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Biohydrogen production from food waste by coupling semi-continuous dark-photofermentation and residue post-treatment to anaerobic digestion: A synergy for energy recovery

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ABSTRACT

This study aimed at maximizing the energy yields from food waste in a three-step conversion scheme coupling dark fermentation (DF), photofermentation (PF) and anaerobic digestion (AD). Continuous H_2 production was investigated over a period of nearly 200 days in a thermophilic semi-continuous DF process with no pH control. The highest H_2 yield of 121.45 ± 44.55 N L H_2/kg VS was obtained at an organic loading rate of 2.5 kg VS/m^3/d and a hydraulic retention time of 4 days. The DF effluents mainly contained volatile fatty acids (VFAs) and alcohols as metabolites and un-hydrolyzed solid residues. The supernatant, after separation, was used to recover H_2 in a PF using *Rhodobacter sphaeroides*. The solid residual fraction along with PF effluent was converted into methane by anaerobic digestion. By combining DF and PF, the H_2 yield from the food waste increased 1.75 fold. Moreover, by adding AD as a post treatment of the DF residue, the total energy yield was substantially increased to reach 5.55 MJ/kg $VS_{food\ waste}$ added, versus 3.55 MJ/kg $VS_{food\ waste}$ when applying solely AD.

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Introduction

The inherent characteristics of hydrogen (H_2), such as higher energy content (142 MJ per kg), energy and water as the only by-products generated from its combustion, application in fuel cells for electricity generation and the ability to be produced biologically, makes H_2 a very interesting alternative future sustainable energy carrier [1]. Among several biological technologies proposed for H_2 production, dark fermentation (DF) is emerging as one of the prominent options, shown by the increasing research interests in this technology [2]. The advantages such as the flexibility to operate under different conditions of temperature and pressure, higher production rates, possibility to use renewable waste biomass as feedstock and the treatment capability make the DF process attractive. Waste biomass such as agricultural residues, the organic fraction of municipal solid waste (OFMSW) and agro-industrial wastes are economically competitive when considering a supply of sustainable feedstock, aiming at the industrial development of DF systems for biological treatment of waste [3–5].

OFMSW which is mainly composed of food waste (FW) has been receiving a lot of attention because of its potential to be used for the production of biofuels and other value added products [6]. Especially, about 1.3 billion tonnes of food per year get wasted, which is approximately one-third of the food produced for human consumption [7]. FW is generated from agricultural production, industrial manufacturing processes and final consumption in households. In the European Union, the total annual generation of FW is estimated around 89.3 million tonnes, comprising 37.7 million tonnes generated from household consumption alone [8]. The volatile solids content in FW ranges from 21 to 27% which shows its high organic carbon content that can be further valorized [9], and in particular for H_2 production by DF as demonstrated in the literature [10–15]. Some studies have reported the operational feasibility of continuous H_2 production using food or kitchen wastes as a feed in DF processes [10,14,16].

With the advantage of a stable operation, continuous DF processes are usually preferred and scaling-up is more viable in comparison to batch processes which involve regular downtime periods of maintenance [17]. However, stable operation of continuous DF of FW is highly influenced by bioreactor operating parameters such as pH, temperature, organic loading rates (OLRs) and hydraulic retention times (HRTs) [4,5,18]. These factors also influence the microbial communities and thus the biochemical pathways that can affect the total H_2 yields in mixed cultures [19]. In addition, there is growing interest in coupling DF either with photo-fermentation (PF) [20,21] or bioelectrochemical systems (BES) [22] to obtain higher overall H_2 yields or with anaerobic digestion (AD) for methane production [23–25], due to the post-treatment requirement of DF effluents (DFEs) and net positive energy gain from coupling these bioprocesses [26].

H_2 production rates and total H_2 yields are mainly a function of substrate types and OLRs applied [2]. A varying range of optimal OLR values has been reported for dark fermentative H_2 conversion from FW carried out in thermophilic DF processes [2]. Shin et al. [27] found an optimal H_2 yield of 126.25 L H_2/kg VS at an OLR of 8 kg VS/m^3/d, while the H_2 production decreased when the OLR was increased to 10 kg VS/m^3/d. The authors reported 8 kg VS/m^3/d, 5 days and a pH of 5.5, respectively, as optimal OLR, HRT and culture pH. In a study coupling DF and AD, Cavinato et al. [10] reported 66.7 L H_2/kg VS added at an optimum OLR of 16.3 VS/m^3/d, a HRT of 3.3 days and for a pH maintained in the range of 5–6 through the recirculation of AD effluent. Generally, HRTs in a range of 2–6 days have been reported as optimum for DF of organic FW in a CSTR process [2]. This range of HRTs is similar to the first stage of a two-stage AD process [28]. Moreover, the HRT is also a function of the substrate type and bioreactor operational parameters.

It has been well documented that dark fermentative H_2 production is generally due to the conversion of the initial soluble fraction of carbohydrates present in the complex organic biomass, that will lead to accumulation of volatile fatty acids (VFAs) and alcohols in DFEs [29,30]. Some recent studies have shown the potential of these DFEs to be utilized in PF processes for H_2 production [20,21]. Combining DF with PF, Su et al. [31] achieved an increase in H_2 yield from 76.7 to 596.1 L H_2/kg VS from water hyacinth. Meanwhile, Rai et al. [20] achieved 43% higher volumetric H_2 yields from acid hydrolyzed sugarcane bagasse in two step DF-PF systems. However, during the conversion of complex organic biomass like FW, a part of the unhydrolyzed solid residues will remain that can be further valorized in AD systems producing methane (CH_4) in a three steps conversion scheme (Fig. 1). Xia et al. [32,33] reported that a three-step conversion of algal biomass combining DF-PF-AD can achieve 1.7 and 1.3 times higher energy yields in comparison to a two-stage DF-AD and an one stage AD process, respectively.

High OLRs are often responsible for a decrease in culture pH due to the accumulation of VFAs present in DFE. Thus, most of the continuous DF systems utilizing acidic substrates such as food waste requires constant addition of external alkalinity sources such as alkaline chemicals (NaOH or KOH) or buffering agents (bicarbonate or phosphate buffers) [14,27,34]. A long-term study of continuous H_2 production at varying operating conditions of OLR and HRT to establish a long-term operability for continuous H_2 production in relation with the production of metabolites could provide further insights for the development of scaled-up DF systems. Similarly, a three-step conversion process (DF, PF and AD) might contribute to an increase in overall energy yield and could provide the biological treatment to the by-products generated from DF systems.

This study aims to demonstrate the long-term operational feasibility of continuous H_2 production from FW using a semi-continuous thermophilic DF reactor at various low OLRs and HRTs without pH control. The experiment also aimed at reducing the dependency on chemical buffering agents that are used to maintain the culture pH at working conditions. H_2 production through different possible biochemical pathways was discussed in relation to major metabolites present in DFEs, obtained during the varying experimental conditions. The potential of coupling DF with photofermentative H_2 production was investigated in batch PF experiments by using the liquid fraction of the DFE after physical separation. Further, the waste streams generated from the coupling of DF-PF were