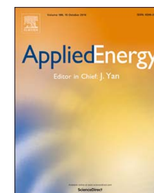
Applied Energy 206 (2017) 83–89

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



An integrated engineering system for maximizing bioenergy production from food waste

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HIGHLIGHTS

- An integrated system was developed for bioenergy production from food waste.
- Fungal mash promotes the food waste hydrolysis compared with commercial enzyme.
- 235 g of ethanol and 82 L of methane were produced from 1 kg of dry food waste.
- About 90% of total solid reduction was achieved in the proposed integrated system.
- Engineering feasibility and economic viability of the integrated system was clarified.

ARTICLE INFO

Keywords:
Food waste
Integrated engineering system
Fungal mash
Bioethanol
Biomethane

ABSTRACT

In this study, an integrated engineering system was developed for bioenergy production from food waste pretreated with a cost-effective and highly active enzyme mixture, namely fungal mash which was also in-situ produced from food waste. Under the optimized conditions, 141.5 g/L of glucose was obtained with 67.5% of total solid reduction after hydrolysis of food waste by fungal mash, while 71.8 g/L of bioethanol was produced from subsequent glucose fermentation. The remaining hydrolysis residue was further anaerobically digested for biomethane production with 22.8% of total solid reduction. As the result, about 90% of total solid reduction of food waste was achieved in the integrated engineering system with the outputs of bio-renewable energy in the forms of bioethanol and biomethane. The cost-benefit analysis clearly suggests that the bioenergy production from food waste in the proposed integrated engineering system is technically feasible and economically viable.

1. Introduction

Biorenewable energy has attracted increasing attention due to global climate change, environmental pollution issues and exhaustion of fossil fuels [1,2]. As a typical green bioenergy source, bioethanol is more preferable due to its renewability and non-pollution, and has been mainly produced from starchy and sugar-based substrates including corn, potato, grain, sugarcane and molasses etc. [3–5]. However, use of agricultural land for growing energy crops may not be sustainable as it inevitably compromises future food supply [6], while the production cost of ethanol production from energy crops was much higher than the current production cost of petroleum due to the high cost of the feedstock, and was not profitable [7–9]. Therefore, there is an urgent need to explore alternative material source for bioethanol production.

About 1.6 billion tonnes of food waste was generated in 2012, and only 10–20% was recycled [10]. Obviously, food waste is massively available and can be used as a suitable feedstock for bioenergy production. In the past years, food waste rich in starch (e.g. 55–65%), proteins (e.g. 15–20%), fats (e.g. 10–15%) and less cellulose (e.g. 5–10%) has been used for producing bioethanol through anaerobic or aerobic fermentation. However, the hydrolysis of food waste has been identified as a bottleneck that controls the fermentation efficiency in the ethanol production process [11–13]. Thus, many different hydrolysis methods of food waste have been developed, of which enzymatic pretreatment has been shown to be efficient and environmentally friendly compared to physical and chemical means [14,15]. Nevertheless, commercial enzymes used for hydrolysis of food waste towards bioethanol production are extremely expensive and generally available in a single form which may not be suitable for efficiently hydrolyzing complex food waste. Therefore, developing in-situ production of

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http://dx.doi.org/10.1016/j.apenergy.2017.08.190
Received 1 June 2017; Received in revised form 3 August 2017; Accepted 21 August 2017
Available online 23 August 2017
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costless and high-efficiency mixed enzymes would significantly reduce the pretreatment cost and improve hydrolysis efficiency of food waste. Kiran et al. [14] reported that 89.1 g/L glucose could be produced from the 50 g/L of dry food waste pretreated by homemade fungal mash rich in various hydrolytic enzymes which was produced from the waste cake, and the hydrolysis efficiency was 1.2 times than that of commercial compound enzyme. Recent reports also showed that high concentration bioethanol could be obtained from food waste through different pretreatment ways [16–18], but little information is available regarding the analysis of engineering feasibility and economic viability for ethanol production from food waste.

In addition, in the current practice, a substantial amount of the solid residue rich in organic matter and nutrients produced from hydrolysis of food waste still needs to be further disposal off or incinerated, causing many economic and environmental concerns. So reasonable recovering bioenergy (e.g. biomethane) from these biodegradable hydrolysis residues could maximize profit as well as solid reduction, in turn relieve the demand on and burden to incineration and landfill.

Therefore, this study aimed to develop an integrated engineering system for bioethanol production from real food waste pre-hydrolyzed with a fungal mash rich in various hydrolytic enzymes which was in-situ produced from the same food waste. More importantly, residual solid produced from hydrolysis of food waste was further anaerobically digested for biomethane recovery and further volume reduction, while the engineering feasibility and economic viability of the proposed integrated system was also elucidated.

2. Material and methods

2.1. Materials

Food waste was collected from a canteen at Nanyang Technological University with a total solid content (TS) of 20.0 ± 0.3%. *Aspergillus oryzae* (ABM Chemicals Ltd, Cheshire, England) was used to produce fungal mash with the food waste as substrate. For compared with fungal mash, commercial glucoamylase, amylase, cellulase and protease (Genencor, Danisco Singapore Pte. Ltd) were also used for hydrolysis of food waste. In this study, *Zymomonas mobilis (Lindner) Kluyver and van Niel (ATCC® 31821™*) from the American Type Culture Collection were employed for ethanol fermentation. The *Zymomonas mobilis* were first incubated on agar plates with ATCC 1341 RM medium (i.e. 20 g/L glucose, 10 g/L yeast extract, 2 g/L dipotassium phosphate and 15 g/L agar) for 48 h at 30 °C. The microbial culture developed on the agar plates was transferred into the ATCC 1341 RM medium without agar, and was then aerobically activated at 30 °C for 24 h. The activated *Zymomonas mobilis* were used as inoculum for ethanol production.

2.2. An integrated engineering system for bioenergy production from food waste

The integrated engineering system developed for bioenergy production from food waste consists of (i) a solid state fermentor (SSF) for fungal mash production; (ii) a hydrolysis unit for glucose production from food waste; (iii) a solid-liquid separation unit; (iv) a fermentor for ethanol production and (v) an anaerobic digestion unit (Fig. 1).

2.2.1. Solid state fermentor for fungal mash production

Fungal mash rich in various hydrolytic enzymes was in-situ produced from food waste, and the detailed procedure can be found in previous study [19,20], an AKBF 115 solid state fermentor (BINDER GmbH, Germany) with the auto-control of dissolved oxygen, humidity and temperature was used for fungal mash production from food waste with 10% (v/g) of *Aspergillus oryzae* as inoculum. The fermentor was operated at 30 °C for 7 days, and the oxygen and humidity were maintained at 50% and 70% of saturation, respectively, while the pH and the water content of food waste used were controlled at about 5.5 and 77%. The produced fungal mash was then directly applied for hydrolysis of food waste without further separation.

2.2.2. Hydrolysis and solid-liquid separation units

Food waste was hydrolyzed by prior produced fungal mash in a 10 L hydrolytic bioreactor with a working volume of 8 L (Fig. 1), which is equipped with proper agitation and monitoring systems. The operation parameters of this unit including food waste loading (50–200 g/L), temperature (40–70 °C), hydrolysis time (0–24 h), mixing power (100–300 r/min) and fungal mash loading (2.5–10%) were examined to reach the most hydrolysis of food waste. In this study, the solid and liquid in hydrolysate produced from the hydrolysis unit was separated by a filter press with a 0.5 μm pore diameter filtering membrane and a vacuum pump with the maximal pressure of 1 Mpa (Major Science, America).

2.2.3. Ethanol production unit

The liquid prior separated from the hydrolysate of food waste with high-concentration glucose was fed into a 5 L reactor with 3 L working volume for ethanol fermentation, to which *Zymomonas mobilis* was inoculated. The ethanol production process was maximized in terms of pH (5 − 7), temperature (20–40 °C), inoculum loading (5–15%), residence time (0–48 h), mixing speed (0–300 r/min), and aeration rate for improving ethanol production.

2.2.4. Anaerobic digestion unit

The solid residue separated from the hydrolysate of food waste with 18.9 ± 0.6% Total solids (TS) and 17.9 ± 0.5% volatile solids (VS) was fed to the anaerobic digester for biomethane production and volume reduction. The anaerobic sludge taken from a local full-scale anaerobic digester was used as inoculum according to a biomass to substrate ratio of 1:1. The digester was operated at 35 °C with the mechanical mixing of 150 rpm. The biochemical methane potential (BMP) tests were carried out by using the automatic methane potential test system (AMPTS) II (Bioprocess Control AB, Sweden). A blank was performed with the inoculum only. All experiments were carried out in duplicate.

2.3. Enzymatic activity assays

The enzymatic activity of fungal mash was determined according to the methods previously reported [11], for example, glucoamylase activity (GA) was measured using 2% (w/v) soluble starch (Sigma) in 100 mM of sodium acetate buffer with pH of 5 at 60 °C. One unit (1 U) of GA activity was defined as the amount of enzyme required for releasing 1 μmol glucose equivalent per minute under the assay conditions. Cellulase activity was determined by the filter paper assay at 60 °C, pH 5, and expressed as FULL NAME (FPU) according to IUPAC recommendations [21,22]. Amylase activity was quantified by the amylase activity assay kit (Sigma). Protease activity was obtained through the formation of free amino nitrogen (FAN) in hydrolyzing 15 g/L of casein solution (Sigma) in 100 mM of acetate buffer with pH 5 at 60 °C. One unit activity (U) of protease was defined as the protease required for producing 1 g FAN in 1 min.

2.4. Analytical methods

Starch content was determined using Megazyme's total starch kit (Bray, Ireland), while the reduction in sugars was quantified by dinitrosalicylic acid (DNSA) method with glucose as standard [23]. Total carbon and nitrogen were determined using HR Test'n tube TC and TN kit (HACH, US), while protein content was estimated according to the Kjeldahl method with a conversion factor of 6.25. The lipid content was determined by hexane/isopropanol (3:2) method [24]. The cellulose content was determined according to the method previously reported [25]. Glucose and ethanol concentrations were determined by Fast

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