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Hydrothermal treatment coupled with mechanical expression at increased temperature for excess sludge dewatering: Heavy metals, volatile organic compounds and combustion characteristics of hydrochar

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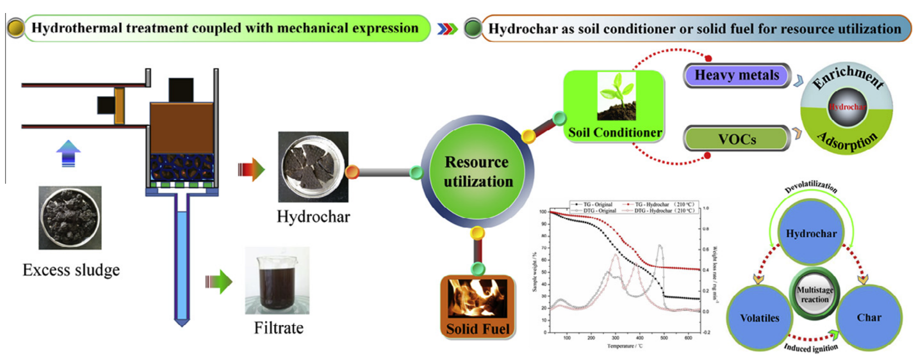
HIGHLIGHTS

- Potential application of hydrochar as solid fuel or soil conditioner was identified.
- Energy rich solid fuel was obtained during coupled dewatering of excess sludge.
- Hydrochar combustion followed pathways of devolatilization first and then burning.
- Multistage reaction process of hydrochar combustion is derived.
- Heavy metals and VOCs showed a significant enrichment in obtained hydrochar.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrothermal treatment coupled with mechanical expression at increased temperature in two separate cells is effective for the dewatering of excess sludge with low energy consumption. The obtained hydrochar can be applied as soil conditioner or solid fuel in order to utilize excess sludge material. In this study, the investigation was aimed at verifying the feasibility of hydrochar as soil conditioner in the view of heavy metals and volatile organic compounds as well as the combustion behavior by means of thermogravimetric analysis. Heavy metals like Pb, Cd, Hg, Cu, Zn and Cr all showed an accumulation in hydrochar, of which the potential risk generally depends on the environmental characteristics of land, the loading rate and the bioavailability. Higher temperature of the hydrothermal treatment resulted in some nutrients such as P, Ca and Mg enrichment into the hydrochar in particular. Among the major volatile organic compounds were a wide range of aldehydes, alkanes and volatile fatty acid as well as minor amounts of pyrazines, ketones and alcohols. The increases in adsorbed volatile compounds on the hydrochar were obvious with increasing temperature of the hydrothermal treatment. Thermogravimetric analysis showed that the pathway of combustion decomposition of hydrochar was first devolatilization and subsequently burning. The devolatilization and combustion reactions were best fitted to the first order mechanism for both excess sludge and hydrochar. Isoconversional analysis revealed that the release of volatiles and the oxidation of hydrochar structural components were all multistage reaction processes. The generated hydrochar as solid fuel proved to be having a good combustion performance.

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1. Introduction

Biological treatment is an effective method to reduce the emissions of environmental pollutants during the wastewater treatment [1]. However, a large quantities of excess sludge generated during the process has posed a serious threat to the normal operation of wastewater treatment plant and the environment and human health [2]. This is mainly due to the high moisture content and poor dewaterability of excess sludge resulting in high energy consumption during the disposal and utilization [3–5]. Excess sludge dewatering, especially deep dewatering (moisture content is below 60%) under low energy investment, has proven to be an effective and obligatory method to alleviate the problem.

It is not until recently that the hydrothermal carbonization regains great attention as a promising technology for efficient wet biomass conversion to bio-coal, although it has been used to simulate natural coalification for over a century. In response to the present situation, a novel dewatering technology, hydrothermal treatment coupled with mechanical expression process at increased temperature (HTME), has been presented to realize an improved water removal as liquid with low energy consumption, as shown in previous studies [6,7]. The results showed that when the dewatering condition was a temperature of 210 °C for 60 min and a mechanical pressure of 6 MPa for 20 min respectively, it only required an energy consumption of 846.10 kJ kg^{-1} $_{\text{(water removed)}}$ and the produced hydrochar with a final moisture content of less than 20% [6]. If the theoretically exothermic heat of reaction during the hydrothermal treatment of excess sludge, about 405.30 kJ kg^{-1} $_{\text{(excess sludge)}}$ at 210 °C, is taken into account, such dewatering process will be at an advantage in the view of energy saving [6].

Excess sludge application to soil has been practiced over a long time due to excess sludge generally being rich in organic and inorganic plant nutrients and hence as a substitute for fertilizer [8]. Heavy metals and toxic organic compounds in excess sludge, however, may present the potential risk to ecological system [9]. After dewatering of excess sludge by HTME at increased temperature, a solid product of carbonaceous matter termed hydrochar was generated, which has been suggested for various applications such as soil conditioner and alternative fuel [10,11]. The hydrochar gives more benefits than original excess sludge as a soil amendment, but encounters the same problem of the potential risk of heavy metals and toxic organic compounds being present in the hydrochar. The use of hydrochar for soil conditioner initially emanated from the discovery of fertile black soils in Amazonia, popularly known as Terra Preta [12]. The charred organic material was identified as a key component of Terra Preta by Glaser et al. [13]. From the assumptions of Terra Preta formation, soil properties could be ameliorated by using hydrochar as a conditioner, based on its improved water and plant nutrients holding capacity, cation exchange capacity and microbial community [14]. The hydrochar, however, may have the potential phytotoxicity to plant growth due to the presence of a variety of heavy metals and volatile organic compounds (VOCs) in hydrochar [15–18]. The investigations on the evolution characteristics of heavy metals and VOCs in hydrochar with hydrothermal conditions thus become very important for soil/land application of hydrochar.

In the other hand, the produced hydrochar with lower moisture content, higher bulk density and higher energy content is believed to have better combustion performance as an alternative solid fuel [19]. Hydrothermal treatment is also considered to be the most efficient for carbon fixation by binding the organics of biomass into solids fuels as a way of depositable carbon, which to some extent is helpful to decrease the net CO_2 emission to the environment in further [20]. Besides that, the low sulfur and nitrogen content for most biomass also contribute to a lower emission of SO_2 and NO_x during the combustion [19]. At present, the combustion of sludge is considered as one of the best options because of facilitating the recovery of valuable resources during the process of sludge ultimate disposal, such as phosphorus from the ash [21]. Therefore, it is strongly believed that the generated hydrochar as a solid fuel would be a great choice for solving the problems related to the energy crisis and excess sludge disposal. Harsher hydrothermal treatment (increasing temperature and residence time) led to an increase of energy content of hydrochar and an improvement of liquid/solids separation of excess sludge [6,22]. Although to date, the characteristics of the hydrochar have been conducted extensively from the points of elemental composition and calorific value which of the hydrochar are very similar to brown coals [7,23,24], little information is available on the combustion performance of such hydrochar produced by the coupled dewatering process in energetic use.

So this work primarily focused on the investigation and utilization of the obtained hydrochars after hydrothermal treatment of excess sludge coupled with mechanical dewatering at increased temperature and sought to provide comprehensive data for the popularization of such novel dewatering process. The specific objectives of this study were to (1) investigate the composition and evolution characteristics of heavy metals and VOCs in the hydrochar under different dewatering conditions; (2) evaluate the combustion behavior of the hydrochar as alternative solid fuel based on thermogravimetric analysis.

2. Materials and methods

2.1. Excess sludge sample

The excess sludge sample used in this study was no-stabilized but mechanically dewatered biological sludge (moisture content of 85.60%; dry base volatiles, fixed carbon and ash contents of 62.52%, 8.92% and 28.56%, respectively; C, H, N, O contents of 35.12%, 5.13%, 6.19% and 22.47%, respectively). It was collected from a wastewater treatment plant in Dalian, China. The wastewater treatment plant has a capacity of wastewater treatment of 80,000 m^3 d^{-1} and is equipped with anoxic–oxic process. The sludge retention time (SRT) is controlled around 7 days for chemical phosphate elimination. The generated excess sludge is thickened in the gravitational thickener and is dewatered further with a belt press.

2.2. Dewatering experiments

A detailed description of the dewatering device and experimental procedure was illustrated in the previous study [6]. In brief, a tubular reactor (280 mL) heated in an electric heating jacket was used to perform the hydrothermal treatment of excess sludge in the laboratory scale, linked with expression dewatering cell (400 mL). In a typical run, about 250 g excess sludge was loaded in the tubular reactor. The reactor was sealed and heated up to the desired temperature with a heating rate of 276 K min^{-1}. A series of dewatering runs were performed at the temperatures of 120 °C, 150 °C, 180 °C and 210 °C respectively with the residence time of 60 min and the mechanical pressure of 6 MPa for 20 min. This process parameters were chose on the basis of previous research that temperature of hydrothermal treatment governing the extent to which the dewatering process occurred [25]. After the desired duration at the target temperature, the produced hydrothermal sludge was pushed into the expression cell by horizontal piston and dewatered immediately upon a constant pressure applied by vertical presser. During hydrothermal sludge being transferred and compressed, the whole cell of the