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Effects of rice husk powder and thermal hydrolysis on sludge characteristics

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ABSTRACT

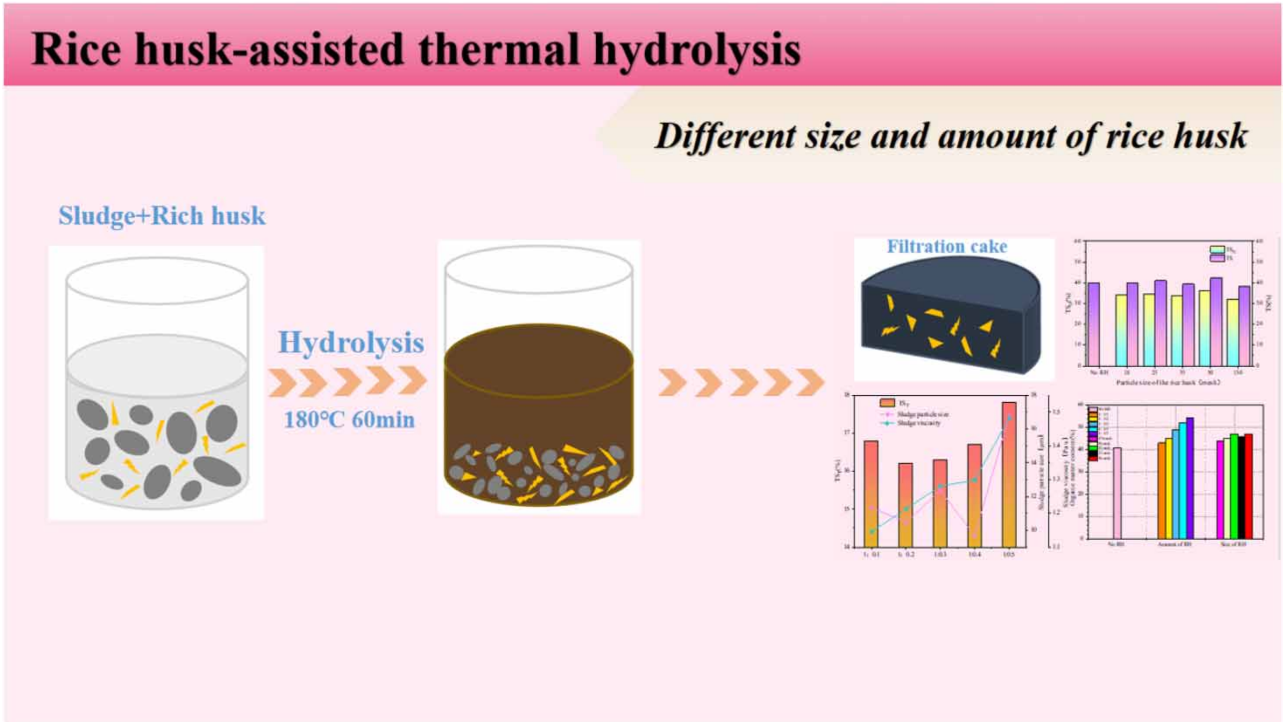
To reduce the water content and improve the incineration characteristics of sludge, rice husk and thermal hydrolysis were employed in this study. Effects of rice husk and thermal hydrolysis on the characteristics of the sludge were investigated. The results showed that synergistic thermal hydrolysis with rice husk could effectively destroy sludge particles and release more bound water. For rice husk with a particle size of 50-mesh and an additional amount of rice husk at 1:0.2, the solid content of the sludge was reduced from 17.4 to 16.2%, and the sludge particle size was reduced by 6%. Filtration time and specific resistance to filtrate (SRF) were shortened by 88.9 and 98.7%, respectively. The organic matter content of the filtration cake increased by 14%, compared with the sludge treated by thermal hydrolysis without rice husk. Furthermore, it could be shown that the most optimal conditions were rice husk of particle size 50-mesh and an additional amount of rice husk at 1:0.2, which could lead to effective thermal hydrolysis and higher organic matter content of the filtration cake.

Key words: rice husk, sludge characteristics, sludge dewatering, thermal hydrolysis

HIGHLIGHTS

- The optimal process of collaborative thermal hydrolysis of rice husk was selected by changing the grain size and the additional amount of rice husk.
- Good drainage channels can be formed in the dehydration process of rice husk after the thermal hydrolysis of sludge to improve the efficiency of dehydration.
- Rice husk combined with thermal hydrolysis can improve the organic matter content of sludge-dehydrated filter cake.

GRAPHICAL ABSTRACT



INTRODUCTION

With the increasing urbanization in China, a large amount of residual sludge was generated in wastewater treatment. Municipal sludge production exceeded 40 million tons (water content with 80%) in China in 2016 (Dai 2017). Also, it was preliminarily estimated at 55.52 million tons in 2021, which was 8.23% more than that in 2020. It was expected that the production of municipal sludge would increase to 70 million tons in 2025. Effective resourceful treatment of sludge is currently a key topic.

Sludge is a kind of complex non-homogeneous suspension, which is composed of a large amount of water, extracellular polymers (EPSs), proteins, lipids, carbohydrates, microorganisms, and inorganic substances (Wei *et al.* 2018a, 2018b; Zhu *et al.* 2018). Moisture composition in sludge mainly includes interstitial water, surface adsorbed water, capillary water, and bound water (Tang *et al.* 2018; Wei *et al.* 2018a, 2018b). EPS with high surface charge tends to form stable gel suspension structures, causing moisture to bind tightly with the EPS surface, generating hydrophilicity and water encapsulation, which hinders the release of water (Vaxelaire & Cézac 2004). During mechanical dewatering, extreme compression of sludge leads to the closure of water release channels, resulting in low permeability of the filtration cake and inhibiting the release of all kinds of water (Wu *et al.* 2016, 2018). Thus, releasing bound water is the most optimal choice for sludge pretreatment to improve the dewatering ability.

There are more methods to release bound water in sludge, including thermal hydrolysis, ultrasound, oxidation, and acid condition. Thermal hydrolysis is an efficient and chemical-free pretreatment method. The technical principle is that the microbial flocs in the sludge get disintegrated under high temperature and pressure, and the cells get ruptured. Also, the macromolecular organic matter is further hydrolyzed into smaller molecules (Feng *et al.* 2020). The preferred temperature parameters for thermal hydrolysis technology are generally 160–180 °C with a reaction time of 30–60 min (Zhuang *et al.* 2017; Ren *et al.* 2021). However, the higher reaction temperature could consume more energy, and the organic matter content in the sludge after thermal hydrolysis decreases, which is not conducive to subsequent resource utilization of sludge.

Carbonaceous skeleton materials such as wood chips, bamboo powder, rice husk, wheat residue, and walnut shell, are commonly used in sludge dewatering to improve the dewatering efficiency and increase the organic content of the filtration cake. The addition of disorganized or special fibrous carbonaceous skeletal materials is beneficial for creating a tubular network effect and inter-layer channels in the filtration cake (Zhang *et al.* 2019). As a result, both the specific resistance to filtrate (SRF) and the water content of the filtration cake were reduced. Yang *et al.* (2017) employed rice husk powder instead of quicklime as a filtration aid to condition the sludge and studied the effect of rice husk powder co-flocculant on sludge dewatering performance. Results showed that rice husk powder co-flocculant could significantly reduce the sludge capillary water absorption time, SRF, and filtration cake water content, which played an important role in improving filtrate quality and reducing chemical oxygen demand (COD) and ammonia nitrogen values.

However, the physical mixture of carbonaceous skeletal material and sludge had a limited effect on sludge dewatering performance, which could not release bound water. Wang *et al.* (2020) first added wood chips to sludge in thermal hydrolysis pretreatment and studied their role as a filtration aid in sludge dewatering. It was shown that the interaction between wood chips and sludge in thermal hydrolysis could not only improve the permeability of the sludge during dewatering but also remove more water and save energy. Therefore, a combination of thermal hydrolysis and carbonaceous skeleton provided a new idea to improve the sludge dewatering efficiency and subsequent incineration treatment.

The main compositions of rice husk are SiO_2, cellulose, and lignin, which are distributed in their network structure and have good mechanical strength (Li & Li 2017; Hu *et al.* 2022). Compared with carbonaceous skeletons such as wood chips, rice husk as a common agricultural waste is widely sourced. Also, it has the characteristics of high organic content, low ash content, and non-hazardous. After thermal hydrolysis of sludge, organic matter decomposes in large quantities, resulting in a lower calorific value of filtration cake and unstable combustion. While rice husk can not only play a supporting skeleton role in dewatering but also increase the solid content of the filtration cake. Thus, the organic matter and calorific value of the filtration cake were improved to meet subsequent incineration (Wang *et al.* 2016; Zheng *et al.* 2019). However, rice husk was previously used only as a filtration aid to improve sludge dewatering efficiency, and the bound water content was almost unchanged. Thermal hydrolysis could destroy sludge cells and release more bound water. Furthermore, rice husk as a supported skeleton could create better hydrophobic pore channels for sludge dewatering and increase the organic matter content of the dewatered filtration cake.

Therefore, in this paper, the advantages of rice husk and thermal hydrolysis were combined to condition the sludge, in order to explore a more efficient sludge treatment process. The mechanism for combining thermal hydrolysis and rice husk was investigated. Effects of rice husk particle size and additive amount on sludge characteristics such as particle size, viscosity, net solids content, and SRF during thermal hydrolysis and dewatering were all studied. Also, optimal rice husk particle size and additive amount were determined.

MATERIALS AND METHODS

Experimental materials

The raw sludge used for this experiment was taken from a municipal wastewater treatment plant in Taiyuan City (China) during summer and was dewatered by a horizontal spiral centrifuge. It was the fact that underwatered sludge has high water content and large volume, resulting in more energy consumption and larger equipment during thermal hydrolysis. Therefore, dewatered sludge was employed in this study. The physical properties of sludge were tested in accordance with the standard (CJ/T 221-2005), which are shown in Table 1.

Experimental drugs and instruments

The rice husk powder used in this experiment was commercially available and was placed in an oven at 105 °C for 12 h to dry. After the volume was kept constant, it was removed for subsequent experiments. The characteristic parameters of rice husk in the experiment are shown in Table 2.

A reactor and a dewatering apparatus were used for thermal hydrolysis reaction and sludge dewatering, respectively. An analytical balance (ME204E), electric blast drying oven (FXB 101-1), muffle furnace (Sx2-2.5-10), and a HAKKE rheometer

Table 1 | Characteristic parameters of raw sludge

Type of sludge	Total solid content (%)	Organic matter content (%)	Ash content (%)	pH	Sludge particle size (μm)
Raw sludge	17.4	46.8	53.2	7.01	49.8

Table 2 | Characteristic parameters of rice husk

Sample	Moisture content (%)	Organic content (%)	Mesh	Size (mm)	Elemental analysis (dry wt.%)				
					C	H	O	N	S
Rich husk	11.8	91.6	150	0.09–0.1	39.28	5.00	37.57	0.31	0.00
			50	0.25–0.3					
			35	0.425–0.5					
			25	0.6–0.71					
			18	0.85–1					

were all used for the measurement of sludge characteristics. Rice husk elemental analysis was performed by an element analyzer (Flash Smart).

Experimental methods

Experimental method of thermal hydrolysis

Specific experimental processes were as follows. Sludge of 1,000 g and rice husk of 34.8 g (the mass ratio of rice husk and sludge dry solid was 1:0.2) were put into the reactor, and the reactor was closed. Then, nitrogen was supplied into the reactor to ensure oxygen-free condition until the pressure was kept at 1.5 MPa. The reactor was stirred at 200 rpm and was heated to a preset temperature (180 °C), which was maintained for 60 min. After the reaction was completed, the reactor was cooled down to room temperature by circulating water. Also, the sludge was taken for subsequent experiments for different rice husk characteristics (including different particle sizes and additional amounts), and experimental steps of thermal hydrolysis are followed as mentioned previously.

Dehydration experimental methods

In this experiment, 200 mL of sludge after thermal hydrolysis was dewatered by an intermittent filter under a pressure of 0.3 MPa. Filtration time and filtrate amount were recorded at the same time. As foam and gas blew out from the outlet, the filtration process was considered to be finished. Then, the filter chamber was opened and the filtration cake was removed, which was used as the measured sample.

Analysis methods

The net solid content (TS_T and TS_D) indicated only sludge solid content except for the rice husk in thermal hydrolysis and filtration cake, respectively. A certain amount of thermal hydrolysis sludge and dewatered filtration cake were dried in an oven at 105 °C for 24 h until constant. The TS_T and TS_D were calculated using the following formula:

$$TS_T = \frac{M_3 - M_0 - M_2}{M_1 - M_0 - M_2} \times 100\% \quad (1)$$

where M_0 is the mass of the beaker (g), M_1 is the thermal hydrolysis sludge (dewatered filtration cake) plus the mass of the beaker (g), M_2 is the mass of the rice husk in thermal hydrolysis sludge (filtration cake) (g), M_3 is the sludge and beaker mass after drying (g).

Determination of the organic matter content of dewatered filtration cake (ω): first, dewatered filtration cake was dried, and then it was placed in the muffle furnace at 550 °C for 2 h. The ω was calculated using the following formula:

$$\omega = \frac{G_1 - G_3}{G_1 - G_0} \times 100\% \quad (2)$$

where G_0 is the mass of the crucible (g), G_1 is the mass of the crucible plus filtered cake (g), and G_3 is the mass of the crucible and the calcined sludge (g).

SRF measurement: SRF indicates the difficulty of sludge filtration, and was calculated using the following formula (Hu 2021):

$$\alpha_m = \frac{2\Delta P(1 - ms)}{\mu\rho s K} \quad (3)$$

where K is the Ruth filtration factor, m^3/s; P the is filtration pressure, Pa; μ is the filtrate viscosity, Pa·s; α_m is the average filtration specific resistance, m/kg; ρ is the filtrate density, kg/m^3; s is the solid content of the material, %; m is the ratio of wet weight to dry weight filtration cake.

The sludge particle size was measured by the Bettersize2000 laser particle size meter, and the sludge viscosity was measured by the HAKKE rheometer.

RESULTS AND DISCUSSION

Thermal hydrolysis temperature was initially set at 180 °C, which was maintained for 60 min, and the additional amount of the rice husk was 34.8 g (the ratio of dry solid mass in sludge to rice husk mass was 1:0.2). For the sake of description and discussion, synergistic thermal hydrolysis with rice husk and non-*synergistic* thermal hydrolysis with rice husk (add rice husk after thermal hydrolysis) were denoted as RT_S and RT_{NS}, respectively (*S* represents for synergistic, *NS* represents for non-synergistic).

Comparison of RT_S and RT_{NS}

Effect of RT_S and RT_{NS} on sludge characteristics

At a reaction temperature of 180 °C, reaction time of 60 min, and additional amount of rice husk at 1:0.2, the effect of rice husk particle size on sludge characteristics was studied. The raw sludge and RT_S sludge are shown in Figure 1. It could be seen that the raw sludge was in the form of paste and had no flow properties, while RT_S sludge had better flow properties.

As shown in Figure 2(a), sludge viscosity after thermal hydrolysis without rice husk was 1.007 Pa·s, while the viscosity of RT_S sludge and RT_{NS} sludge was always greater. It might be due to the formation of a hard framework structure between the rice husk and sludge. The difference between RT_S and RT_{NS} sludge viscosity at rice husk particle size of 18-mesh was not significant. For the other rice husk particle size, the sludge viscosity of RT_S was greater than that of RT_{NS}, which showed that the rice husk in RT_S could form a better-associated structure in the sludge and make the system more stable. However, the sludge viscosity was too large for the subsequent industrial pipeline transport inconvenience and increased energy consumption (Qian 2020).

The particle size of sludge after thermal hydrolysis is an important index to identify thermal hydrolysis efficiency. The smaller the sludge particle size, the better the thermal hydrolysis effect (Feng *et al.* 2015). As shown in Figure 2(b), the particle size of sludge after RT_S was smaller than that of RT_{NS} sludge. As the particle size of rice husk was 18-mesh and 50-mesh, it

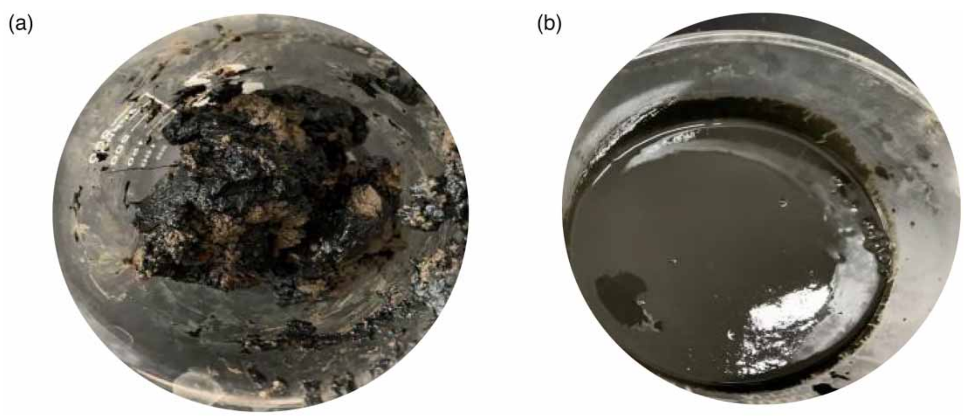


Figure 1 | Types of the sludge: (a) raw sludge and (b) RT_S sludge.

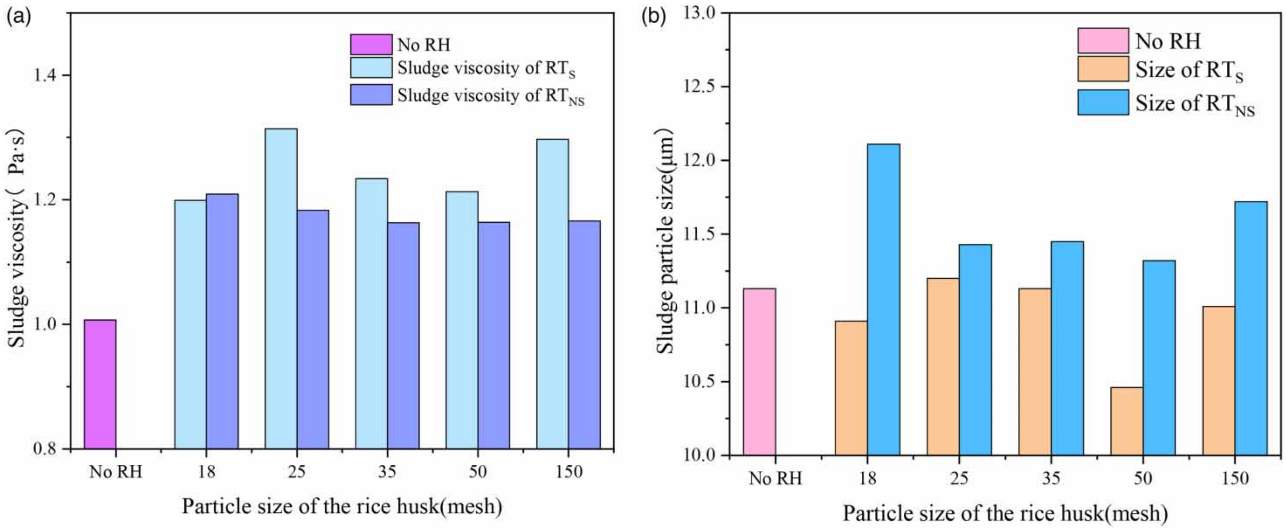


Figure 2 | Effect of RT_S and RT_{NS} on sludge viscosity and sludge particle size.

decreased by 9.9 and 7.5%, respectively, indicating that rice husk could effectively destroy sludge particles and accelerate thermal hydrolysis in the RT_S process.

Effect of RT_S and RT_{NS} on sludge dewatering

According to the experimental method, the sludge was dewatered after RT_S and RT_{NS}, respectively. The experimental results are shown in Figure 3.

As shown in Figure 3(a), with the decrease in rice husk particle size, the TS_D of RT_S sludge was always lower than RT_{NS} after dewatering, which showed two different trends. Different treatment ways might result in different association structures of rice husk with the sludge, which had an impact on the filtration of sludge after thermal hydrolysis. At the same rice husk particle size and reaction conditions, except for the effect of rice husk quality on sludge, TS_D reflected that water in the RT_S filtration cake was larger than that in the RT_{NS}. It was confirmed that rice husk could effectively accelerate thermal hydrolysis and destroy the EPS structure, leading to more released water. With different rice husk particle sizes, the difference in TS_D of filtration cake after RT_{NS} was not significant, while the change in TS_D of filtration cake after RT_S was obvious.

Filtration time is also an important indicator to show filtration efficiency. Figure 3(b) reflected the effect of RT_S and RT_{NS} on the filtration time. The former filtration time was always smaller than that of the latter. When the particle size was 18-mesh, the difference was the largest, which was 26 min for the former and 186 min for the latter. When the size of the rice husk was 50-mesh, the filtration time of RT_S reached the minimum value of 12 min, which was 88.9% less than that without the rice husk (108 min). The filtration time was reduced by 83% compared with that of RT_{NS}. The addition of rice husk to thermal hydrolysis could change the accumulated way of particles in the filtration cake, resulting in better drainage channels and shorter filtration time.

Figure 3(c) shows the effect of RT_S and RT_{NS} on sludge-specific resistance. Specific resistance could reflect sludge dewatering ability. As could be seen from the figure, when the particle size of rice husk was 25-mesh and 35-mesh, the difference between sludge-specific resistance of RT_S and RT_{NS} was not obvious. And the former was smaller than the latter for 18-mesh, 50-mesh, and 150-mesh, respectively, while the variation between 18-mesh and 150-mesh was large. As a result, RT_S could improve the sludge structure and reduce sludge compressibility to increase sludge filtration efficiency.

Effect of rice husk particle size on RT_S and dehydration

Effect of rice husk particle size on the characteristics of RT_S sludge

According to the experimental method, thermal hydrolysis reaction conditions were as follows: temperature: 180 °C, thermal hydrolysis time: 60 min, additional amount of rice husk: 34.8 g, rice husk particle sizes: 18-mesh, 25-mesh, 35-mesh, 50-mesh, and 150-mesh. The TS_T, particle size, and viscosity of the RT_S sludge were shown in Figure 4.

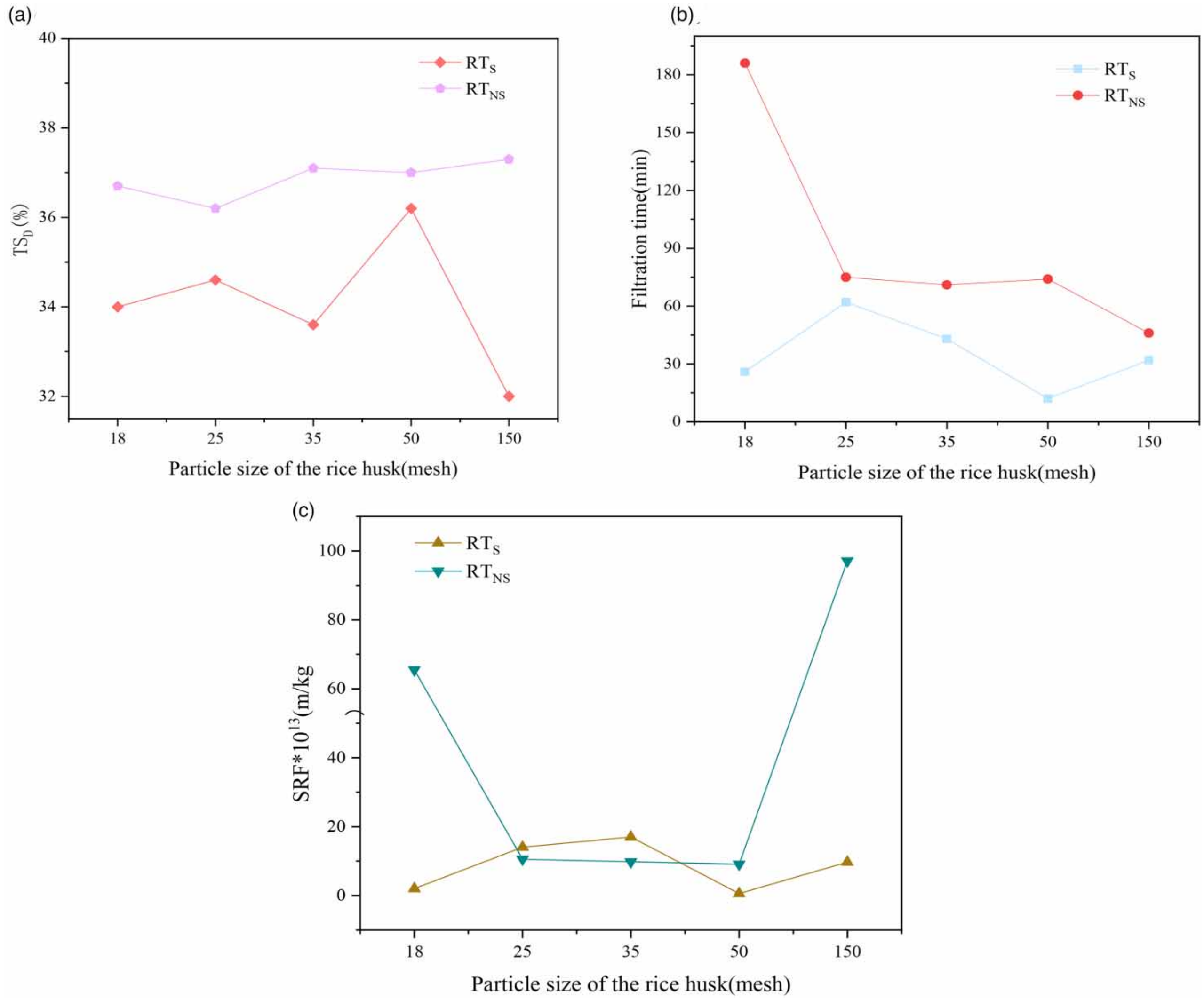


Figure 3 | Effect of RT_S and RT_{NS} on TS_D, filtration time, and SRF of thermal hydrolyzed sludge.

It can be seen from Figure 4 that addition of rice husk could reduce TS_T. As the rice husk particle sizes were 18-, 50-, and 150-mesh, the TS_T of RT_S sludge was 16.1, 16.2, and 16.3%, respectively. It can be seen that rice husk can accelerate thermal hydrolysis, which was similar to the research of Wang *et al.* (2020). But, compared with thermal hydrolysis without rice husk, as the rice husk particle size was 25-mesh, the TS_T was 16.7% and the maximum value was 17% when the rice husk particle size was 35-mesh. The results showed that TS_T for rice husk particle size of 25-mesh and 35-mesh was greater than that for thermal hydrolysis without rice husk, which may be due to the poor combination between rice husk and sludge.

The sludge particle size is an important index to evaluate the effect of thermal hydrolysis. As shown in Figure 4, the smallest sludge particle size after RT_S was 10.46 μm when the particle size of rice husk was 50-mesh. The particle size of RT_S sludge decreased by 6% compared to that of the sludge after thermal hydrolysis without rice husk (sludge particle size of 11.13 μm) when the particle size of rice husk was 50-mesh. The maximum particle size of sludge with thermal hydrolysis was 11.20 μm at the condition of 25-mesh rice husk. The particle size of the sludge was not different for thermal hydrolysis without rice husk. In comparison, the former was 7% smaller than the latter. Therefore, at a rice husk particle size of 50-mesh, RT_S could effectively destroy the sludge structure, and smaller sludge particles were obtained. The change in rice husk particle size had a good effect on the thermal hydrolysis of sludge, and it was most obvious at the particle size with 50-mesh.

Sludge viscosity is an important indicator of sludge flowability. The smaller the viscosity, the better the effect of thermal hydrolysis. As shown in Figure 4, the viscosity of sludge after thermal hydrolysis without rice husk was 1.007 Pa·s, which

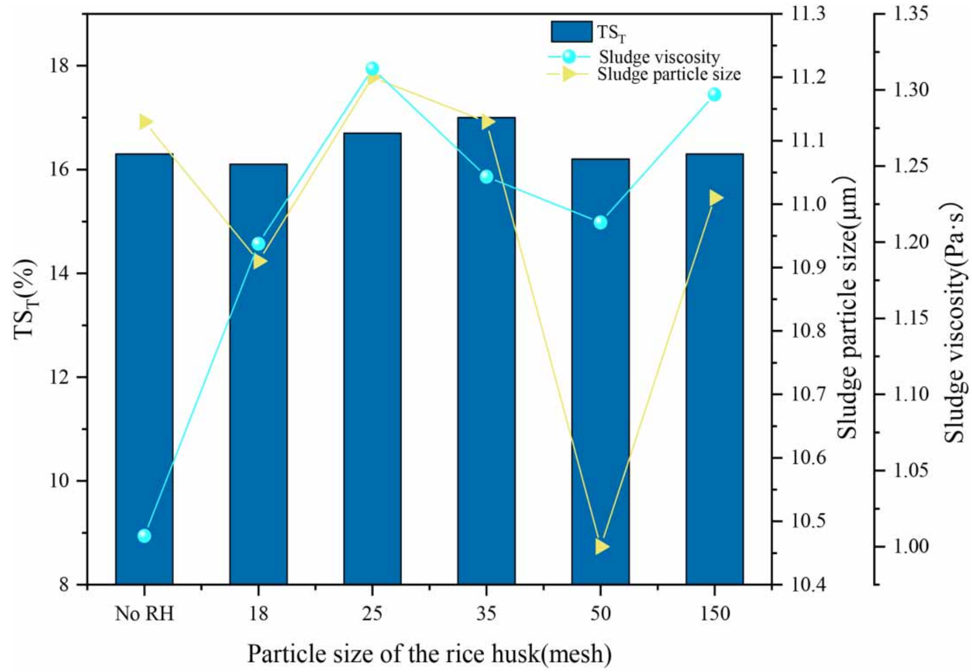


Figure 4 | Effect of rice husk particle size on TS_T, sludge particle size, and sludge viscosity of RT_S.

was lower than that of RT_S. Rice husk with a rigid structure acted as a carbon skeleton during RT_S, and it could form a closer connection structure with the sludge and obstruct flow. As a result, more moisture evacuation pore channels were formed, to provide the foundation for subsequent dewatering. Furthermore, rice husk increased the solid content of sludge, which could have a positive effect on viscosity. The smallest viscosity of sludge after RT_S was 1.199 Pa·s at rice husk particle size with 18-mesh, which had no significant difference with that of 50-mesh, whereas the sludge viscosity reached the maximum value of 1.314 Pa·s at rice husk particle size with 25-mesh. In addition, the rice husk with a particle size of 18-mesh and 50-mesh could effectively promote thermal hydrolysis and form a stable structure.

Effect of rice husk particle size on sludge dewatering performance

According to the experimental method, five kinds of RT_S sludge with different rice husk particle sizes were dewatered. The TS_D, TS, filtration time, and SRF are shown in Figure 5.

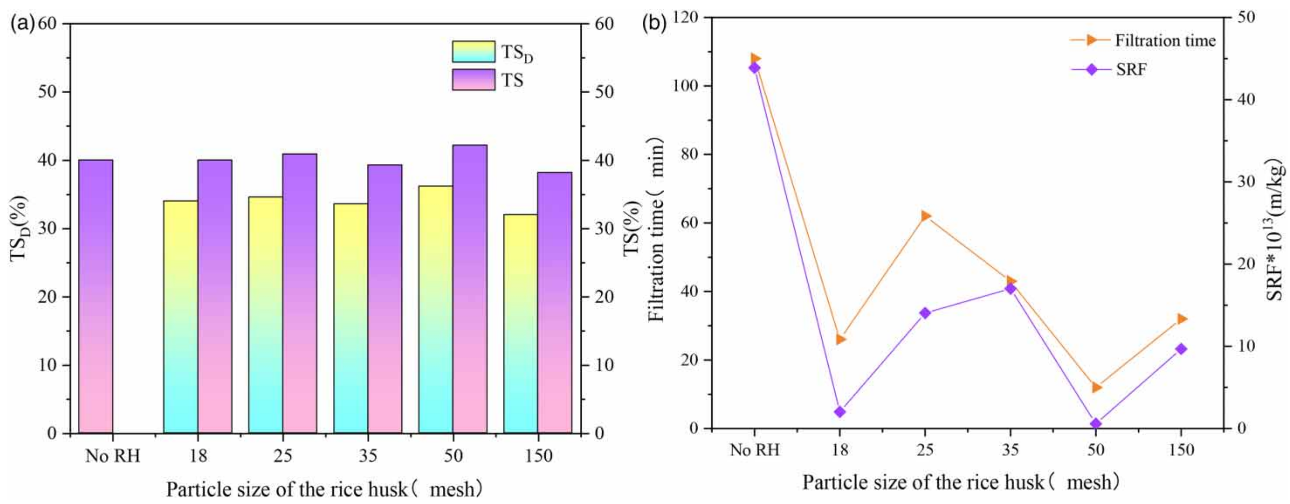


Figure 5 | Effect of rice husk particle size on TS_D, TS, filtration time, SRF of RT_S.

TS_D could reduce the influence of rice husk on filtration cake and reflect the performance of filtration cake more intuitively. As shown in Figure 5(a), the lowest and the highest TS_D were 32 and 36.2% at the rice husk particle size of 150-mesh and 50-mesh, respectively. Small rice husk particles may block part of the hydrophobic channels, leading to difficulty in dewatering and resulting in low TS_D. On the contrary, rice husk with a particle size of 50-mesh could support the pore channel, which increased the specific surface area in contact with the sludge, resulting in lower sludge compressibility and higher permeability. Therefore, higher TS_D was obtained. However, they had no difference in TS_D after sludge dewatering for rice husk particle sizes of 18-mesh, 25-mesh, and 35-mesh. Dong *et al.* (2016) employed walnut shells to condition the sludge for dewatering, where the solid content of dewatered sludge became higher as the walnut shell particle size decreased, which was similar to the results of this paper.

As shown in Figure 5(a), the *TS* (total solid) content of RT_S sludge (rice husk particle size of 50-mesh) enhanced by 5.5% compared to that of thermal hydrolysis without rice husk. Meanwhile, the experimental results showed that TS_D of RT_S sludge was always 6% lower than that of *TS*, which might be produced by the volume of rice husk. Also, if the rice husk volume condition was not considered, the *TS* of RT_S sludge was greater than 42.2%.

Filtration time is an important index that can reflect filtration efficiency. As shown in Figure 5(b), five different particle sizes of rice husks could reduce the filtration time of RT_S sludge. The filtration time for RT_S sludge with a particle size of 50-mesh was 12 min, which was reduced by 88.9% compared to that of thermal hydrolysis without rice husk. Also, the filtration time was reduced by 75.9, 42.5, 60.2, and 70.4% at the rice husk particle size with 18-mesh, 25-mesh, 35-mesh, and 150-mesh, respectively. Furthermore, rice husk particle size with 50-mesh could form more hydrophobic pore channels and increase the filtration cake permeability, which could effectively reduce the filtration time, leading to the best dewatering performance. To reflect the sludge dewaterability, SRF was employed. As seen in Figure 5(b), the SRF was 0.5865×10^{13} m/kg at the rice husk particle size with 50-mesh, which significantly reduced by 98.7% compared to that without rice husk. The significant reduction in SRF might be due to the fact that rice husk acted as a support skeleton in sludge filtration. Also, sludge compressibility is reduced, resulting in porous channels and efficient sludge drainage.

From the above results, it was shown that RT_S and the rice husk particle size of 50-mesh could effectively improve the performance of thermal hydrolysis and sludge dewatering capacity.

Effect of rice husk addition on RT_S and dehydration

Effect of rice husk addition on the performance of RT_S sludge

From the above experimental results, it was obtained that the optimal particle size of rice husk was 50-mesh. At the condition of thermal hydrolysis temperature at 180 °C, thermal hydrolysis time at 60 min, rice husk particle size with 50-mesh, additional amounts of rice husk were set at 1:0.1, 1:0.2, 1:0.3, 1:0.4, and 1:0.5 (the ratio of dry solid in sludge to the rice husk mass) to investigate the effects of rice husk addition. Figure 6 shows the viscosity, particle size, and TS_T of RT_S.

As shown in Figure 6, the TS_T of RT_S sludge decreased first and then increased with an increased additional amount of rice husk amount. The TS_T reached the lowest value of 16.2% at the rice husk addition of 1:0.2, while the highest value was 17.8% at the rice husk addition of 1:0.5. It was found that the TS_T of RT_S sludge was higher than the original sludge solid content (17.4%) when the rice husk was added at 1:0.5. The reason might be the large proportion of rice husk in the sludge, which absorbed a large amount of water after RT_S, resulting in higher TS_T. Meanwhile, it could be found that the TS_T was 16.3% when the rice husk addition was 1:0.3, which was not much different from that of 1:0.2. Therefore, rice husk with 1:0.2 and 1:0.3 could release more water and improve the thermal hydrolysis efficiency. Furthermore, it could be seen that the particle size of both RT_S sludge (the addition of rice husk at 1:0.2 and 1:0.4) reduced by 6 and 13%, compared to that of sludge after thermal hydrolysis without rice husk, respectively. When rice husk was added at 1:0.1 and 1:0.3, the particle size of RT_S sludge increased slightly compared with that without rice husk. As rice husk was added at 1:0.5, the particle size of RT_S sludge was 16.74 μm, which was 50.4% larger than that without rice husk. It was possible that rice husk made up a relatively large portion of the sludge suspension and had an impact on the sludge particle size test. So, the addition of rice husk at 1:0.2 and 1:0.4 had a significant effect on the reduction of RT_S sludge particle size, while the other three additions had an inhibitory effect.

As shown in Figure 6, sludge viscosity gradually increased with the increasing additional amount of rice husk, and the maximum viscosity was 1.482 Pa·s when the additional amount was 1:0.5. The viscosity of RT_S sludge was greater than that of sludge after thermal hydrolysis without rice husk. It was maybe due to the fact that rice husk with a rigid structure as a carbon skeleton could form a stable structure with sludge during thermal hydrolysis. At the same time, the solid-phase

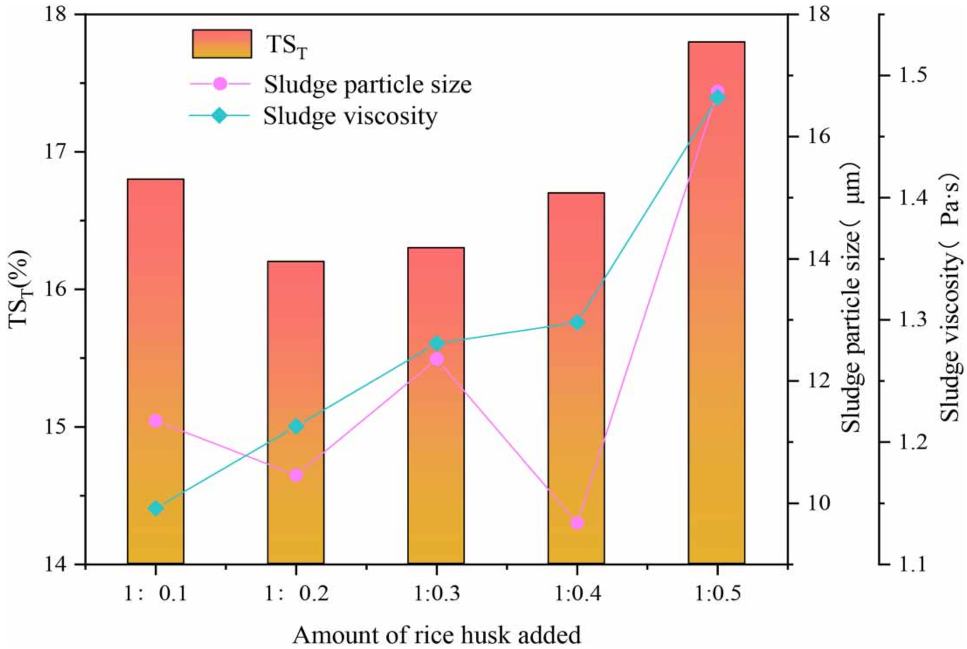


Figure 6 | Effect of additional amount of rice husk on viscosity, particle size, and TS_T of RT_S sludge.

concentration of rice husk in the sludge was also one of the factors affecting the sludge viscosity. As the amount of rice husk increased, the viscosity of RT_S sludge was more reflected in the influence of rice husk. The higher the sludge viscosity the worse the sludge flow properties. Therefore, more energy would be consumed during the sludge transportation process.

Effect of rice husk on sludge dewatering performance

According to the experimental method, five kinds of RT_S sludge with different rice husk additions were dewatered at the pressure of 0.3 MPa, respectively. The filtration time, total filtrate volume, TS_D, and TS are shown in Figure 7.

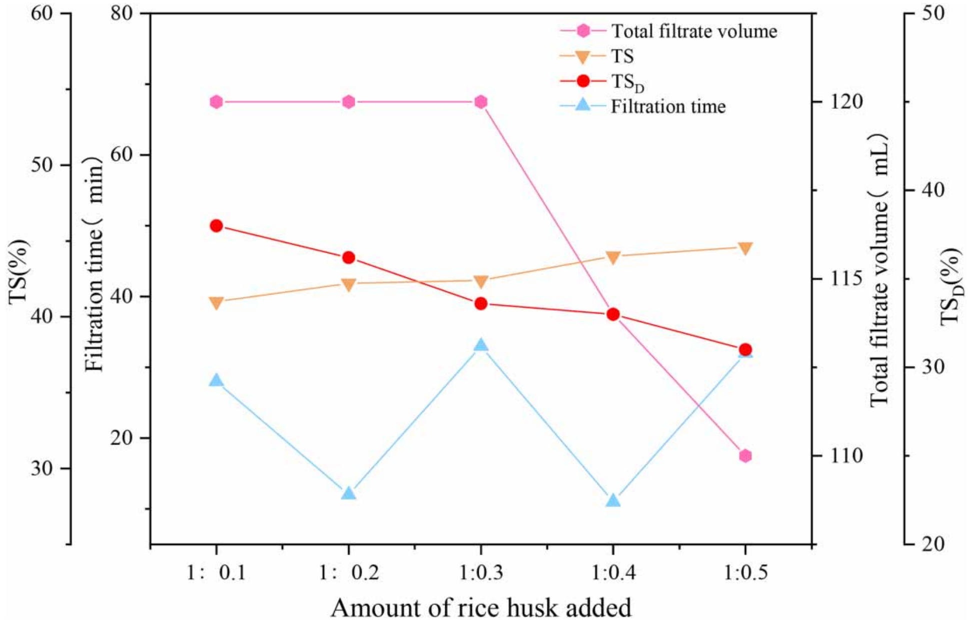


Figure 7 | Effect of rice husk addition on the total filtrate volume, TS_D, TS, and filtration time of dewatering after RT_S.

As shown in Figure 7, the total filtrate volume was kept constant as the additional amount of rice husk was lower than 1:0.3, while it decreased with the increase of the rice husk additional amount. At the rice husk amount of 1:0.3, the filtrate was 120 mL, which increased by 9% compared with that of 1:0.5. It was analyzed that an excessive amount of rice husk would lead to blockage of the drainage channel and hinder the removal of water (Xu 2018). At the same time, rice husk had strong water absorption, resulting in more water retained and decreased total filtrate.

As the additional amount was 1:0.5, the *TS* reached 44.6%, which increased by 11.5% compared with that thermal hydrolysis without rice husk. It was analyzed that the larger percentage of rice husk in the sludge resulted in a larger number of solids in the sludge system, which led to a gradual increase in *TS*. Liu *et al.* (2017) used wood chips to condition the activated sludge for the deep dewatering process. With a higher proportion of wood chips, the *TS* of the filtration cake increased gradually. Conversely, when the rice husk addition increased to 1:0.5, the TS_D of RT_S sludge reached the lowest level of 31%, which was 22.5% lower compared to the thermal hydrolysis without rice husk. Therefore, in order to ensure a high TS_D for RT_S sludge, the additional amount of rice husk was more appropriate at 1:0.2 to meet the discharge standard of dewatered sludge.

As shown in Figure 7, all five different rice husk additions were able to reduce the filtration time of RT_S sludge. The filtration time was 12 and 11 min at the rice husk addition of 1:0.2 and 1:0.4, respectively. Also, it was 88.9 and 89.8% lower than that without rice husk thermal hydrolysis. The difference in filtration time between 1:0.2 and 1:0.4 of rice husk addition was not significant. Considering economic benefits and later transport treatment, the rice husk additional amount of 1:0.2 was the most suitably chosen.

Effect of RT_S on organic matter of sludge

Incineration is one of the important methods for sludge resource utilization. Due to the decomposition of a large amount of organic matter during thermal hydrolysis, it was necessary to add rice husk to compensate the deficiency in sludge. The organic matter content in the filtration cake of RT_S sludge was analyzed according to analysis methods, which is shown in Figure 8.

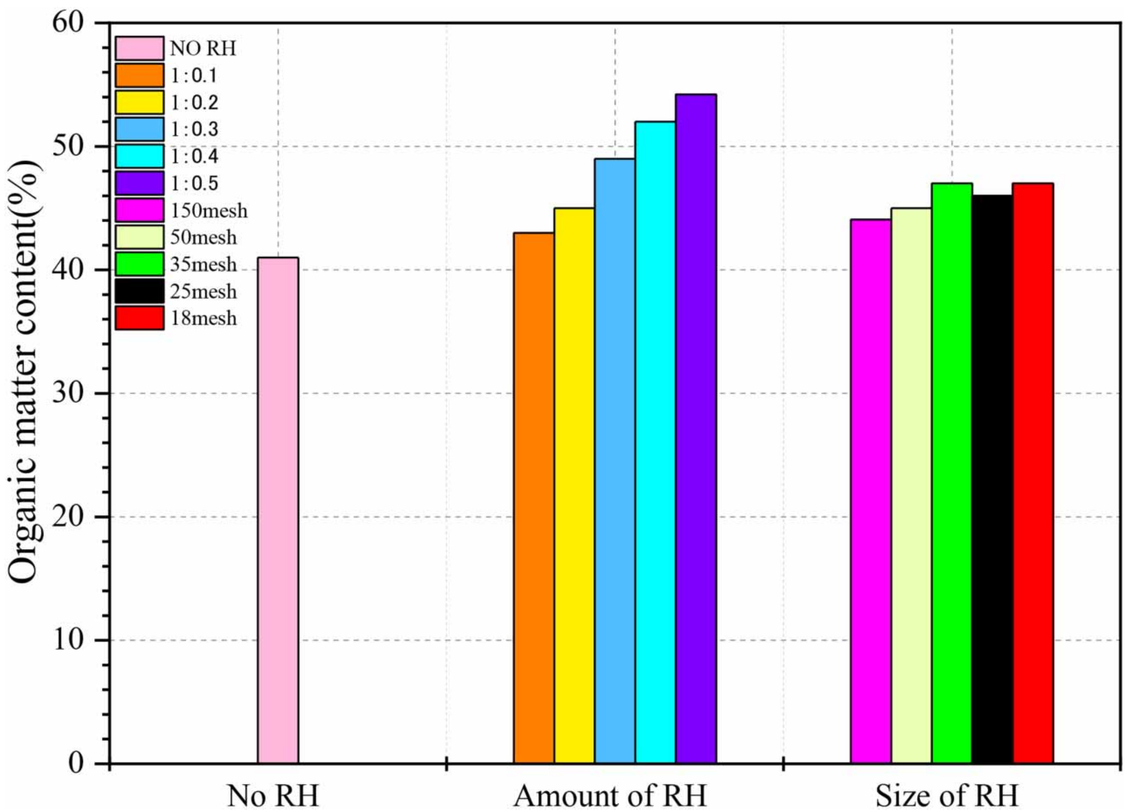


Figure 8 | Effect of rice husk on organic matter content of dewatered filtration cake after RT_S.

As shown in Figure 8, the organic matter content in the filtration cake of RT_S sludge increased with the variation of rice husk particle size and additional amount. As the rice husk particle size increased from 150- to 18-mesh, the organic matter content in the filtration cake gradually increased. At the rice husk particle size of 50-mesh, the organic matter content was 45%, which increased by 10% than the filtration cake without rice husk in the thermal hydrolysis. Also, at the rice husk particle size of 18-mesh and 35-mesh, the organic matter content reached the maximum of 47%, which might be due to the fact that both of them did not decompose completely. In contrast, a rice husk particle size of 50-mesh not only effectively improved the performance of RT_S sludge but also significantly increased the organic matter content in the filtration cake.

The organic matter content in the filtration cake of RT_S sludge not only depended on the rice husk particle size but also depended on the additional amount of rice husk to a large extent. As shown in Figure 8, the organic matter content in the filtration cake improved with the increase of rice husk additional amount (from 1:0.1 to 1:0.5), maybe due to the higher content of rice husk. As the rice husk additional amount was 1:0.5, the organic matter content increased by 32% compared with the sludge after thermal hydrolysis without rice husk. In order to meet the actual industrial needs, it was necessary to obtain higher organic matter content in filtration cake. At the same time, considering the influence of rice husk on sludge performance and economic benefits, the rice husk additional amount of 1:0.2 was the most suitable.

CONCLUSION

Synergistic thermal hydrolysis with rice husk (RT_S) and non-synergistic thermal hydrolysis with rice husk (RT_{NS}) were studied respectively, in order to improve the thermal hydrolysis efficiency and increase the organic content of the filtration cake. Thermal hydrolysis could break sludge particles and release the bound water. Rich husk as a typical carbonaceous skeleton not only further increased the permeability of the filtration cake by a skeleton effect but also accelerated thermal hydrolysis reaction. The results showed the effect of RT_S was better than RT_{NS}. During the RT_S process, as the rice husk particle size was 50-mesh and the additional amount was 1:0.2, the viscosity and particle size of RT_S sludge significantly reduced. In addition, TS_T decreased by 6% (from 17.4 to 16.2%). SRF and filtration time of RT_S sludge in dewatering were greatly reduced, where the TS improved to 42.2%. And the organic matter content of the filtration cake increased, which could satisfy the requirements of subsequent sludge treatment. This study provides a new idea for the sludge treatment process. However, it is necessary to estimate the operation cost and filtrate disposal before actual implementation.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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