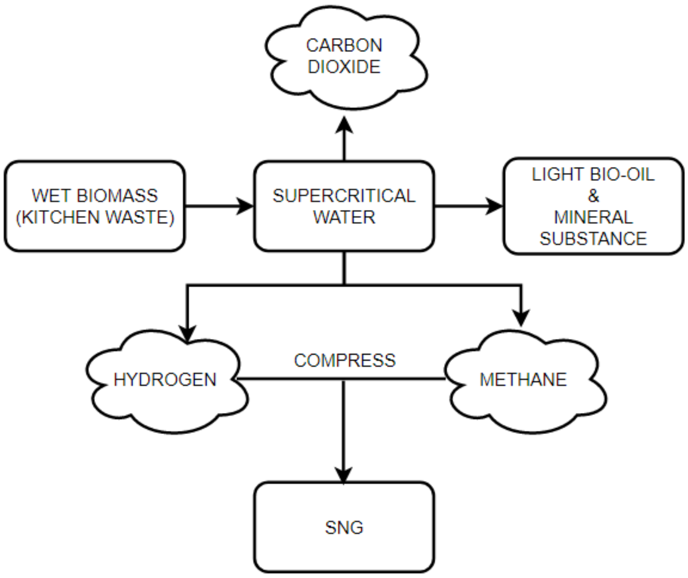

Fig 3. Hydrothermal gasification process of kitchen waste. (Photo/Picture credit: Original)

3.2. Pyrolytic Technique

Biomass pyrolysis is defined to be the process of thermal decomposition of biomass under anaerobic or anoxic and high-temperature conditions, with large-molecule organic matter cracking into small-molecule substances. Pyrolysis is suitable for treating organic biomass waste with low moisture content, including waste paper, hair, etc. It can directly treat MSW that has been pre-dried without garbage classification. MSW generally undergoes three stages during pyrolysis. The first stage is the preliminary pyrolysis, which occurs at 200-400 °C. The second stage occurs when the temperature reaches 400 °C or more and the second pyrolysis occurs, and the third stage, with the final temperature of pyrolysis, is 700-800 °C [14]. Similar to hydrothermal technologies, pyrolysis can ultimately produce bio-oils, gases dominated by H_2, CH_4, CO_2 and CO, and biochar, where the main types of products are related to the pyrolysis temperature and heating rate. Based on these factors, pyrolysis technologies are categorized as slow pyrolysis, fast pyrolysis and flash pyrolysis. Low temperatures (300-500 °C) and low heating rates (0.1-1 °C/s) correspond to slow pyrolysis [14], which is the most conventional and traditional type of pyrolysis, at which time biochar is the greatest product. Reactions with medium temperatures (500-700 °C) and higher heating rates (10-200 °C/s) are fast pyrolysis, and the main product is bio-oil. High temperatures (≥700 °C) and very high heating rates (≥1000 °C/s) correspond to flash pyrolysis, and the main product is non-condensable combustible gas. In fact, pyrolysis produced oil is not as high quality as hydrothermal produced oil, which has a relatively high calorific value and is easier to use as a liquid fuel. Because pyrolysis oil has relatively more hydrophilic organic compounds and high water content, low calorific value, and less stability. In this regard, many domestic and foreign researchers are also studying the co-pyrolysis, which can reduce the reaction temperature and increase the yield and quality of bio-oil compared to the individual pyrolysis of biomass.

3.3. Anaerobic Treatment

Anaerobic digestion is a common anaerobic treatment method, and is currently the main way to resource utilization of urban kitchen waste in China. Anaerobic digestion refers to the process of using anaerobic organisms to decompose biodegradable organic matter in an anaerobic environment. As shown in Fig. 4, it consists of three stages: hydrolysis, acid production and methane production, which can convert starch, cellulose and carbohydrates in kitchen waste into biogas. The saccharides produced by hydrolysis can also be used to produce fuel ethanol. Waste oils and fats from kitchen waste can be used to make biodiesel through high-temperature cracking or other methods. Fuel ethanol and biodiesel are two liquid biomass fuels that are currently mainstreamed globally. They are renewable and clean energy sources with low carbon emissions compared with traditional fossil fuels, with 34.00-56.00 g/MJ for fuel ethanol and 39.00-76.00 g/MJ for biodiesel [15].

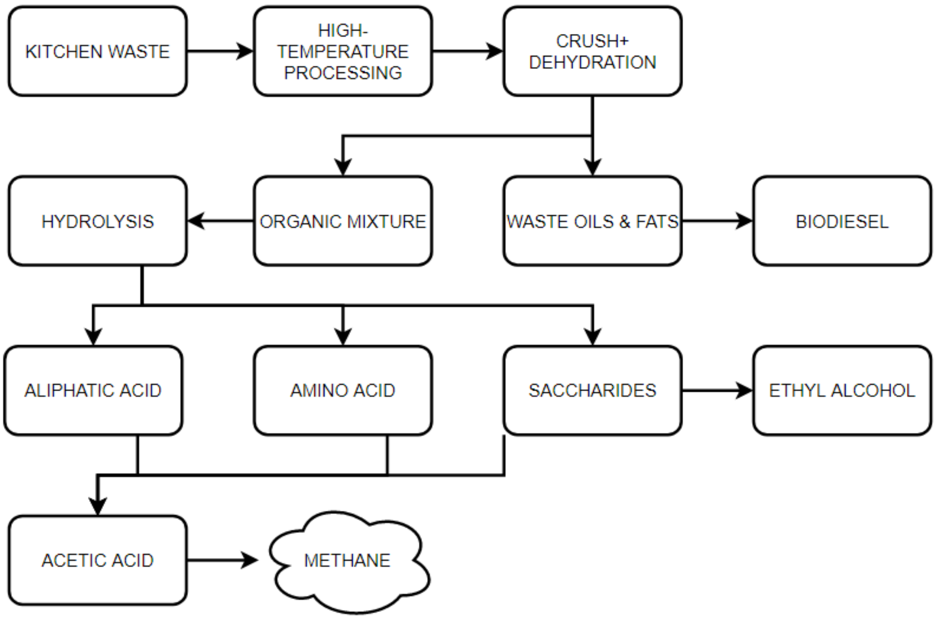

Fig 4. Process of producing fuel ethanol and biogas from kitchen waste by anaerobic treatment. (Photo/Picture credit: Original)

4. Analysis of Current Status of Carbon Emissions and Carbon Reduction Potential

Anaerobic treatment has been a popular way to deal with kitchen waste resources in cities for a long time, but it has not yet been widely used. Hydrothermal technology for kitchen waste treatment is still rarely used and has not been industrialized, and the technology is not yet mature enough. Kitchen waste in some cities is still sent to landfills or incinerators. However, landfills not only emit large amounts of carbon, but also cause atmospheric or soil pollution. As a result, this method of waste disposal has been eliminated in many countries, and China is gradually reducing the amount of landfills. As for the incineration of kitchen waste, it is not only inefficient in resource utilization, but also produces dioxin and other toxic gases that pollute the atmosphere. Incineration is also not used for the treatment of hazardous waste because of the release of harmful toxic substances. But it has to be admitted that incineration can process a large amount of garbage efficiently, with high carbon emission reductions. In contrast, pyrolysis is a relatively low-polluting technology with similarly high carbon emission reductions. It is an emerging waste treatment method in recent years.

Currently, incineration is the main treatment method for MSW in China, followed by sanitary landfill. In 2020, the amount of harmless MSW treatment in China was 234,523,300 tons, of which 146,076,400 tons were incinerated and 77,715,400 tons were sanitary landfilled [4]. Calculated according to the basic carbon emission formula (1) provided by IPCC and the carbon emission factor data in Table 1, the total carbon dioxide emission reduction from incineration and landfill in 2020 is 42,365,825 tons (in terms of CO_2 equivalent).

$$\text{GHGs Emissions } (tCO_2e) = \text{Activity Data } (t) \times \text{Emission Factor } (tCO_2e/t) \tag{1}$$

Table 1. Carbon emission data for four types of waste disposal.

Treatment	Carbon dioxide emission factor (tCO_2e/t)	Explanation	References
Sanitary landfill	0.577	Based on the characteristics of waste components in Shanghai, China	[16]
Incineration power generation	-0.597	Based on a sample of domestic waste obtained from Shanghai, China And the method of Life Cycle Assessment (LCA)	[17]
Anaerobic digestion	0.03653	Based on a 300 t/day anaerobic digestion plant in Shanghai, which anaerobic digested 1t of kitchen waste and the product methane was purified and used to generate electricity	[16]
Pyrolysis power generation	-0.535	Based on a sample of domestic waste obtained from Shanghai, China and method of LCA	[17]

According to the data on the amount of harmless treatment of MSW from 2015 to 2020, it is concluded that the compound annual growth rate of the amount of harmless treatment of MSW in these five years is about 0.054% [4]. From this growth rate is expected in 2025 the amount of MSW harmless treatment will reach 305,333,000 tons. Then take 38% of it as the predicted amount of kitchen waste treatment, that is, 116,026,540 tons, then the rest of the waste treatment amount is 189,306,460 tons. Assuming that all kitchen waste will be completely treated by anaerobic digestion and landfill treatment will be abolished in 2025. If the rest of the waste is incinerated for power generation, the carbon emission reduction will reach 108,777,507 tons (in terms of CO_2 equivalent). And if the rest of the waste is pyrolyzed for power generation, the carbon emission reduction can reach 97,040,506 tons (in terms of CO_2 equivalent), which shows a huge potential for carbon emission reduction.

5. Conclusion

The utilization of biomass resources from MSW achieves synergy between MSW treatment and carbon reduction. This paper states that the utilization of biomass resources from MSW has a clear relationship with carbon emission reduction in the current context of global warming control, by converting MSW into resources that can be used to replace fossil fuels. Newer utilization methods in the last decade include anaerobic treatment, hydrothermal technology, which is less commonly used, and pyrolysis. The first two of them are suitable for the resource-based treatment of kitchen waste in MSW, while the latter can directly treat MSW. This paper estimates that the annual waste treatment capacity in 2025 will reach about 305,333,000 tons. When all kitchen waste is anaerobically digested in 2025 and the rest of the waste is incinerated or pyrolyzed, it can bring about nearly 100 million tons of carbon dioxide equivalent emission reductions, so the biomass resources in MSW have a bright carbon emission reduction prospect. The future development direction will be biomass co-pyrolysis or co-hydrothermal or synergistic anaerobic, as well as the coupling between technologies such as anaerobic-incineration, anaerobic-pyrolysis, etc., which can improve the production efficiency and product quality. This study provides implications for the subsequent MSW resource treatment methods and the carbon emission reduction prediction.

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