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Upscaling of biohydrogen production process in semi-pilot scale biofilm reactor: Evaluation with food waste at variable organic loads

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ABSTRACT

The present account focuses on upscaling of biohydrogen (H_2) production at semi-pilot scale bioreactor using composite food waste. Experiments were conducted at different organic load (6, 12, 18, 30, 40, 50 and 66 g COD/l) conditions. H_2 production increased with an increasing organic load up to 50 g COD/l (9.67 l/h) followed by 40 g COD/l (6.48 l/h), 30 g COD/l (1.97 l/h), 18 g COD/l (0.90 l/h), 12 g COD/l (0.78 l/h) and 6 g COD/l (0.32 l/h). H_2 production was affected by acidification (pH drop to 3.96) at 66 g COD/l operation due to the excess accumulation of soluble metabolites (5696 mg VFA/l). Variation in organic load of food waste influenced the overall hydrogen production efficiency.

Introduction

Fermentative hydrogen (H_2) production is a promising approach for economical and sustainable energy source generation in which dark/acidogenic fermentation process is one of the promising method [1–3]. Dark fermentative H_2 production from renewable resources (waste/wastewater) using mixed consortia appears to be the most attractive method compared to other H_2 production processes [4,5]. The main criteria for substrate (waste/wastewater) selection are availability/nature, cost and biodegradability [6–9]. Various types of wastewater, viz., designed synthetic, chemical, distillery and dairy wastewaters having different degrees of biodegradability and composition especially for H_2 production [4]. Apart from industrial wastewaters, commercial wastes like food waste have attracted attention in recent years from bioenergy recovery viewpoint, due to its higher energy potential, biodegradability and inexhaustibility [10]. At present, in India, a fresh estimate about Rs 580 billion worth of food items get wasted every year [11]. But only 1% of these are utilized. Food waste is generally composite in nature and composed of rich organics fraction along with high moisture content and is highly variable depending on its source. Exploitation of this highly biodegradable food waste as source for biological H_2 production with simultaneous treatment can be considered as a viable and promising approach [11].

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H_2 production potential depends not only on the nature of wastewater, but also on operating conditions like reactor configuration, mode of reactor operation, substrate load, feeding redox condition and nature of substrate. Operation at acidophilic conditions (pH 6.0), selective enrichment of parent inoculum, biofilm configuration and batch mode operation showed positive influence on the H_2 production at bench scale level reactors [4]. Beyond the optimization of H_2 production process at lab and bench scale level bioreactors, the next stage of H_2 production system is design and operation at the pilot scale level. Upscaling of H_2 production process is critically important for understanding H_2 production efficiency at higher organic loading operation of wastewater. Optimization of organic loading of wastewater at pilot scale level reactor for efficient H_2 production is a complex process, especially when using mixed microflora and wastewater. Also it depends on the bioreactor and conditions applied for the fermentation process. Thus, the main objective of this report is to upscale the H_2 production process from bench scale level to semi-pilot scale level. In this direction, the performance of the bioreactor was assessed to find the optimum organic load of food waste by monitoring H_2 production rate (HPR), cumulative hydrogen production (CHP), hydrogen conversion efficiency (HCE), and change in the system pH, volatile fatty acids (VFA) production and COD removal efficiency throughout the cycle operation.

Materials and methods

Semi-pilot scale bioreactor

Semi-pilot scale biofilm configured anaerobic reactor was designed and fabricated in the laboratory using 'Perspex' material. Fig. 1 depicts the schematic details of the semi-pilot plant bioreactor. The bioreactor was designed to have an L/D ratio of 6 (length $\times$ diameter; 120 $\times$ 20 cm) and was filled with coir pith (void fraction $\sim$ 0.18) as fixed bed packing material to support the growth of H_2 producing microflora (Table 1). The reactor has working/total volume of 20/34 l and gas holding capacity of 4.5 l (head space). The bioreactor was operated in batch mode with an up-flow velocity of 0.50 m/day (14 l/day) at mesophilic temperature (30$\pm$2°C). The recirculation ratio (recirculation: feed ratio) of 1:2 was maintained. Outlet from the reactor was collected from the bottom and biogas generated during the reactor operation was collected by water displacement method through an outlet provided at the top of the bioreactor.

Acidogenic mixed consortia

The anaerobic mixed consortium was taken from the recycled stream after the bio-treatment stage of a municipal wastewater treatment plant in Hyderabad. The seed sludge was kept under anaerobic condition for several days before being used. It was used as seed inoculum after removing stone, sand and other coarse material. Prior to use the culture was selectively enriched three times in nutrient broth (32°°C; 120 rpm; 48 h) under acidophilic conditions (pH 6) [12]. This permits selective enrichment of acidogenic bacteria from anaerobic culture. The resulting acidogenic consortia were used as parent culture for inoculation. Prior to inoculation parent culture was enriched in designed synthetic wastewater (DSW) [glucose – 3 g COD/l; NH_4Cl – 0.5 g/l, KH_2PO_4 – 0.25 g/l, K_2HPO_4 – 0.25 g/l, $MgCl_2$ – 0.3 g/l, $CoCl_2$ – 25 mg/l, $ZnCl_2$ – 11.5 mg/l, $CuCl_2$ – 10.5 mg/l, $CaCl_2$ – 5 mg/l, $MnCl_2$ – 15 mg/l, $FeCl_3$ – 25 μg/l, chemical oxygen demand (COD – 3 g COD/l)] under anaerobic-acidogenic microenvironment at pH 6.0.

Composite food waste

The food waste was collected from the canteen of CSIR-IICT, Hyderabad and stored manually by removing any non-food particles. CSIR-IICT canteen caters about 700–1000 people per day and the generated waste is composite in nature comprising uneaten food and food preparation leftovers which mostly comprising of boiled rice (60$\pm$5%; wet weight basis) followed by cooked vegetables (14$\pm$4%), un-cooked vegetables (spoiled) (2$\pm$1%), cooking oil (6$\pm$2%), vegetable peelings (3$\pm$2%), cooked meat (4$\pm$2%), cooked fish (2$\pm$1%) and boiled spices (1.5$\pm$1%). The water content of waste varied between 15 and 24%. The collected food waste was masticated using electrical blender and filtered through stainless steel sieve to remove coarse materials so as to avoid clogging problems. Oil present in the waste was separated using an oil-separating system, that works on the principle of gravity. The oil free filtrate was used as a substrate after adjusting the various OLs viz., 6, 12, 18, 30, 40, 50 and 66 g COD/l by tap water as required. The food waste was analyzed for pH, COD, nitrogen, protein TS and VS as per standard methods [12] and the results are depicted in Table 2. Food waste showed a high concentration of COD (5.15 kg COD/l) with a good biodegradable fraction (BOD/COD–0.75). Prior to feeding the bioreactor; the redox condition of the food waste was adjusted to 6.0.

Operation and analysis

Experiments were conducted to evaluate the influence of organic load (OL) on acidogenic consortia in semi-pilot scale bioreactor utilizing food waste as substrate. Prior to start up, the bioreactor was inoculated with anaerobic (acidogenic) consortia [12] (20% of the total bioreactor volume) along with DSW (3 g COD/l) to support the biofilm formation on the supporting medium (coir pith) by adjusting substrate pH to 6. To adopt the acidogenic microflora with food waste, initially the bioreactor was operated at a lower OL of 6 g COD/l of food waste. In the beginning of each cycle, immediately after withdrawal (earlier sequence), a predefined volume (20 l) of food wastewater was fed to the reactor during fill phase and the reactor volume was circulated in closed loop at recirculation rate (recirculation volume to feed volume ratio) of 3 during the reaction phase to achieve a homogeneous distribution of the substrate as well as uniform distribution of requisite consortia along the reactor depth. A peristalitic pump was used to regulate the feed, recirculation, and decant operations. Biohydrogen generated during the fermentation was estimated using a microprocessor based pre-calibrated H_2 sensor (ATMI GmbH Inc., Germany). H_2 monitoring was done under closed conditions to avoid external environmental contamination.