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Hydrothermal carbonization of anaerobic granular sludge: Effect of process temperature on nutrients availability and energy gain from produced hydrochar

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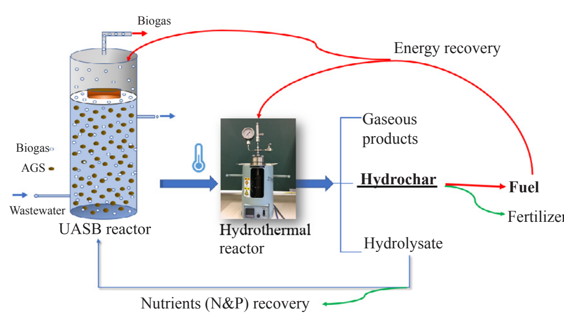
HIGHLIGHTS

- Anaerobic granular sludge was hydrothermally treated for energy/nutrients recovery.
- A lower hydrothermal temperature gained increase in net energy output.
- Most phosphorus in the hydrochar existed in bioavailable forms.
- E^2-Energy concept was applied for hydrothermal carbonization of granular sludge.

GRAPHICAL ABSTRACT



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ABSTRACT

Anaerobic granular sludge (AGS) has been applied for most highly efficacy anaerobic digestion systems like upflow anaerobic sludge blanket and expanded granular sludge bed reactors. As a by-product from these systems, AGS is prospected as a promising resource for energy and nutrients recovery from wastewater. In this study, hydrothermal carbonization (HTC) of AGS was investigated at different temperatures (160–240 °C) regarding the distributions of C, N and P in the hydrothermal products to maximize the utilization efficiency of AGS. Elemental composition and fuel characteristics of the hydrochar were evaluated. Results indicated that the percentages of C in hydrochar increased from 43.79% to 49.81% with the increase in HTC temperature, while N showed an opposite trend, decreasing from 9.58% to 5.49%. The higher heating value of hydrochar increased up to a maximum of 24 MJ/kg at 240 °C from 20 MJ/kg at 160 °C. However, the hydrochar yield decreased remarkably from 62% to 32%. As a result, the highest net energy output was about 6.86 MJ/kg achieved at 160 °C. Results from the van Krevelen diagram suggested that dehydration and decarboxylation reactions occurred during the HTC of AGS. In addition, the thermogravimetric analysis implied that the combustion of the produced hydrochar could be completed in two phases rather than the one phase as the raw AGS. With regard to other resources utilization, HTC was proved to be effective for AGS to immobilize and recycle phosphorus. The increase in HTC temperature exerted a limited effect on P distribution, resulting in less than 5% being released into the liquid at all tested HTC temperatures. Most of P were immobilized into the produced hydrochar where the bioavailable P fractions > 80%.

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1. Introduction

Over the past years, reclamation and utilization of energy and chemicals from wastewater is becoming one of the critical issues. Sewage sludge, a mixture of organic and inorganic species, has high commercial values after being treated and used as fuels and fertilizers. Recently, anaerobic granular sludge (AGS) has been applied worldwide in upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) systems to treat high-strength organic wastewaters. This biotechnology has demonstrated its incomparable advantages of high loading rate, easy solid-liquid separation and low energy consumption in numerous practical applications [1]. However, there are still few detailed reports on energy and nutrients recovery from AGS.

Hydrothermal conversion is a promising technology for energy and nutrients recovery from biowastes like sewage sludge without prior drying. During the hydrothermal process, the solid fraction can be separated from the liquid fraction efficiently accompanying by the redistributions of elements. Reaction temperature is the most important factor for hydrothermal conversion processes, which greatly affects the distribution of the products [2]. Hydrothermal carbonization (HTC), liquefaction and gasification can mainly happen at reaction temperature < 250 °C, 300–350 °C, and > 350 °C, respectively [3]. Most recently, HTC is paid much attention due to its relatively low operation cost and high resources recovery potential. To date, HTC has been applied for energy and resources recovery from a variety of waste materials such as lignocellulosic biomass [2], Tetra Pak waste [4], algae [5], and food waste [6]. Results indicated that the produced hydrochar is an energy rich carbonaceous material with great potential as a solid fuel. On the other hand, it is crucial to obtain hydrochar with lower nitrogen content when being used as the solid fuel. Related study suggested that HTC could control the NO_x emission effectively from sludge combustion [7]. Seiichi et al. reported that under > 150 °C hydrothermal condition, 60% of the N in sludge could be transferred into the liquid phase due to the solubilization and decomposition of the N compounds [8]. Instead of a pollution source, the concentrated ammonium in the liquid can be recovered and recycled by using air stripping process [9]. In addition, since most of phosphorus (P) could be accumulated in the solid fraction, the hydrochar is a potential source as fertilizer [10]. As reported by McGaughy and Reza, the hydrochar produced from septic tank waste contained high P content of 100–130 kg/tonne, demonstrating its high potential for fertilizer use [11]. As a consequence, HTC is regarded as an energy-efficient method for AGS treatment. It is known that sludge dewatering is an energy consumption process. The latent heat of vaporizing 1 kg of water is about 3.15 MJ, resulting in a substantial energy consumption during the sludge drying process [12]. HTC technology is promising for cutting this energy consumption, which is expected to realize energy recovery from efficient conversion of AGS to hydrochar.

AGS possesses excellent settleability [13], and contains various microorganisms, which are mainly composed of proteins, carbohydrates and lipids, reflecting great potential for energy recovery from wastewater. The higher heating value (HHV) of the AGS derived hydrochar could further be increased through the dehydration and decarboxylation reactions during HTC [14]. And the disintegration of various organics into inorganic substances is considered beneficial for enhancement of nutrients (N and P) availability in the produced hydrochar. Therefore, AGS-based hydrochar is prospected as an excellent energy carrier and fertilizer. Moreover, an "Environment-Enhancing-Energy" (E^2-Energy) concept has been established to produce fuels from biowaste and to recover nutrients from the biowaste during wastewater treatment as well [15]. This concept has been practiced on bio-crude oil production from algae cultivated from wastewater treatment via hydrothermal treatment [16]. Fig. 1 illustrates the E^2-Energy concept for the HTC of AGS. As shown, the energy recovered from the hydrochar combustion can provide energy for the HTC process and the wastewater treatment system like UASB for maintaining its temperature. The hydrolysate containing numerous nutrients can be recirculated to the anaerobic reactor for biogas production and adjustment of its organic loading rate. Up to the present, however, the nutrients (including C, N and P) distribution in the hydrothermal products remains unknown, let alone the detailed characteristics and energy recovery potential of the AGS-based hydrochar. These key issues are crucial for the E^2-Energy concept of AGS biotechnology and HTC.

This study for the first time investigated the HTC of AGS. The major purpose of this work was to fully evaluate the energy and nutrients recovery potentials from the AGS at different HTC temperatures. The mass balance in the HTC products, e.g. hydrochar and hydrolysate, and the energy balance during the HTC process were analyzed. In addition, the physical, chemical and thermal properties of the hydrochar were systematically characterized so as to provide scientific references for the AGS-based hydrochars being further alternatively used as clean fuels or fertilizers.

2. Materials and methods

2.1. Materials

AGS used in this study was sampled from Asahi Beer Brewery in Ibaraki Prefecture, Japan. The supernatant liquor was discarded and the

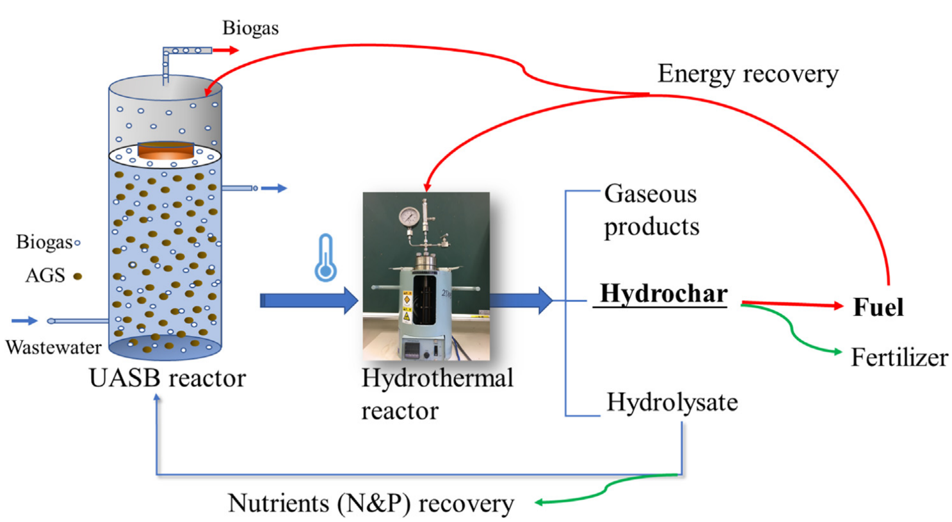

Fig. 1. Conceptual image o Environment-Enhancing-Energy (E^2-Energy) technology based on the hybrid process coupling anaerobic granular sludge (AGS) wastewater treatment with hydrothermal carbonization (HTC) of AGS. UASB, upflow anaerobic sludge blanket.