Short communication

Simultaneous production of biohydrogen and bioethanol with fluidized-bed and packed-bed bioreactors containing immobilized anaerobic sludge

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Abstract

Hydrogen and ethanol are promising biofuels and of great potential to become alternatives to fossil fuels. In this work, two bioreactor systems, namely fluidized-bed (FBR) and packed-bed (PBR), were developed to produce H2 and ethanol simultaneously from dark fermentation of carbohydrate substrates using polyethylene–octane elastomer immobilized anaerobic sludge as the biocatalyst. The H2 and ethanol production in FBR essentially increased with increasing upflow velocity ($v_{up}$), as sucrose and fructose was better substrate for the yield of H2 and ethanol, respectively. With FBR operated at $v_{up} = 0.91$ cm s$^{-1}$, sucrose gave the highest H2 production rate (59 mmol h$^{-1}$ l$^{-1}$) among the three sugar substrates (sucrose, glucose, and fructose) tested, but the best H2 yield (1.04 mol mol hexose$^{-1}$) was obtained with glucose at $v_{up} = 0.55$ cm s$^{-1}$. For ethanol production in FBR, fructose was the favorable substrate, resulting in maximum ethanol production rate and yield of 378 mmol h$^{-1}$ l$^{-1}$ and 0.65 mol mol hexose$^{-1}$, respectively, when operating at $v_{up} = 0.91$ cm s$^{-1}$. At a hydraulic retention time of 4 h, the PBR system produced H2 and ethanol at a slower rate of 16 and 6 mmol h$^{-1}$ l$^{-1}$, respectively, by using glucose. However, the yields of H2 and ethanol were comparable to those for FBR. The soluble metabolites were dominated by ethanol, accounting for 43–65% of total soluble microbial products. The production of acetate and butyrate was less significant when compared to cultures optimized for H2 production. Comparison of the yield of H2 and ethanol shows that production of H2 and ethanol was reversely correlated. The total energy generation based on the heat values of H2 and ethanol was calculated to assess the overall efficiency of energy production. In FBR, the energy generation rate was higher when a faster upflow velocity was used. The best energy generation rate and yield was 526 kJ h$^{-1}$ l$^{-1}$ and 1048 kJ mol hexose$^{-1}$, respectively, both occurred with fructose-feeding FBR operated at $v_{up} = 0.91$ cm s$^{-1}$. The PBR system displayed a lower energy generation rate, whereas the energy yield was comparable or even higher than those for FBR.

1. Introduction

Biomass energy has emerged as one of the most attractive and promising alternative energy carriers to fossil fuels. Ethanol can be supplemented to gasoline as a fuel for transportation and could replace MTBE (methyl tert-butyl ether) as a more environment-compatible gasoline additive in the future [1,2]. Ethanol can also be used as a substrate for biodiesel production [3]. Hence, converting biomass feedstock to bioethanol and/or biodiesel is heavily focused bioenergy technology at this moment [4]. Nevertheless, as a clean, recyclable, and efficient energy carrier, hydrogen is still considered to play a pivotal role in future energy supply [5]. Producing H2 via fermentative routes is more environmentally friendly and less energy intensive, thereby being competitive to conventional H2-producing methods (e.g., thermo-chemical means) [5,6]. In particular, dark H2 fermentation carried out with heterotrophic anaerobic microorganisms (e.g., *Clostridium* sp.) [7–14] is considered the most commercially viable bioH2 process, because it has a higher H2 production rate and can be easily incorporated into existing waste treatment systems for simultaneous waste reduction and clean energy generation [15]. In addition to H2 production, anaerobic fermentation also produces a significant amount of alcohols (such as ethanol) [16]. Although formation of alcohols that would consume free electrons from NADH is usually unfavorable for H2 production, it might be feasible to allow

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a balanced production of both gaseous and liquid biofuels (i.e., H₂ and ethanol) through proper operation of dark fermentation processes toward an optimal total energy gain.

Entrapped-cell systems were shown to be suitable for batch and continuous H₂ fermentation with mixed cultures [17–19]. In particular, the immobilized cells could be integrated with a variety of bioreactor design, such as fluidized-bed [20,21] or fixed bed [22] for efficient bioH₂ production. In this study, acclimated H₂-producing sludge were immobilized by polymeric matrix polyethylene–octene elastomer (POE), which is a commercially available elastomer widely used in various industrial applications due to its excellent balance of mechanical properties along with favorable processability [23–25]. In the present work, the POE-entrapped cells were used for H₂ production in a fluidized-bed reactor (FBR) possessing favorable characteristics for the production of gaseous products [20] as well as in a packed-bed reactor (PBR) that is cost effective with simple setup and easy operation [26]. Using three types of sugar (namely, sucrose, glucose, and fructose) as the sole carbon substrate, the performance of continuous H₂ and ethanol production was investigated at different upflow velocity for FBR and at a fixed hydraulic retention time for PBR. The objective of this work was to develop innovative fermentation technology for dual production of two most critical biomass energy products—H₂ and ethanol.

2. Materials and methods

2.1. Hydrogen-producing sludge and fermentation medium

The seed sludge was collected from the final sedimentation tank of a municipal wastewater treatment plant located in central Taiwan. The sludge was pretreated with HCl at pH 3.0 for 24 h to eliminate the methanogenic activity [22]. The acid pretreated sludge was acclimated in continuous culture operated at a HRT of 12 h to maintain stable H₂-producing activity. The medium used for cell growth and H₂ production contained 20 g COD l⁻¹ of sugar (sucrose, glucose, or fructose) as the sole carbon source along with a sufficient amount of inorganic salts, including (mg l⁻¹) NH₄HCO₃, 5240; NaHCO₃, 6720; K₂HPO₄, 125; MgCl₂·6H₂O, 100; MnSO₄·5H₂O, 15; FeSO₄·7H₂O, 25; CuSO₄·5H₂O, 5; and CoCl₂·5H₂O, 0.125.

2.2. Cell immobilization

Fifty milliliters of acclimated H₂-producing sludge (ca. 0.15 g VSS) was well mixed with 90 g polyethylene–octene elastomer (POE). The resulting mixture was introduced to an extruder at a temperature of 70 °C and was extruded to form cell-entrapped colloid beads (1.5 mm in diameter). After being rinsed with deionized water, the colloid bead was immersed into a solution containing 0.5 g sodium alginate, 0.6 g zirconium oxide and 5 g of the acclimated sludge and was then transferred to 0.1 M CaCl₂ for solidification. The resulting immobilized-cell beads had an average density of 1.1 g cm⁻³.

2.3. Setup and operation of the fluidized-bed reactor

Schematic description of the fluidized-bed reactor (FBR) used in this study is shown in Fig. 1a. Main body of the FBR reactor was a glass column with a diameter of 2.7 cm and a height of 120 cm. In the beginning of FBR operation, 100 g of the immobilized cells and 1.4 l of the aforementioned medium were placed in the reactor. The static bed height of the immobilized-cell particles was 4.5 cm. Argon gas (device no. 1) was used to sparge the reaction liquid thoroughly to create an anaerobic condition. The medium (device no. 13) was fed from the bottom into the immobilized-cell-loaded FBR reactor (device no. 2). The effluent of the reactor was introduced to a gas–liquid separator (device no. 9), where the gaseous and soluble products were collected separately. The operation temperature and pH in the bed was controlled at 35 °C and 5.8–6.8 throughout the operation. The medium was fed into the reactor with the adjustment of liquid flow rate (v₀ = 0.55–0.91 cm s⁻¹) to fluidize the bed materials. When a steady state was reached, the hydraulic retention time was controlled at a designated value with the adjustment of recycle stream (device no. 3). The steady-state operation was defined as a nearly constant average H₂ and ethanol production rate (within 10% variation) for 3–4 days. The biogas (consisting of CO₂ and H₂) production was monitored by a gas flow meter (Type TGI; Ritter Inc., Germany). The gas volumes were calibrated to 25 °C and 760 mmHg. The compositions of gaseous and soluble products were also analyzed by gas chromatography at designated time intervals.

2.4. Setup and operation of the packed-bed bioreactor

The pack bed reactor (PBR) was composed of a glass column 3.2 cm in diameter and 120 cm in height (Fig. 1b). Before PBR operation, 100 g of immobilized-cell beads was packed into the reactor with a bed height of 5 cm, a porosity of 65%, and a working volume of 3.86 l. The sugar-containing medium was then fed from bottom into the immobilized-cell-loaded column for continuous H₂ production. The reactor was operated at HRT of 4 h. The definition of steady-state operation was similar to that for FBR. Operation temperature of the reactor was controlled at 35 °C and initial pH of the medium was controlled at 6 ± 0.1. The composition of gas products and soluble metabolites produced was determined at designated time intervals. A gas meter was used to record the quantity of gas products generated.

2.5. Analytical methods

The gas products were analyzed by gas chromatography (GC) using a thermal conductivity detector (TCD). The volatile fatty acids and ethanol were also detected by GC using a flame ionization detector (FID). The conditions and columns used for GC analysis were identical to those reported previously [26–28]. Standard Methods [29] were used to determine biomass concentration (in terms of volatile suspended solid; VSS). The carbohydrate concentration in the effluent was also measured using Standard Methods (via phenol-sulfuric acid method) [29].

3. Results and discussion

3.1. H₂ and ethanol production with fluidized-bed bioreactor

The performance of H₂ and ethanol (EtOH) production with the fluidized-bed bioreactor is indicated in Table 1. Regardless of the type of sugar substrate, the H₂ production rate essentially increased with an increase in upflow velocity (v₀) as the highest v₀ tested (0.91 cm s⁻¹) gave the highest H₂ production rate of 59, 53, and 33 mmol h⁻¹ l⁻¹ for sucrose, glucose, and fructose, respectively (Table 1). The highest ethanol production rate also reached 287, 196, and 378 mmol h⁻¹ l⁻¹ for sucrose, glucose, and fructose, respectively, when the fluidized-bed was operated at a v₀ of 0.91 cm s⁻¹. The positive effect of upflow velocity on the production rate of H₂ and ethanol is most likely due to better mass transfer efficiency arising from higher upflow velocity. Among the three sugar substrates used (all at a concentration of 20 g COD l⁻¹), sucrose appeared to be the preferable substrate stimulating the rate of H₂ production, while fructose led to better ethanol production rate (Table 1). On the other hand, Table 1 shows that glucose seemed to exhibit higher
Fig. 1. Schematic description of (a) the fluidized-bed reactor (1, argon tank; 2, fluidized-bed column; 3, recycle pump; 4, liquid sampling site; 5, pressure gauge; 6, thermal couple; 7, heating coil; 8, temperature controller; 9, gas-liquid separator; 10, gas sampling site; 11, gas flow meter; 12 and 15, peristaltic pump; 13, substrate tank; 14, product collect) and (b) the packed-bed reactor used in this study (1, argon tank; 2, packed-bed column; 3, gas sampling site; 4, liquid sampling site; 5, product collection; 6, gas collection; 7, substrate tank; 8 and 9, peristaltic pump).
H₂ yield than the other two sugars, while using fructose as the carbon source could achieve the best ethanol yield. There was no clear trend for the effect of upflow velocity on H₂ yield, but in general the ethanol yield increased when \( v_{up} \) was increased. The best H₂ yield (1.04 mol H₂ mol hexose\(^{-1}\)) was obtained with sucrose at a \( v_{up} \) of 0.55 cm s\(^{-1}\), while using fructose as the substrate could achieve the highest ethanol yield of 0.65 mol EtOH mol hexose\(^{-1}\).

The foregoing correlation between biofuels production and carbon substrates could be resulted from the difference in sugars metabolism by the mixed bacterial population in the sludge culture, in which H₂-producing bacteria may have a different carbon source preference from the population that tended to produce carbon dioxide (e.g., ethanol). In our previous studies, Enterobacter, Klebsiella or Clostridia species were present in the seed sludge identical to that used in this work [7,18]. The former two facultative anaerobes are known to be effective alcohol producers [18,30] and thus might contribute significantly to ethanol production while catabolizing the sugar substrates. In contrast, Clostridial species (e.g., *Cl. acetobutylicum*) could produce H₂ and ethanol/organic acid (e.g., acetate) mixtures, but when more ethanol and less acetate are produced, the intracellular NADH/NAD\(^+\) ratio decreases, leading to a poor H₂ production rate [31,32].

Thus far very few reports in the literature describing the use of three phase fluidized-bed bioreactors for H₂ production. Our recent work demonstrated that fluidized-bed (FBR) could be effective in H₂ production [20,21] since the special feature of FBR is very suitable for the production of gaseous fuel (H₂) and liquid fuel (ethanol) and is, to our best knowledge, one of the early attempts in this regard. It should be noted that the bacterial community structure of the mixed culture producing H₂ and ethanol at an equally important rate could be markedly different from the culture producing mainly H₂, because H₂ and ethanol production seem to be competitive events from the perspective of metabolic electron transfer and energy generation [1,31–34].

### 3.2. H₂ and ethanol production with packed-bed bioreactor

A packed-bed bioreactor (PBR) containing PEO immobilized H₂ producing sludge was also used for continuous H₂ and ethanol production. As indicated in Table 2, the PBR system was able to produce H₂ at a volumetric rate of 10.3, 16.1, and 7.2 mmol h\(^{-1}\) l\(^{-1}\) for sucrose, glucose, and fructose, respectively, whereas only 254–500 mg COD l\(^{-1}\) of ethanol was formed [20,21], which is nearly an order of magnitude lower than our results. In contrast, the present work emphasizes a balanced production of both gaseous fuel (H₂) and liquid fuel (ethanol) and is, to our best knowledge, one of the early attempts in this regard.

Table 1

<table>
<thead>
<tr>
<th>Substrate</th>
<th>( v_{up} ) (cm s(^{-1}))</th>
<th>H₂ production rate (mmol h(^{-1}) l(^{-1}))</th>
<th>EtOH production rate (mmol h(^{-1}) l(^{-1}))</th>
<th>H₂ yield (mol H₂ mol hexose(^{-1}))</th>
<th>EtOH yield (mol EtOH mol hexose(^{-1}))</th>
<th>Energy generation rate (kJ h(^{-1}) l(^{-1}))</th>
<th>Energy yieldb (kJ mol hexose(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>Sucrose</td>
<td>0.55</td>
<td>45</td>
<td>86</td>
<td>0.64</td>
<td>0.24</td>
<td>126</td>
<td>511</td>
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<td></td>
<td>0.73</td>
<td>57</td>
<td>177</td>
<td>0.61</td>
<td>0.38</td>
<td>258</td>
<td>694</td>
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<td></td>
<td>0.91</td>
<td>59</td>
<td>287</td>
<td>0.51</td>
<td>0.49</td>
<td>409</td>
<td>792</td>
</tr>
<tr>
<td>Glucose</td>
<td>0.55</td>
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<td>103</td>
<td>1.04</td>
<td>0.29</td>
<td>151</td>
<td>694</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>20</td>
<td>136</td>
<td>0.44</td>
<td>0.29</td>
<td>192</td>
<td>522</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>53</td>
<td>196</td>
<td>0.91</td>
<td>0.33</td>
<td>283</td>
<td>711</td>
</tr>
<tr>
<td>Fructose</td>
<td>0.55</td>
<td>8</td>
<td>74</td>
<td>0.23</td>
<td>0.16</td>
<td>103</td>
<td>284</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>4</td>
<td>253</td>
<td>0.09</td>
<td>0.50</td>
<td>347</td>
<td>709</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>33</td>
<td>378</td>
<td>0.56</td>
<td>0.65</td>
<td>526</td>
<td>1048</td>
</tr>
</tbody>
</table>

\( a \) Energy generation rate = H₂ production rate (mol h\(^{-1}\) l\(^{-1}\)) \times 286 kJ mol H₂\(^{-1}\) + EtOH production rate (mol h\(^{-1}\) l\(^{-1}\)) \times 1366 kJ mol EtOH\(^{-1}\) [42,43].

\( b \) Energy yield = [mol H₂ produced \times 286 kJ mol H₂\(^{-1}\) + mol EtOH produced \times 1366 kJ mol C₂H₅OH\(^{-1}\)]/mol hexose consumed [42,43].

Table 2

<table>
<thead>
<tr>
<th>Substrate</th>
<th>H₂ production rate (mmol h(^{-1}) l(^{-1}))</th>
<th>EtOH production rate (mmol h(^{-1}) l(^{-1}))</th>
<th>H₂ yield (mol H₂ mol hexose(^{-1}))</th>
<th>EtOH yield (mol EtOH mol hexose(^{-1}))</th>
<th>Energy generation rate (kJ h(^{-1}) l(^{-1}))</th>
<th>Energy yieldb (kJ mol hexose(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sucrose</td>
<td>10.3</td>
<td>6.2</td>
<td>0.44</td>
<td>0.49</td>
<td>11</td>
<td>795</td>
</tr>
<tr>
<td>Glucose</td>
<td>16.1</td>
<td>5.8</td>
<td>0.70</td>
<td>0.53</td>
<td>13</td>
<td>924</td>
</tr>
<tr>
<td>Fructose</td>
<td>7.2</td>
<td>2.1</td>
<td>0.58</td>
<td>0.14</td>
<td>5</td>
<td>357</td>
</tr>
</tbody>
</table>

\( a \) Energy generation rate = H₂ production rate (mol h\(^{-1}\) l\(^{-1}\)) \times 286 kJ mol H₂\(^{-1}\) + EtOH production rate (mol h\(^{-1}\) l\(^{-1}\)) \times 1366 kJ mol EtOH\(^{-1}\) [42,43].

\( b \) Energy yield = [mol H₂ produced \times 286 kJ mol H₂\(^{-1}\) + mol EtOH produced \times 1366 kJ mol C₂H₅OH\(^{-1}\)]/mol hexose consumed [42,43].
when HRT was shortened, H₂ production rate increased, but H₂ yield decreased [35,36]. The possible cause for why the production rate and yield could vary in an opposite direction is that the high H₂ production rate may cause over-accumulation of H₂ in the aqueous phase [36–38], thereby resulting in inhibition of H₂ production activity. Moreover, using higher organic loading rate (like in FBR) could lead to a higher H₂ production rate but the substrate conversion was lower than using PBR (lower organic loading rate). This may also contribute to the lower yield in FBR.

In PBR system, glucose appeared to be more efficient in producing both H₂ and ethanol, with a steady-state yield of 0.7 and 0.53 mol mol hexose⁻¹. This trend is different from that observed in FBR system, in which fructose was the favorable substrate for ethanol production (Table 1). The reason for the different trend could be due to the variation in predominant bacterial population in the two reactors, since there is a significant difference in mass transfer efficient and hydrodynamic patterns between FBR and PBR. In addition to variation in bacterial composition, it is also likely that a metabolic shift occurred due to different culture environment arising from distinct bioreactor operations. This could also lead to a different substrate-dependence of fermentation products [39].

There were a few examples using immobilized-cell packed-bed reactors for dark H₂ fermentation, but again those studies mainly focused on producing H₂ [8,40]. For instance, Rachman et al. [41] utilized a PBR reactor containing self-flocculated cells of Enterobacter aerogenes to produce H₂ from glucose, attaining a maximum H₂ production rate of 58 mmol l⁻¹ h⁻¹, while their ethanol production was only 52 mM (i.e., 230 mg COD⁻¹), which is an order of magnitude lower than that obtained in our PBR system (2393 mg COD⁻¹ obtained from using glucose as the carbon source). Moreover, our recent work [26] using biofilm-based packed-bed bioreactor could achieve a H₂ production rate of ca. 50 mmol l⁻¹ h⁻¹, but also produced a small amount of ethanol (ca. 200 mg COD⁻¹). These comparisons show that the present PBR process was indeed an ethanol-rich dark fermentation system.

3.3. Composition of gaseous and soluble metabolites

The biogas products in the fluidized-bed and packed-bed bioreactors were mainly H₂ and CO₂, while methane was under the detectable level of the gas chromatography device. The H₂ content in biogas was within the range of 20–40% (Tables 3 and 4). In soluble metabolites (i.e., soluble microbial products; SMP), regardless of the type of bioreactor, the major product was ethanol, which accounted for the 43–65% of total SMP (Tables 3 and 4). The next abundant products were acetate and propionate, contributing to 12–35 and 11–28% of SMP, respectively. Meanwhile, a small quantity of propionate was also produced. This soluble metabolite composition indicates that the culture environment was unfavorable to H₂ production metabolism of the bacterial populations in the two bioreactors, because in most efficient H₂ producing system, butyrate or...
indicate the trends).

acetate was the predominant product [17,20,22]. In contrast, ethanol production would consume free electrons from NADH, reducing the amount of electron substrates for hydrogenase-catalyzed H2 production reaction [34]. The conflicts between H2 and ethanol producing pathways can also be observed from Fig. 2, showing that, with few exceptions, the H2 and ethanol yields were in general inversely correlated irrespective of the type of sugar substrate or bioreactor. Linear regression results show that the correlation between ethanol yield (y) and H2 yield (x) for fructose, sucrose, and glucose can be expressed as

\[ y = -1.640x + 0.617 \]  \( (r^2 = 0.883) \]

\[ y = -1.433x + 1.202 \]  \( (r^2 = 0.886) \]

\[ y = 0.729x + 1.028 \]  \( (r^2 = 0.947) \) respectively.

The electron mass balances for the fermentation cultures operated in two bioreactor systems were also carried out. The results indicate that the balances were satisfactorily consistent with the missing electron equivalents ranging from 6 to 15%.

3.4. Energy production efficiency

Since our dark fermentation systems produced a significant amount of gaseous and liquid biofuels (i.e., H2 and ethanol), the process performance in terms of energy generation derived from the combination of the two biofuels was calculated according to their combustion heat values [42,43]. As depicted in Tables 1 and 2, the fluidized-bed processes gave a much higher energy generation rate (EGR) over the packed-bed reactor. The EGR of FBR tended to increase as \( v_{up} \) increased, which is quite obvious because both \( H_2 \) and ethanol production rate increased with increasing \( v_{up} \) (Table 1). The maximum energy generation rate was 526 kJ h\(^{-1}\) l\(^{-1}\), taking place when FBR was fed with fructose at \( v_{up} = 0.91 \) cm s\(^{-1}\) (Table 1). Despite a much lower energy generation rate when compared to FBR, the PBR had comparable or even higher energy yields (EY) than those for FBR (Tables 1 and 2), suggesting that PBR has the potential for improving energy production rate if properly adjusting bioreactor operation parameters (e.g., by shortening the HRT). The best EY (1048 kJ mol hexose\(^{-1}\)) was also obtained from fructose-fed FBR with \( v_{up} = 0.91 \) cm s\(^{-1}\). For FBR, using fructose as substrate, in general, led to better EGR and EY, whereas PBR obtained the highest energy generation efficiency with glucose (Table 2). As mentioned earlier, this difference could be attributed to the variation in bacterial population structure in the two bioreactor systems. From the aspect of total energy generation, production of both \( H_2 \) and ethanol may be superior to producing sole biofuel. Moreover, since \( H_2 \) and ethanol are present in different phases, separation of the two biofuels would be relatively easy, leading to additional economical benefits arising from simple down-stream processing.

4. Conclusions

This work demonstrated feasible bioreactor systems for simultaneous production of \( H_2 \) and ethanol as biofuels. With better mass transfer efficiency, fluidized-bed reactors (FBR) were able to produce \( H_2 \) and ethanol at a significant higher rate than packed-bed reactors (PBR). However, the production yields were comparable for the two bioreactor systems. Production of the two biofuels seemed to have substrate preference. For instance, in FBR sucrose was favorable for \( H_2 \) production, while ethanol production was better with fructose. However, in PBR, glucose gave the best performance in terms of production rate and yield of the two biofuels. This difference in substrate preference could be due to variations in bacterial population structure resulting from different bioreactor configuration. The highest production rate for \( H_2 \) and ethanol attained from this work was 59 and 378 mmol h\(^{-1}\) l\(^{-1}\), respectively, while the highest yield was 1.04 and 0.65 mol mol hexose\(^{-1}\), respectively. All those values were obtained from using FBR. This work also utilized energy generation rate and yield (based on heat values of \( H_2 \) and ethanol) as a performance indicator for overall energy production efficiency of the bioprocesses examined. Again, the FBR allowed a better energy generation rate, whereas PBR attained a comparable or even higher energy yield. Using fructose as substrate, the FBR system operated at \( v_{up} = 0.91 \) cm s\(^{-1}\) exhibited the best energy generation rate and yield of 526 kJ h\(^{-1}\) l\(^{-1}\) and 1048 kJ mol hexose\(^{-1}\), respectively.

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