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Study of Molding and Drying Characteristics of Compressed Municipal Sludge-Corn Stalk Fuel Pellets

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Abstract: Sludge incineration is a sludge resource management and disposal method that can greatly decrease the volume of sludge, reduce the degree of harm and realize the recovery of sludge heat energy. Most of the research on sludge incineration focuses on the combustion process and gas emissions, but there are relatively few studies on the sludge fuel molding and drying process before sludge incineration. Besides, independent incineration of sludge has high energy consumption. This paper proposes a pre-incineration treatment method in which sludge and corn stover are mixed to make fuel pellets and then dried. specifically, the influence of molding pressure, raw material ratio and raw material particle size on the physical properties of the fuel, and the related mechanism, were studied. The density of fuel particles is mainly affected by the forming pressure, and the impermeability is mainly determined by the proportion of sludge in the raw material. The order of the variables based on their effect of improving fuel physical properties was: molding pressure > raw material ratio > raw material particle size. Moreover, the influence of drying temperature (40 °C, 60 °C, 80 °C, 100 °C, 120 °C) has been explored. When the initial water content is similar, the drying rate increases with the increase in temperature. It provides a reference for the sludge fuel molding and drying process, and promotes the practical application of mixing sludge and corn stalks to make fuel.

Keywords: municipal sludge; corn stalks; fuel pellets; influencing factors; drying characteristics

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1. Introduction

The annual output of sewage sludge in China is about 20 million tons [1] and, with economic development and population growth, the amount of sewage sludge continues to grow. Municipal sludge is generated through the operation of urban sewage treatment plants, usually with moisture content from 93% to 99.5% [2]. The incineration of sludge in China requires a moisture content of less than 30%. Recently, mechanical dewatering technologies such as belt type, centrifugal type and vacuum type dehydrators are widely used [3]. The moisture content of sewage sludge after mechanical dehydration is still as high as 70–80%, which means it is unable to reach to the requirements of disposal methods such as landfill and incineration [4,5]. Moreover, mechanical dehydration usually requires the addition of conditioning agents; if not properly handled, these agents will cause secondary pollution. Compared with mechanical dehydration, electro-osmotic dewatering (EDW) technology has a deeper degree of dehydration of sludge [6], and without any chemical addition. However, the study showed that when the sludge moisture content reaches 65%, the continued use of EDW technology for dehydration will cause a sharp increase in energy consumption [7]. Therefore, it is not advisable to use EDW technology for continuous dehydration, in consideration of the cost [6]. The sludge contains pathogens, heavy metals, organic pollutants and other harmful substances, which are harmful to the sustainable development of the ecological environment. Disposal technologies such as composting or storage cannot effectively solve these problems [8]. Landfill disposal of sludge requires a large amount of land. In addition, disposal costs have recently risen sharply due to limitations pertaining to the life spans of landfills [9]. sludge incineration can achieve a sludge reduction of about 95%, and the organic matter is completely oxidized, while a large amount of heavy metal elements can be collected or retained in the ashes of incineration [10]. However, with separate incineration of sludge, it is difficult to achieve self-sustained combustion, and there are also problems of incomplete combustion and high energy consumption.

The thermochemical treatment technology of sewage sludge is considered to be one of the most promising technologies for the treatment of sludge [10]. Many researchers have reported on the thermochemical treatment process and application of sludge. Song et al. [11] carried out related research on the hydrothermal carbonization process of sludge, while the phosphorus decrease in influence and applicability of the upgrading method were verified. Pulka et al. [12] evaluated the dynamics of sewage sludge torrefaction, and identify the influence of working temperature on fuel characteristics of torrefied outcomes. Đurđević et al. [13] discussed Croatia’s sludge treatment and disposal plan. The method of incineration of sewage sludge and energy recovery is considered feasible. The pyrolysis and gasification process conditions, and the equipment required, of sludge are complicated, and the energy consumption is high, therefore it is currently not widely used. In contrast, sludge incineration technology is more feasible.

The pre-treatment of sludge incineration mainly includes sludge dewatering and drying in two parts. At present, mechanical dehydration is still the main method of dehydration in China [14]. However, the traditional mechanical dehydration performance is poor, and it is difficult to meet the dehydration requirements. New dehydration technology has a high cost and requires complex equipment. Direct drying [15] has a higher heat transfer efficiency and drying rate than indirect drying. However, the high energy consumption in the early stage of drying prevents the widespread use of direct drying. The BioCon™ belt dryer [16] is a belt-type low-temperature dryer with easy operation and low energy consumption. However, the equipment covers a large area and the cost is high. Moisture content is a key factor for sludge incineration. The treatment before sludge incineration determines the calorific value and energy consumption of sludge incineration. Therefore, it is necessary to develop a new pre-treatment process for sludge incineration.

Crop straw is a renewable waste resource. In 2016, the amount of crop straw in China was about 750 million tons, and its’ safe and reasonable disposal had caused great pressure on the local agricultural department [17,18]. In China, more than 140 million tons of crop stalks were randomly discarded and burned, and the emissions and ashes from the combustion caused environmental pollution [19]. However, the independent molding of biomass straw fuel requires high energy consumption. At the same time, the fuel quality produced is low.

Therefore, this article proposed a pre-treatment method of incineration. First, electro-osmotic municipal sludge and corn stalks are mixed to make fuel pellets, and then the molding and drying characteristics of sludge-corn stover fuel pellets are studied. specifically, electro-osmosis dehydrated sludge (moisture content 60–65%) and corn stalks (moisture content 12–15%) were mixed, and high-pressure molding technology was used to prepare the fuel at room temperature. The influence of molding pressure (the molding pressure ranges from 2.5 MPa to 12.5 MPa, and the interval for each group of pressure values was 2.5 MPa), raw material particle size (raw material particle size ranges from 20 mesh to 80 mesh, and the interval for each group was 20 mesh) and raw material ratio (mass ratio 1:1, 1:2, 1:3, 1:4, 1:5, 1:6, 1:7) to fuel physical properties (density, durability index and impermeability) were studied. The drying characteristics of fuel particles at different temperatures (40 °C, 60 °C, 80 °C, 100 °C, 120 °C) were discussed.

The sludge particles used in this study are dehydrated by electro-osmosis, and the moisture content is controlled at 60–65%. The sludge dewatering process is more efficient and energy-saving, and does not require added chemicals. We added corn stalk pellets to mix with sludge instead of coal pellets, because corn stalk pellets are clean and renewable energy. The addition of corn stalks promotes the drying of fuel particles and reduces the energy consumption of fuel particle drying. Different from pure biomass fuel pellets, the addition of sludge reduces the energy consumption of molding. The sludge and corn stalks are pressed into fuel pellets to facilitate transportation and combustion.

2. Materials and Methods

2.1. Suppression of Shaped Sludge Fuel Pellets

2.1.1. Electro-Osmotic Sludge Particles

A sewage treatment plant in shandong Province provided sludge for this experimental study. The treatment plant adopts the "A^2O + biological filter treatment process", and discharges after disinfection. The moisture content of the original sludge was 80–85%, and the organic matter content was 48–52%. The process of preparing electro-osmotic sludge particles was as follows:

1. A certain amount of sludge was sent to the electro-osmotic dewatering equipment through the sludge hopper, and the sludge was evenly arranged on the filter screen through the conveyor belt. When the electro-osmosis dehydration equipment was working, the anode pressure was 0.3 MPa and the voltage was 16 V. We recorded the electro-osmosis dehydration experiment time with a stopwatch, and then repeatedly measured the sludge moisture content until it met the experimental requirements (moisture content 60–65%);
2. The electro-osmotic dewatering sludge was ground. The next step was that the ground electro-osmotic sludge particles were sieved into 20 mesh, 40 mesh and 60 mesh. Finally, they were placed into a labeled sample bag for later use.

2.1.2. Preparation of Corn Stover Pellets

The process of preparing corn stalk pellets from corn stalks was as follows:

1. The corn stalks were washed and dried, and then the stalks were guillotined by a straw machine to reduce their length to less than 100 mm. Next, the corn stalks were crushed by a pulverizer;
2. The crushed corn stalks were sieved into particles from 20 mesh to 80 mesh, and then corn stalk particles were placed in a drying box at 120 °C and dried to a moisture content of 12–15%.

The process of the municipal sludge mixed with corn stover being compressed into fuel is shown in Figure 1. The fuel molding machine was used for the molding test of electro-osmotic sludge mixed with corn stalks. The overall size of the equipment was 140 × 140 × 105 mm (Length × width × height), and the effective pressure test range was 0–50 MPa (the accuracy was 0.1 MPa). The working process of the fuel forming machine was as follows: first, the forming mold containing the mixture of electro-osmotic sludge particles and corn stalk particles was placed on the workbench. The fuel particles containing electro-osmotic sludge and corn stover were compressed and molded by the up and down movement of the worktable. During the entire compression molding process, the bottom machine base was fixed, and only the worktable was able to move up and down. The molding pressure value during the compression process could be determined by reading the oil pressure gauge. When the pressure reached the test pressure, test pressure was maintained for 2 min, then the pressure was released and the fuel particles were removed.

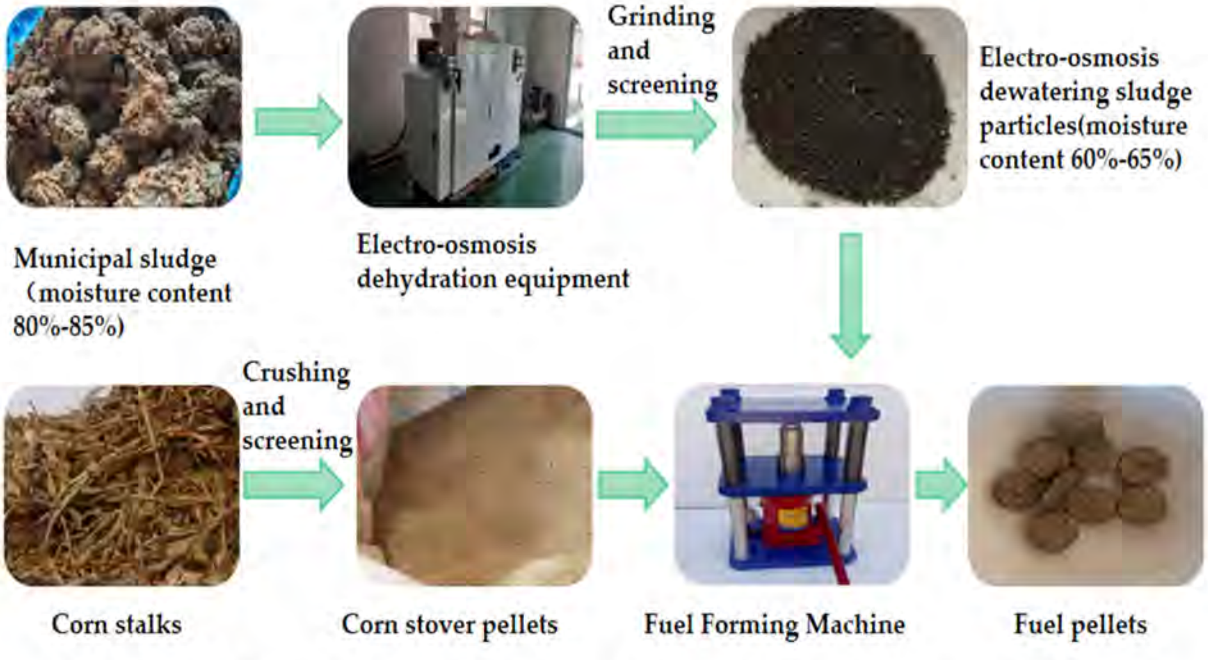


Figure 1. Compressed fuel molding process of municipal sludge mixed with corn stalks.

2.2. Fuel Physical Characteristics Test Method

2.2.1. Fuel Density

The density obtained by demolding the fuel after compression molding was called the particle density, which was measured after the completion of the molding experiment. Because the fuel was a regular cylinder made by a mold, the particle density of the fuel could be calculated. The mass of the sample of the shaped fuel particles was weighed with an analytical balance (the accuracy iss 0.1 mg, and the linearity error is 0.2 mg), and the height and diameter of the shaped fuel particles were measured by a vernier caliper (the accuracy is 0.1 mm).

We referred to the CEN/TS 15103 to test particle bulk density. The container was filled with fuel particles as much as possible. At this time, the ratio of the total mass of the fuel particles to the container volume was the bulk density of the fuel particles. We took 15 fuel particles and put them into a 50 mL graduated cylinder (the accuracy is 0.1ml). The total mass of 15 fuel particles was weighed by an analytical balance. The ratio of the total mass of 15 fuel particles to the volume occupied by the measuring cylinder was the bulk density of the shaped fuel particles.

The fuel particles were compressed and molded. Under the action of elastic deformation and stress relaxation, the density of the molded fuel particles would gradually decrease over time. After being placed for seven days (usually three to seven days) under natural ventilation at room temperature, the density of the fuel particles tended to stabilize. At this time, the density of the fuel particles was the relaxation density.

2.2.2. Durability Index

We referred to the tumbling tank method [20] to test the particle durability index. The shaped fuel particles were packed into a closed metal box, while ensuring that the metal box would rotate and fall at a certain height (2 m), and repeated this five times. Due to repeated rubbing and collision between the molded fuel particles and the inner wall of the metal box, a part of the fuel would fall off. We used an analytical balance (the accuracy is 0.1 mg, and the linearity error is 0.2 mg) to weigh and record the mass of fuel particles before and after the experiment.

2.2.3. Impermeability

The impermeability test adopted the method commonly used by experimenters. The molded fuel sample was placed under the water surface at a temperature of about 25 °C, and a glass rod was used to prevent the molded fuel from floating to the water surface. We continued to observe and used a stopwatch to record the time it took for the molded fuel to loosen completely.

2.3. Moisture Content Test Method

A certain mass of fuel particles was weighed and the initial mass was recorded, and then that mass was placed in a constant temperature drying oven. Drying was carried out at different temperatures. Next, they were weighed at 15 min intervals until the weight was constant.

2.4. Calculation Equation

The particle density of the shaped fuel particles is calculated by the following Equation (1):

$$\rho = \frac{\mathrm{m}}{\mathrm{v}} = \frac{\mathrm{m}}{\pi \mathrm{d}^2 \times \frac{1}{4}} = \frac{4\mathrm{m}}{\pi \mathrm{l} \times \mathrm{d}^2}, \tag{1}$$

where ρ refers to the particle density of the shaped fuel particles, $\mathrm{g/cm^3}$; m refers to quality of the fuel pellets just after demolding, g; v is the volume of shaped fuel particles, $\mathrm{cm^3}$; d is the diameter of shaped fuel particles, cm; l is the height of shaped fuel particles, cm; π is the constant of pi, and the value is 3.14.

The bulk density of shaped fuel particles is calculated by the following Equation (2):

$$\rho_v = \frac{M_z}{V}, \tag{2}$$

where ρ_v is bulk density of shaped fuel particles, $\mathrm{g/cm^3}$; M_z is the total mass of 15 shaped fuel pellets, g; V is the volume occupied by the 15 shaped fuel particles in the measuring cylinder, $\mathrm{cm^3}$.

The relaxed density of the shaped fuel particles is calculated by the following Equation (3):

$$\rho_0 = \frac{M_v}{V_0}, \tag{3}$$

where ρ_0 is the relaxed density of shaped fuel particles, $\mathrm{g/cm^3}$; M_v is the mass of formed fuel pellets after seven days, g; V_0 is the volume of formed fuel pellets after seven days, $\mathrm{cm^3}$.

The durability index of shaped fuel particles is calculated by the following Equation (4):

$$\mathrm{DU} = \frac{\mathrm{m_A}}{\mathrm{m_E}}, \tag{4}$$

where DU is the durability index of shaped fuel particles; $\mathrm{m_A}$ is the mass of shaped fuel pellets after endurance test, g; $\mathrm{m_E}$ is the mass of shaped fuel pellets before endurance test, g.

The moisture content of the fuel particles was calculated by Equation (5) and the drying rate of fuel particles was calculated by Equation (6):

$$\mathrm{h}_n = \frac{\mathrm{G_n} - G_N}{\mathrm{G_n}} \times 100, \tag{5}$$

$$\mathrm{V}_n = \frac{-(\mathrm{G_{n+1}} - \mathrm{G_n})}{\Delta t \times \mathrm{G_n}}, \tag{6}$$

where h_n refers to the moisture content of the fuel particles, %; V_n refers to the drying rate of the fuel particles, g/(g min); Δt refers to the time interval, min, $\mathrm{G_n}$ (n = 0, 1, 2, …) refers to the wet fuel particles quality, g; $\mathrm{G_n}$ is the dry fuel particles quality, g [21].

3. Results and Discussion

3.1. Influence of Molding Pressure on Physical Characteristics of Fuel

The particle size of electro-osmotic sludge particles and corn stover was 40 mesh. The ratio of raw materials (mass of corn stalk pellets: mass of electro-osmotic sludge pellets) was 1:7. The fuel pellets were compressed under different molding pressures, and the physical properties of the fuel pellets under different molding pressures were tested. The experimental results were shown in Figure 2.

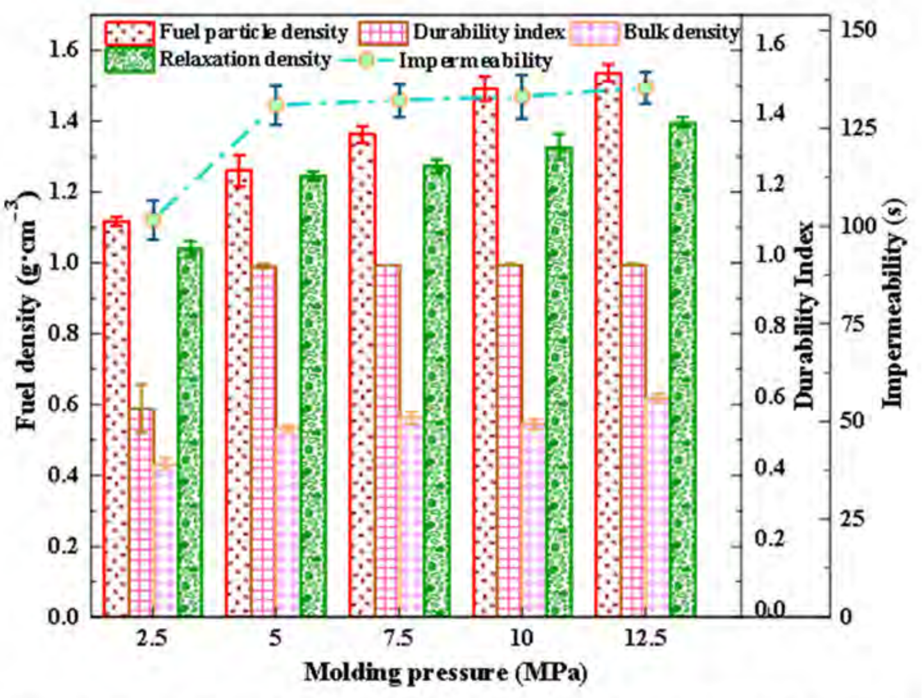


Figure 2. The effect of molding pressure on the physical characteristic of shaped fuel.

Particle density was an index of physical properties used to evaluate the mechanical strength of shaped fuels. The mechanical strength of the fuel particles were improved as the particle density of the shaped fuel and the calorific value per unit mass increased. Technical specifications for biomass pellets from ISO standard required particle density greater than 0.9 g/cm^3.

Figure 2 presents that the particle density of the fuel increased as the molding pressure increased. When the pressure was 10 MPa, the fuel particle density reached 1.490 g/cm^3. The pressure continued to increase and the rate of increase in fuel particle density decreased. The experiments of stelte et al. [22] showed that within a certain pressure range, as the forming pressure increased, the density of fuel particles increased. When the pressure reached a certain value, the trend of density increasing with pressure was no longer significant. A study by saumen [23] also had a similar conclusion. With the increase in molding pressure, the particle density first increased rapidly and then the growth tended to be gentle.

As the pressure gradually increased, the mixed fuel mainly underwent three stages in the forming process. In the first stage, the raw material particles were rearranged, changing from a fluffy state to a relatively compacted status. In this process, the porosity between the raw material particles was reduced, and the shape and characteristics of the raw material particles were basically unchanged. In the second stage, with the pressure increases, the raw material particles underwent elastic and plastic deformation, which further filled the gaps between the particles: the distance between the particles decreased, and the contact surface and the van der Waals force increased. The particles further bonded together. In the third stage, as the pressure continued to increase, the compression volume of the particles decreased sharply. The biomass particles were tightly connected, and the corresponding fuel particle density increased. When the fuel particle density approached the density of the particle cell wall, the particles could not continue to be compressed. Therefore, as the pressure continued to increase, the rate of increase in the particle density of the fuel decreased. There are many research reports on the influence of molding pressure on the density of fuel particles. Wheeler [24] reported that when the straw density was high, the relationship with the forming pressure is a simple power-law. Ooi Chin [25] found that there are multiple exponential relationships between die pressure and the molding density of fuel particles through the study of pellets.

As shown in Figure 2, the particle density of the fuel increased as the molding pressure increased. When the molding pressure was 5 MPa, the bulk density was 0.5327 g/cm^3. When the molding pressure was increased to 12.5 MPa, the bulk density of fuel particles was 0.6178 g/cm3. Each country has its own specifications for the bulk density of fuel particles. ISO requires a bulk density of fuel particles greater than or equal to 0.55 g/cm^3.

Figure 2 presents that the relaxation density increased with the increase of the forming pressure. When the fuel particle density reached 1.3966 g/cm^3, the pressure was 12.5 MPa. As the molding pressure increased, the impermeability and durability index of the mixed molding fuel increased. When the molding pressure reached 5 MPa, with the increase of molding pressure, the increase rate of durability index and impermeability tended to be gentle. When the molding pressure gradually increased, the physical properties of the fuel showed an increasing trend.

3.2. Influence of Raw Material Ratio on Physical Properties of Fuel

The particle size of electro-osmotic sludge particles and corn stover was 40 mesh. The molding pressure was 7.5 MPa. The fuel pellets were compressed under the ratio of the raw materials (the quality of corn stover pellets: the quality of electro-osmotic sludge pellets) of 1:1, 1:2, 1:3, 1:4, 1:5, 1:6 and 1:7, and the physical properties of the fuel pellets under different raw material ratio were studied. Figure 3 presents the experimental results.

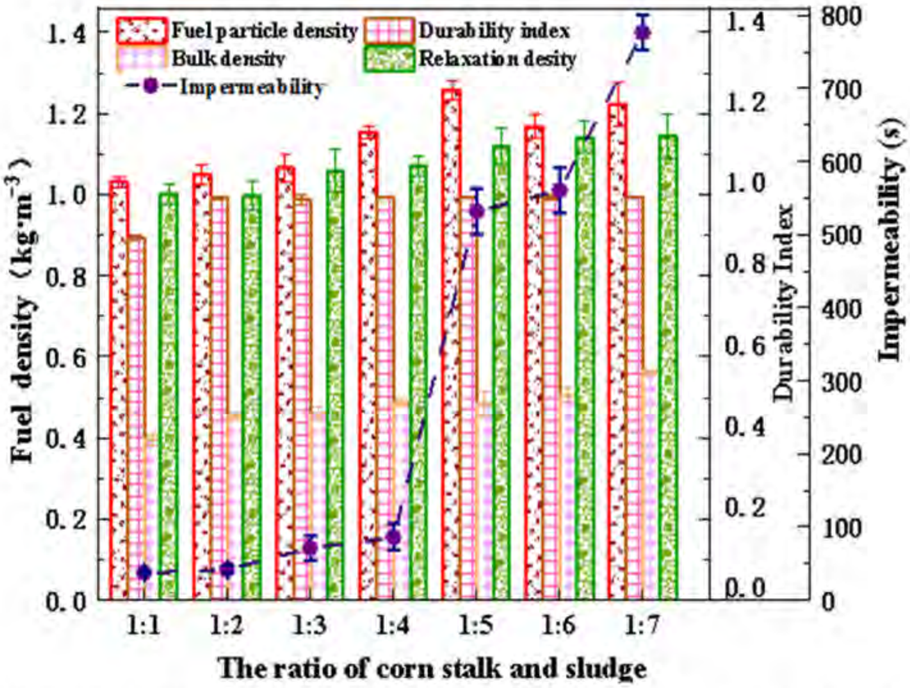


Figure 3. The influence of raw material ratio on the physical properties of fuel particles.

As shown in Figure 3, as the ratio of raw materials increased (the specific gravity of sludge increased), the particle density of fuel particles first increased and then decreased.

When the ratio of corn stalks and electro-osmotic sludge was 1:5, the particle density reached the maximum value of 1.2578 g/cm^3. As the ratio of raw materials increased (the specific gravity of sludge increased), the bulk density, relaxation density, durability index and impermeability of fuel particles increased. When the ratio of corn stalks and electro-osmotic sludge was 1:7, the maximum values of bulk density, relaxation density, durability index and impermeability were respectively 0.5632 g/cm^3, 1.1452 g/cm^3, 0.99 (ISO required greater or equal to 0.96) and 776 s.

It can be seen from the above that with the proportion of sludge in the raw material increased, the physical properties of the shaped fuel particles were improved. This may be caused by the following two aspects. One aspect was the nature of the sludge itself. The large amount of extracellular polymeric substances (EPS) in the sludge made the sludge more viscous [26]. Materials with high viscosity can be used as fillers. The embedding of the viscous material reduces the porosity between the fuel particles, and the durability and hardness of the particles will increase [27]. Furthermore, 70% to 80% of the extracellular organic carbon (polymer) in activated sludge existed in the form of protein and sugar [28]. A large amount of protein denaturation and carbohydrate gelatinization in the sludge played a binding role in the mixed raw materials [29]. The use of binders could reduce energy consumption, reduce equipment wear and enhance the bonding effect between particles and the calorific value of dense biomass [30]. As a binder, sludge could obtain high-hardness particles under low pressure and high temperature conditions. In addition, the addition of sludge could also reduce the unevenness of particle hardness caused by the heterogeneity of biomass [31]. Another aspect was the interaction between sludge particles and biomass particles. sludge and biomass had a good synergistic effect in forming. Biological particles built a framework structure through "bridging". The sludge particles could be well filled in the voids. The two synergistically formed a stable structure to improve the strength of the shaped particles. Therefore, the density of fuel particles was greatly affected by the proportion of sludge in the raw materials. Okey Francis Obi [32] studied the effect of palm oil plant sludge as a binder on the properties of wood chips. It was found that, as the binder content increased from 10% to 100%, the relaxation rate decreased, and the compression and relaxation density, durability grade and water resistance increased. Okey Francis Obi [33] found that when palm oil plant sludge was mixed with rice husk in different proportions, the addition of a certain amount of palm oil plant sludge had a significant impact on the physical characteristics and combustion performance of the formed block ($p < 0.05$). With the increase in the amount of sludge added, the average values of compression and relaxation density, durability grade and water resistance all increased, while the relaxation rate decreased. Jiang et al. [31] pointed out that the ratio of sludge had a significant effect on particle density and hardness, and sludge can be used as a suitable binder for biomass granulation. It can be seen from the above that as the raw material ratio increased, the physical properties of the shaped fuel particles increased.

3.3. Influence of Corn Straw Size on Physical Properties of Fuel

The particle size of electro-osmotic sludge particles was 40 mesh. The molding pressure was 7.5 MPa. The raw material ratio (the quality of corn stover pellets: the quality of electro-osmotic sludge pellets) was 1:7. The mixed fuel particles were compressed and molded using different raw material particle sizes. The physical properties of the fuel pellets under different corn stalks particle sizes were tested. The experimental results are shown in Figure 4.

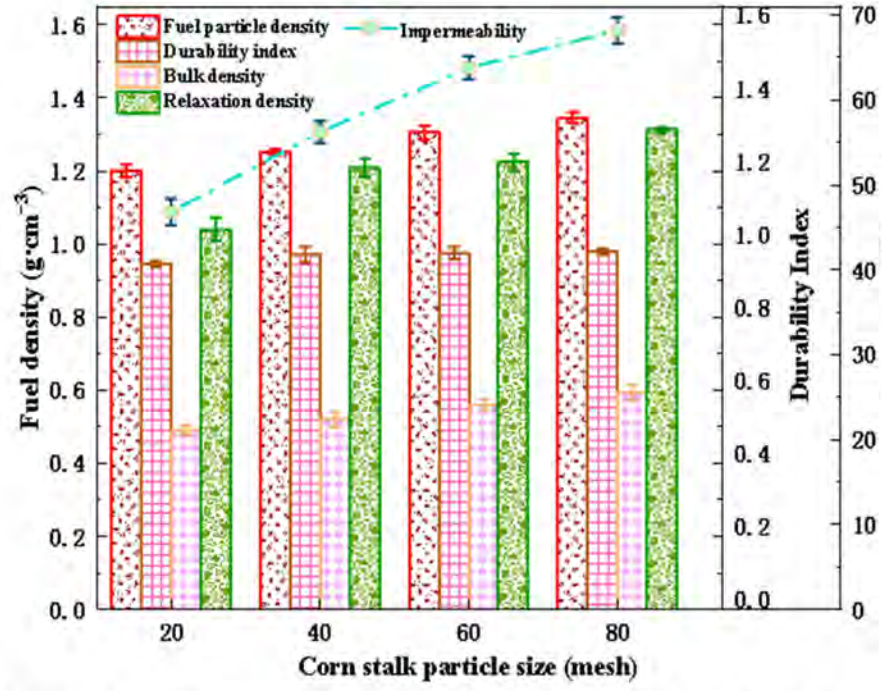


Figure 4. The effect of particle size on the physical characteristic of shaped fuel.

As shown in Figure 4, with the particle size of the corn stover decreased, the particle density of the fuel increased. When the corn stalk particle size reached 80 meshes, the maximum particle density of the fuel was 1.3456 g/cm^3. With the particle size of the corn stover decreased, the particle bulk density of the fuel increased. When the corn stalk particle size reached 80 meshes, the maximum bulk density of the fuel was 0.5942 g/cm^3. An experiment by Mat et al. [34] proved that under the same pressure, as the particle size of the raw material gradually decreased, the density of fuel particles increased. This was because in the compression molding process, particles with a small particle size were better able to flow and fill in the voids. Therefore, the density of fuel particles was high.

In addition, the particle size of the raw material decreased and the porosity between the particles increased, which was beneficial to compression molding. Bal-amurugan et al. [35] had the same conclusion. Under certain other conditions, the reduction of the raw material particle size was beneficial to the compactness and shaping of fuel particles. Another possible reason was that the particle size affected the porosity between the raw material particles. Harun et al. [36] found that the porosity of mixed biomass was affected by the particle size of the raw material, and raw material with a smaller average particle size had a correspondingly smaller porosity, which was conducive to compact molding. Research had shown that the greater the bulk density, the greater the mass of fuel particles [28].

As shown in Figure 4, as the particle size of the corn stover decreased, the relaxation density of the fuel particles increased. According to the bonding mechanism proposed by Rumpf, when the particle size was larger, the internal particles of the fuel were mainly bonded in a way of superimposing and staggering each other. The binding effect was relatively loose, and the relaxation density was relatively low. When the particle size was small, the binding between the particles in the fuel was mainly due to the attraction between the particles and molecules. The bonding effect was obviously enhanced, and the relaxation density increased [37].

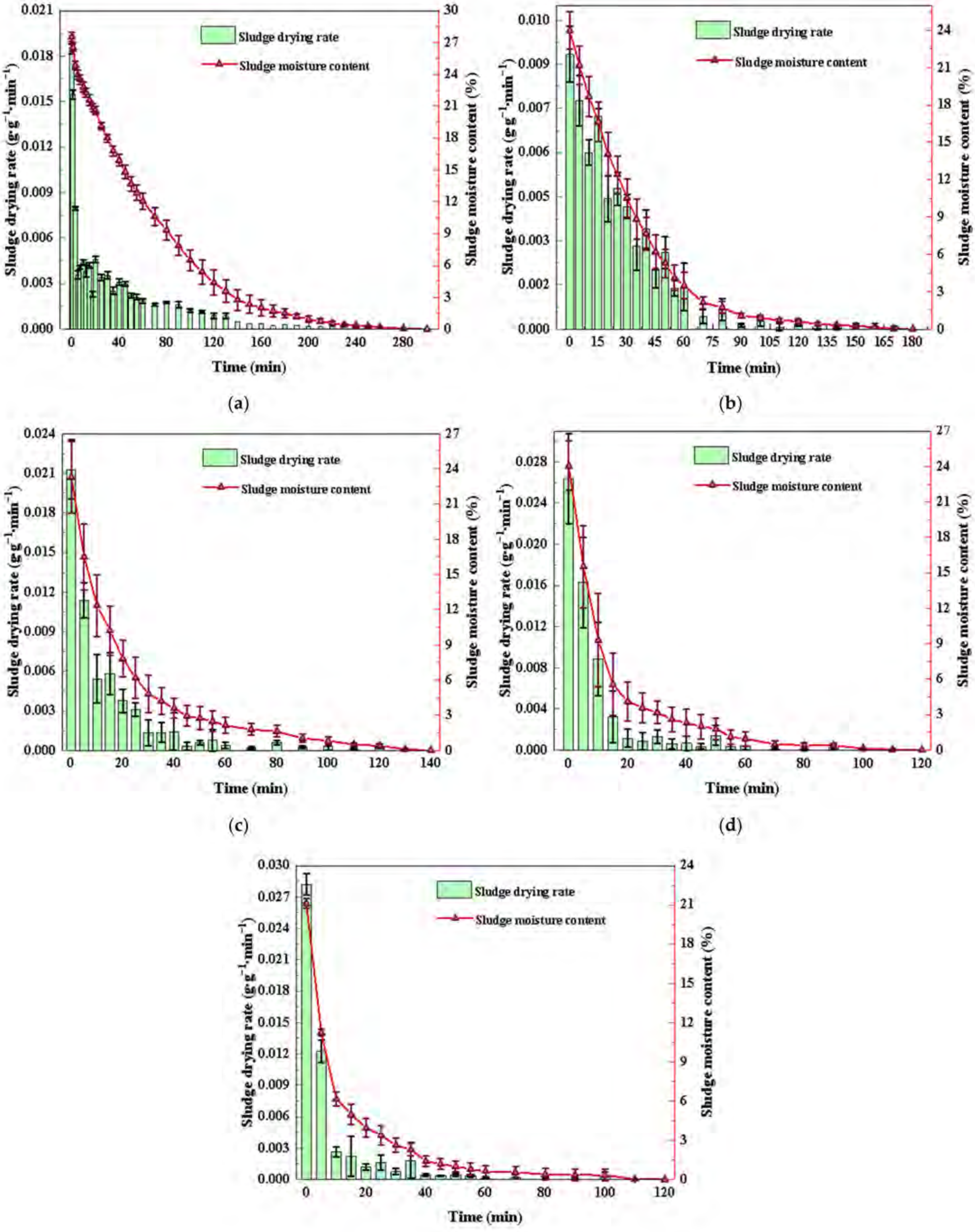
As shown in Figure 4, with the particle size of the corn stover decreased, the durability index and impermeability of the fuel particles increased. Lee et al. [38] studied the optimal particle size required for different types of biomass during molding and found that the overall trend was that as the particle size of the raw material decreases, the durability of the shaped fuel particles becomes higher. Using mixed particle size raw materials for molding could produce better quality shaped particles. Päivi [39] found that the water-permeability and hygroscopicity of cured products were closely related to the particle size. smaller particles had a large specific surface area, which made the molded block easy to absorb moisture and regain moisture. For larger gaps between particles, it is easier to fill and compact when the particles were small. The residual internal stress inside the molded product was reduced. The hydrophilicity of the fuel particles was reduced, and the impermeability was improved.

It can be seen from the above that as the particle size of the raw material decreased, the physical properties of the shaped fuel particles increased. Considering cost and performance improvements, the best condition was that the particle size of the corn stover was 60 mesh.

When the molding pressure in Figure 2 was 7.5 MPa (referred to as condition 1), the corresponding fuel particle density and impermeability were 1.3638 g/cm^3 and 132 s, respectively. When the raw material ratio in Figure 3 was 1:7, the corresponding fuel particle density and impermeability were 1.2234 g/cm^3 and 776 s, respectively (referred to as condition 2). Conditions 1 and 2 differ only in the molding pressure and the ratio of raw materials. Through comparison, it was found that the molding pressure had a greater influence on the density of fuel particles than the ratio of raw materials. The ratio of raw materials to the molding pressure improved the impermeability of fuel particles more significantly. similarly, in comparing Figures 2–4 (the particle size of the raw material was 40 mesh), the order of variables that affect the physical properties of the fuel is molding pressure > raw material ratio > raw material particle size. The compaction process was affected by the interaction between particles, and the complex interaction between the components [40]. Therefore, in actual production, we must comprehensively consider the changes of various influencing factors to find the best conditions. In addition, energy consumption and cost input need to be considered.

3.4. Study on the Drying Characteristics of Fuel Particles

Figure 5 shows the drying characteristics of the shaped fuel particles at different temperatures (Figure 5a under condition of 40 °C. Figure 5b under condition of 60 °C. Figure 5c under condition of 80 °C. Figure 5d under condition of 100 °C. Figure 5e under condition of 120 °C). As shown in Figure 5, the thermal drying experiment of fuel particles was carried out at temperatures of 40 °C, 60 °C, 80 °C, 100 °C and 120 °C, and the corresponding initial moisture content of fuel particles were 27.54%, 23.98%, 23.28%, 24.03% and 21.12%. When the moisture content reached 5%, the corresponding drying time was 110 min, 50 min, 30 min, 20 min and 15 min. As the temperature increased from 80 °C to 100 °C, the drying time of the fuel pellets was reduced by 10 min. As the temperature rose from 100 °C to 120 °C, the drying time of the fuel pellets was reduced by 5 min. When the temperature reached higher than 100 °C, the drying times of the fuel particles became less obvious. The thermal drying process requires heating, and the heating temperature and time directly determine the level of energy consumption. Considering the reduction in energy consumption caused by the reduction in heating time, and the increase in energy consumption caused by temperature rise, a temperature of 100 °C is reasonable.



(a)

(b)

(c)

(d)

(e)

Figure 5. The drying characteristic curve of fuel particles at temperatures of 40 °C (**a**), 60 °C (**b**), 80 °C (**c**), 100 °C (**d**), 120 °C (**e**).

The drying curves of other substances usually only include a falling rate drying period. However, in addition to the initial constant-rate drying period [41], two falling rate periods could be observed in the drying of sewage sludge. The constant rate period corresponded to the evaporation of free water. The first falling rate period is related to the removal of interstitial water, while the second falling rate period is usually related to the removal of surface water [10].

As shown in Figure 5a, only a short constant-speed stage appeared when the drying temperature was 40 °C. As shown in Figure 5, as the temperature increased to 60 °C, 80 °C, 100 °C, and 120 °C, the drying of fuel particles only underwent first and second falling-rate periods. This is because, in the constant speed stage, all the heat absorbed by the sludge was used for the evaporation of free water, and this equilibrium state is easily formed under low temperature conditions [21].

The drying curves of shaped fuel particles under different temperatures were tested, and the results were shown in Figure 6. With the increase in drying temperature by 40 °C, 60 °C, 80 °C, 100 °C and 120 °C, the initial drying rate of shaped fuel particles was 0.0085 g/(g·min), 0.0093 g/(g·min), 0.0213 g/(g·min), 0.0264 g/(g·min) and 0.0282 g/(g·min), respectively. The higher the drying temperature, the greater the reduction in drying rate. This was because the higher the temperature, the greater the power difference, which was more conducive to the evaporation of water. Due to the larger amount of free water in the initial evaporation, the drying rate was higher. As the drying progressed, the surface of the sludge could no longer be fully moist. When the "dry zone" appeared, the internal heat and mass transfer pathways were lengthened and the resistance increased, resulting in a decrease in the drying rate. The higher the temperature, the faster the formation of the dry zone and the greater the decrease in the drying rate.

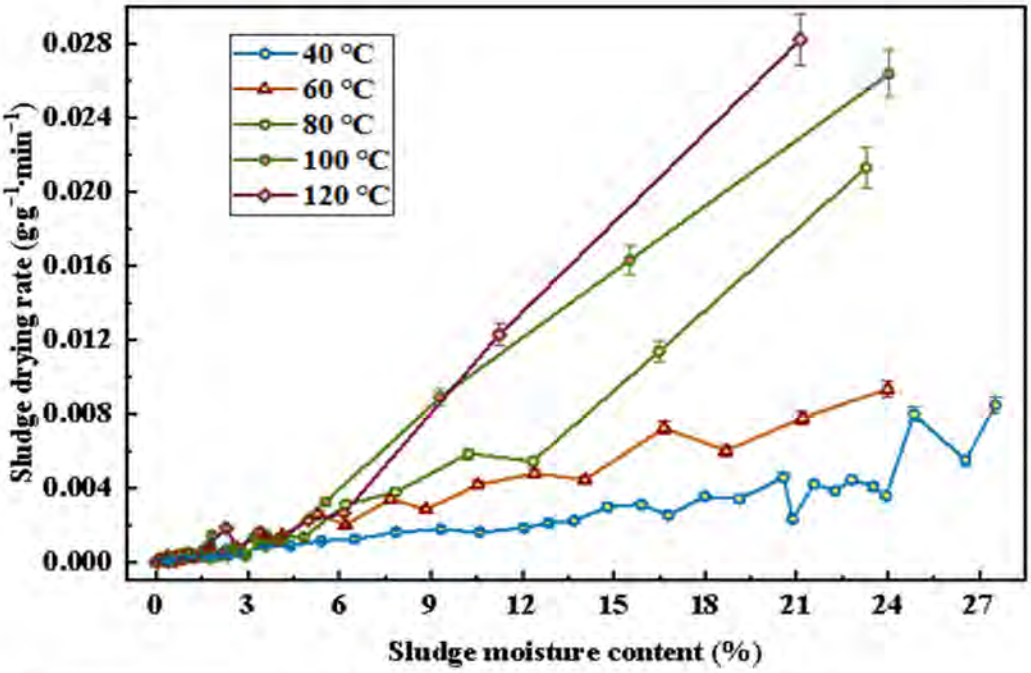


Figure 6. Curve of drying rate of shaped fuel particles versus moisture content.

As shown in Figure 6, with the increase in drying temperature, the drying rate when the water content of the electro-osmotic sludge mixed with corn stover fuel particles reached 5% was 0.0011 g/(g·min), 0.0026 g/(g·min), 0.0013 g/(g·min), 0.0032 g/(g·min) and 0.0022 g/(g·min). When the initial water content was similar, the drying rate increased with the increase in temperature. The drying time decreased with incrasing temperature. This was because the driving force for heat transfer increases with increasing temperature, which was conducive to the evaporation of water on the outer surface and the migration of internal water to the surface [21].

Figure 6 showed that with the increase in the drying temperature, the slope of the drying rate of the fuel particles gradually increased, which was the rate at which the mass of the fuel pellets decreases gradually. When the temperature was in the range of 80–120 °C, the water content of the fuel particles gradually approximated with the same trend over time. At 40 °C and 60 °C, electro-osmotic sludge mixed corn stover briquette fuel particle moisture content was very different from the curve and time curve.

Fuel drying is an indispensable process before incineration, and people are most concerned about the energy consumption of the drying process. The higher the starting temperature of the fuel particles, the greater the drying rate during the first deceleration period of the fuel particles, and the shorter the drying time. Therefore, in practical applications, it is possible to consider heating at a high temperature during the first deceleration period, and low temperature or not heating during the second deceleration period.

4. Conclusions

This article proposes a pre-treatment method of incineration. First, electro-osmotic municipal sludge and corn stalks were mixed to make fuel pellets, and then the molding and drying characteristics of sludge-corn stover fuel pellets were studied. The sludge particles used in this study were processed by electro-osmosis, not conventional sludge. The electro-osmosis dehydration technology was highly efficient and energy-saving, and the sludge obtained after dehydration had stable properties. We added corn stalk pellets instead of coal, because corn stalk pellets are clean and renewable energy. The addition of corn stalk pellets promoted the drying of fuel pellets and saved energy consumption for the drying of shaped fuel pellets. Different from biomass fuel particles, the addition of sludge reduced the energy consumption of molding and enhanced the physical characteristics of the fuel. By studying the forming and drying characteristics of fuel pellets, the following conclusions were obtained.

1. With the pressure increases, the physical properties (density, durability index and impermeability) of fuel particles increase. With the raw material ratio and particle size increased, the physical properties (density, durability index and impermeability) of the shaped fuel particles increased. Considering cost and performance improvements, the best molding conditions are a raw material particle size of 60 mesh, a molding pressure of 10 MPa and a raw material ratio of 1:7.
2. The density of fuel particles is mainly affected by the forming pressure, and the impermeability is mainly influenced by the proportion of raw material sludge. In order of their effect of improving the fuel's physical properties: molding pressure > raw material ratio > raw material particle size.
3. As the drying temperature (40 °C, 60 °C, 80 °C, 100 °C, 120 °C) increases, the fuel drying time decreases and the rate of decrease is gentle. When the initial water content is similar, the drying rate increases with the increase in temperature.

This study points out a right direction for further developments with regards to the production of sludge corn stover fuel with good physical properties, and promotes the development of resource utilization of sludge and biomass corn stover. The development of sludge biomass fuel technology is conducive to reducing the environmental hazards caused by sludge and biomass straw, and it can also generate heat and bring certain economic benefits.

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