ORIGINAL ARTICLE

Energy and Nutrient Recoveries from Faecal Sludge through Hydrothermal Carbonization Process

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Abstract. Hydrothermal carbonization (HTC) is a thermal conversion process which can be applied to convert faecal sludge into a carbonaceous material called hydrochar. However, the HTC liquid by-product or process water (PW) still contains high concentrations of organic matters and nutrients. In this study, the HTC products such as hydrochar and PW were processed to produce a pellet fuel and fertilizer, respectively. The experimental results showed that pelletization of the hydrochar could produce an excellent pellet fuel. The hydrochar-pellet fuels were found to have energy content, bulk density and compressive strength of about 22-24 MJ/kg, 900-1000 kg/m^3 and 8.0-8.5 kN/m^2, respectively. By applying the reduced pressure distillation, nutrient such as nitrogen (N) in the PW can be recovered in the ammonium sulphate ($(NH_4)_2SO_4$) form which can be utilized as an agricultural fertilizer. The experimental results showed that, at pH 11-13, temperature of 55 °C and reaction time of 60 min, N-removal and N-recovery efficiencies were found to be 99.8% and 53.4%, respectively. The results of this study demonstrated the technical feasibility of the HTC process for faecal sludge management which should result in environmental protection, health improvement and resource recovery, all leading to sustainable development.

Keywords: Faecal sludge, Hydrothermal carbonization, Nutrient recovery, Pellet fuel.

1. Introduction

Faecal sludge management (FSM) is a challenging problem for non-sewered sanitation systems in several developing countries. Human excreta containing faeces and urine is commonly disposed into septic tanks, cesspools or pit latrines, and the accumulated sludge from these systems, so called faecal sludge (FS). Because FS generally contains high concentrations of organic matter and pathogens, these untreated FS could cause serious environmental and health risk problems. Typical treatment technologies for treating FS and converting them into valuable products, such as drying bed, constructed wetland, composting, and digestion are well known. However, these technologies cannot be overcome the sanitation and environmental problems. Hydrothermal carbonization (HTC) is a thermal conversion process which can be applied to convert FS into a carbonaceous material called hydrochar within a short period of time (1-5 h) at a relatively low temperature range of 180-250 °C and pressures of up to 30 bar (Fakkaew et al., 2015a). Hydrochar is found in many applications such as solid fuel, energy storage, absorbent, catalyst and soil amendment (Koottatep et al., 2016; Libra et al., 2011; Titirici & Antonietti, 2010). However, the HTC liquid by-product or process water (PW) still contains high concentrations of organic matters and nutrients (Fakkaew et al., 2015b; Oliveira et al., 2013; Poerschmann et al., 2014). In this study, the HTC products such as hydrochar and PW were further processed to produce a pellet fuel and fertilizer, respectively. This study aims to investigate the effects of process parameters such as binder and mixing ratio of hydrochar : binder : water for the pellet fuel production, and pH, temperature and operation time for the nutrient recovery from the PW through the reduced pressure distillation process. The optimum process conditions were also determined.

2. Materials and Methods

2.1 Material

FS, which is the accumulated sludge in septic tanks, cesspools or pit latrine, was collected from a municipal emptying truck, which serviced residential areas in a city located near Bangkok, Thailand. Moisture content of the collected FS samples was adjusted to be 80 % wt using a water bath before feeding to the HTC reactor.

2.2 HTC reactor

Experiments were conducted with a 1-L high pressure reactor made of stainless steel and equipped with pressure gauge, thermocouple and gas collecting ports, as illustrated in Figure 1 An electrical heater equipped with a control panel was used to adjust the temperature and reaction time of the reactor. For the cooling system, a cooling jacket was used to cool down the reactor after finish each HTC experiment.

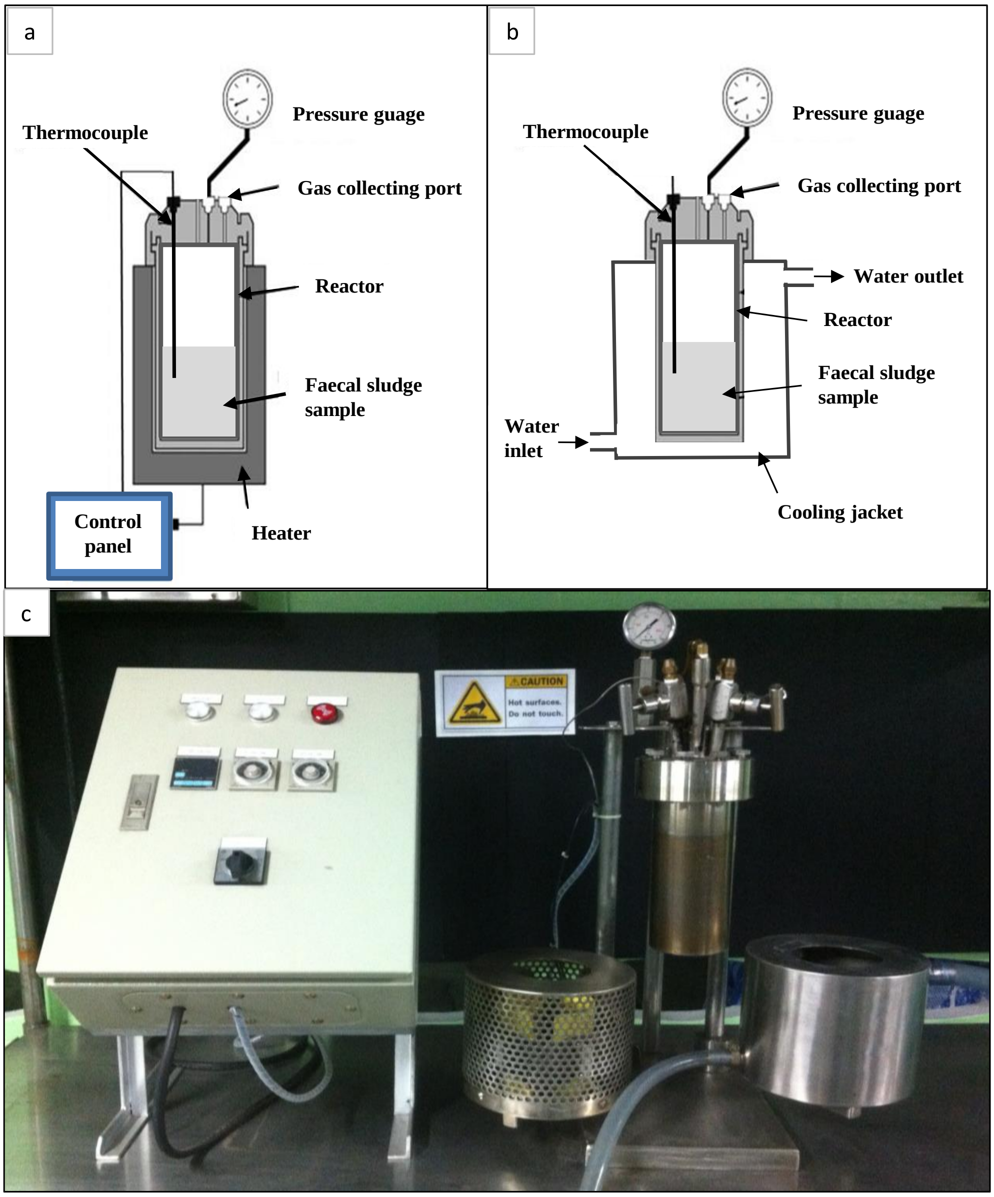

Figure 1. Schematic of HTC reactor: (a) heating system; (b) cooling jacket; (c) photograph of HTC reactor

2.3 Experiments

FS samples were used as feedstock to produce the hydrochar and PW using the HTC reactor. The products from each HTC experiment were separated into solid (hydrochar powder) and liquid (PW) phases. Experiments of the hydrochar-pellet fuel production were conducted using a hydraulic press pelletizer (Figure 2a) at various process conditions such as binder type (lignin powder, starch and $Ca(OH)_2$), binder ratio (0, 5, 10 and 15 % wt) and water ratio (0, 10 and 20 %wt). The hydrochar powder from HTC process, mixed with binders and water, was pelletized at the pressure of 120 bar and then dried at a temperature of 105 °C for 12 h to produce the hydrochar-pellet fuel with size of 10 mm diameter and 30 mm long. Characteristics of the hydrochar-pellet fuel such as energy content, bulk density and compressive strength, were measured.

A reduced pressure distillation system (Buchi Rotavapor R-124, BÜCHI Labortechnik AG, Switzerland) coupled with receiving acid solution (Figure 2b) was applied for recovering nitrogen from the collected PW. The experiments were conducted at a constant reduced pressure of 7 KPa, pH values of 11, 12 and 13; temperatures of 45, 55 and 65 °C; and operation times of 30, 45 and 60 min. The NH_4-N present in the PW was volatilized as NH_3, which was then recovered in the form of $(NH_4)_2SO_4$ through subsequent absorption into receiving 0.25 M H_2SO_4 solution. The receiving acid solution after absorption of distillate from the reduced pressure distillation process is called “N-recovery solution”.

3. Results

3.1 Hydrochar-pellet fuel production

The experimental results, as shown in Figure 3, indicated that adding binders such as lignin, starch and $Ca(OH)_2$ did not significantly affect energy content and bulk density of the hydrochar-pellet fuels (p > 0.05), which were found to be about 18-23 MJ/kg and 900-1000 kg/m^3, respectively. Because the binders acted as a natural glue in the pellatization process, the compressive strengths of the hydrochar-pellet fuel were increased to 7.0-9.5 kN/m^2 higher than that without adding binder which was 6.5 kN/m^2.

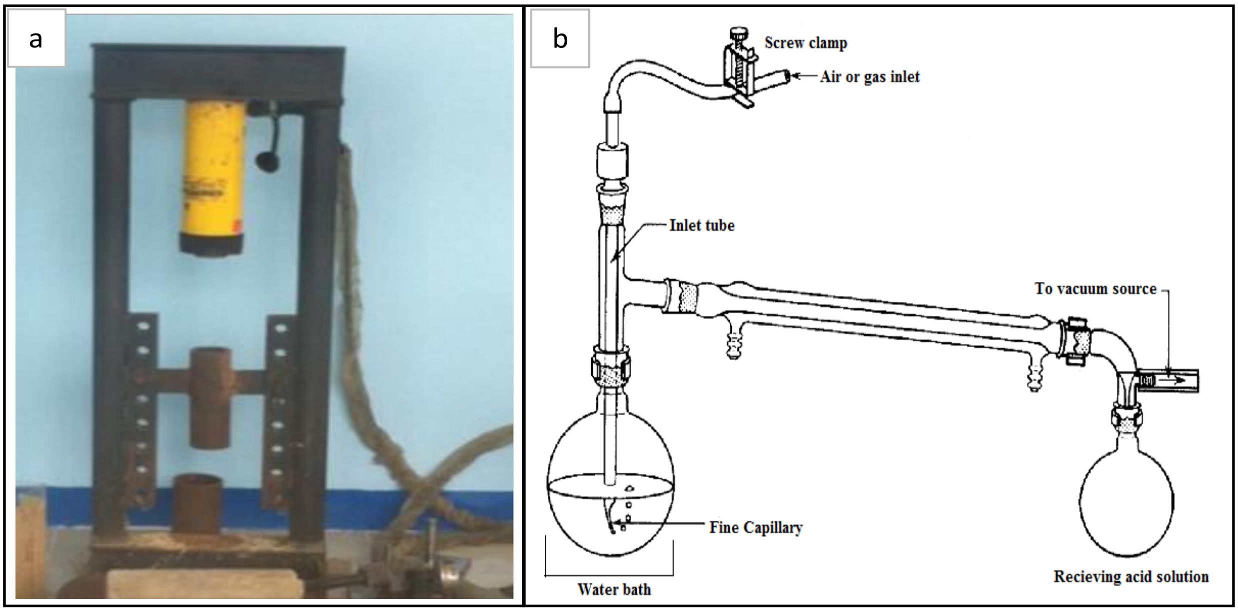

Figure 2. (a) Photograph of hydraulic press pelletizer; (b) Schematic diagram of experimental setup of reduced pressure distillation method

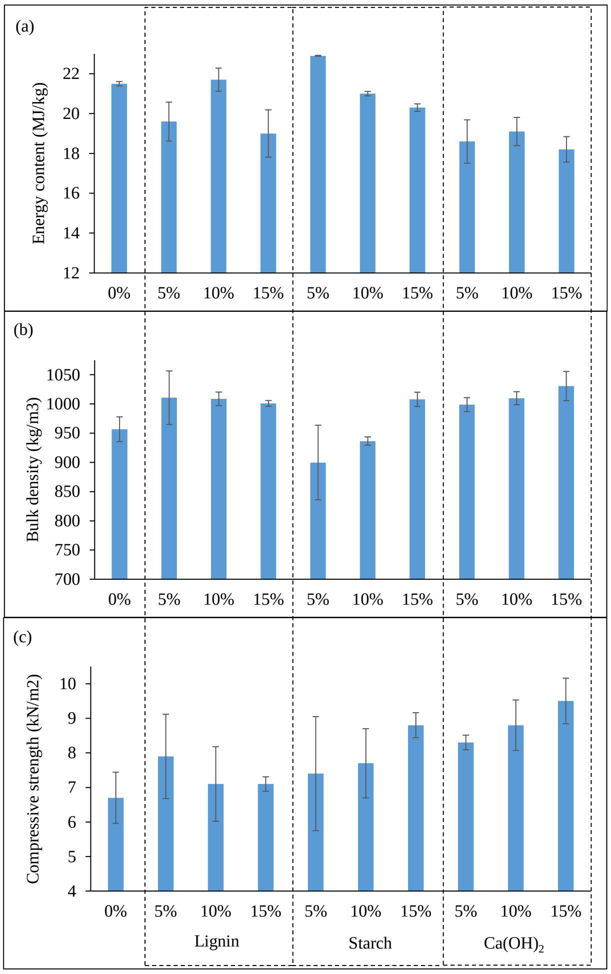

Figure 3. Energy content (a), Bulk density (b) and Compressive strength (c) of hydrochar-pellet fuel produced at different conditions of binder type and binder ratio

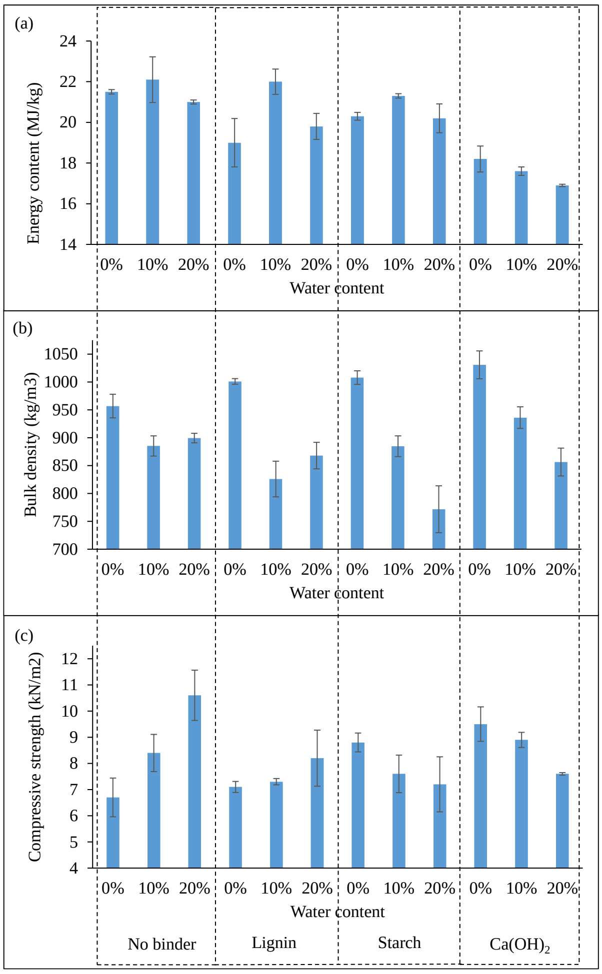

Figure 4. Energy content (a), Bulk density (b) and Compressive strength (c) of hydrochar-pellet fuel produced at various water ratios

Effects of water ratio on the hydrochar-pellet fuel properties, Figure 4, indicated that the water ratio had significant effects on bulk density of the hydrochar-pellet fuel. Increasing water ratios from 0% to 20% resulted in decreased bulk densities from 950-1000 kg/m^3 to 750-850 kg/m^3 (Figure 4b). On the other hand, the compressive strength of the hydrochar-pellet fuel (without binder and water) of about 6.7 kN/m^2 was increased to be 8.4 and 10.6 kN/m^2 at water ratios of 10 and 20 % wt, respectively. Energy contents of the hydrochar-pellet fuel produced with no binder, lignin, starch and $Ca(OH)_2$ were 21-22, 19-22, 20-21, and 17-18 MJ/kg, respectively, and were not affected by the water ratios.

3.2 Nitrogen recovery

The experimental results shown in Figure 5 indicated that among the 3 operating parameters, N-removal efficiency depended significantly on temperature and reaction time (p <0.05). The N-removal efficiency increased with increasing temperatures up to 55 °C after which a slight drop in the removal efficiency was observed, as indicated in Figure 5(a, b). The highest N-removal efficiency of 99.8 % was observed at the temperature and reaction time of 55 °C and 45 min, respectively, and the lowest N-removal efficiency of 6.4 % was observed at the temperature and reaction time of 45 °C and 30 min, respectively. The pH range of 11-13 did not significantly affect N-removal (Figure 5(b, c)).

The N-recovery efficiency was found to be significantly dependent on temperature and reaction time, as shown in Figure 6. The N-

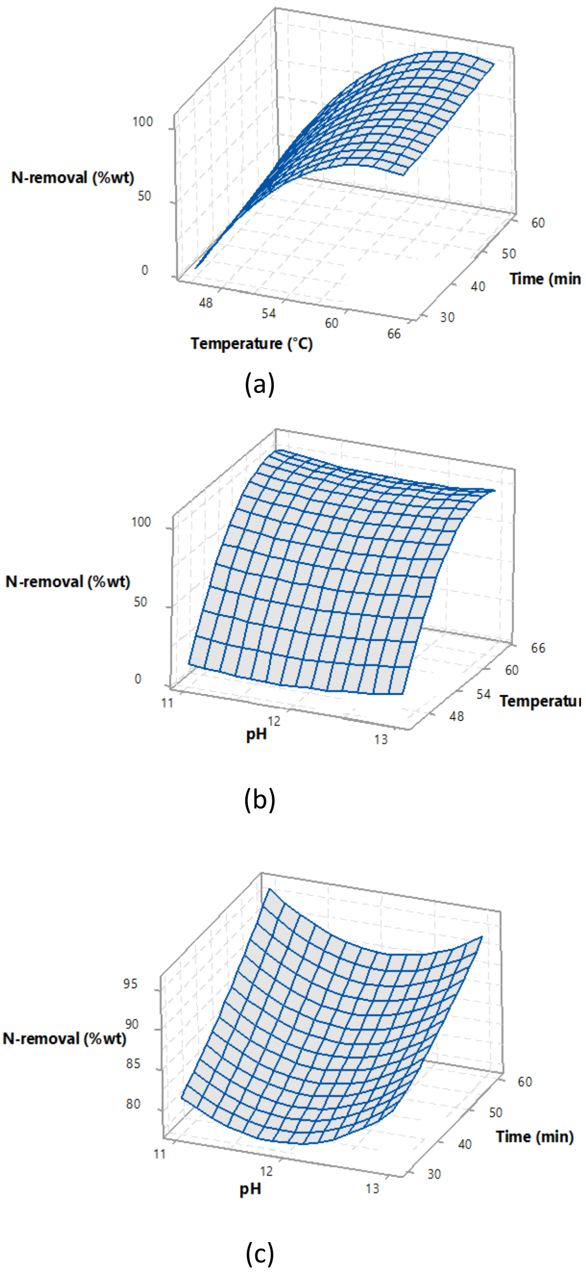

Figure 5. Surface plots of N-removal efficiency vs (a) temperature and reaction time; (b) pH and temperature; (c) pH and reaction time

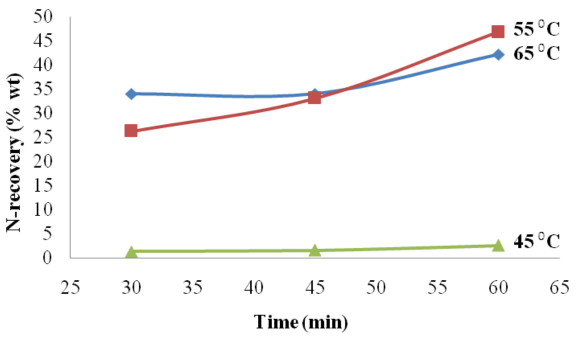

Figure 6. N-recovery efficiency at various temperatures and reaction times

recovery efficiency shared the similar trend with the N-removal efficiency with a slight drop observed in recovery efficiency at higher temperature and reaction time. The highest N-recovery efficiency of 53.4 % was observed at the temperature and reaction time of 55 °C and 60 min, respectively; while the lowest N-recovery efficiency of 0.9 % was observed at the temperature and reaction time of 45 °C and 30 min, respectively. At the optimum operating conditions, the N-recovery solution had the NH_4-N concentration of about 330 mg/L. The pH of the N-recovery solution should be adjusted to be in the neutral range before application to agricultural fields. Experiments are underway to demonstrate the bio-availability of this N-recovery solution to ensure its suitability for use as an agricultural fertilizer.

4. Discussion

The experimental results showed that pelletization of the hydrochar can produce an excellent pellet fuel. The hydrochar-pellet fuels were found to have energy content, bulk density and compressive strength of 22-24 MJ/kg, 900-1000 kg/m^3 and 8.0-8.5 kN/m^2, respectively, comparable to natural coal such as lignite. The hydrochar-pellet fuel form is easy for handling and transportation and can be used in various combustion processes.

By applying the reduced pressure distillation, N in the PW could be recovered in the $(NH_4)_2SO_4$ form which can be utilized as an agricultural fertilizer. The experimental results showed that temperature and reaction time were the important parameters which significantly affected the N-removal and N-recovery efficiencies. At pH 11-13, temperature of 55 °C and reaction time of 60 min, N-removal and N-recovery efficiencies were found to be 99.8% and 53.4%, respectively.

The results of this study demonstrated the technical feasibility of the HTC process for FSM which should result in environmental protection, health improvement and resource recovery, all leading to sustainable development. Economic analysis showed that FS treatment by the HTC process still incurs deficit, but the intangible benefits such as pollution control and health risk minimization cannot be ruled out (Polprasert, 2017). Application of the hydrochar-pellet as a solid fuel, including combustion behavior, marketability and social acceptance, should be investigated. Further studies on the scale-up and cost-benefit analysis of the HTC process are strongly recommended.

Acknowledgements
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