1 Introduction

The imminent ending of the non-renewable natural energetic resources brings the necessity to research for new renewable natural energetic resources, as well as the maximization of productivity and lowering the costs of already known processes. Biomass-based energy sources constitute an important alternative to help solving this problem (Letti and Karp, 2012; Domínguez-Maldonado et al., 2014). Lignocellulosic biomass is the most abundant renewable biological resource and, since is outside the human food chain is also an attractive and relatively inexpensive raw material (Pereira et al., 2012). Lignocellulose is an abundant natural carbohydrate formed by biopolymers such as cellulose, hemicellulose and lignin, which can be transformed into substitute renewable energy resource by microbial conversion.
The advantages of using them as raw materials for ethanol production are their low cost, easy availability, avoidance of conflict with their use for food, and the potential production of fuel from lignin (Liu et al., 2012). However, the heterogeneous and complex structure of lignocellulosic makes their fractionation and further benefit difficult (Romaní et al., 2012). The main stages of the cellulosic ethanol production process are pretreatment, hydrolysis, fermentation, distillation, and further fuel upgrading (Starfelt et al., 2012). There are at least three methods of hydrolysis, including dilute acid hydrolysis, concentrated acid hydrolysis, and enzymatic hydrolysis. The enzyme-based process is more environmental-friendly and gives higher hydrolysis yield than acid hydrolysis (Zheng et al., 2009). Therefore enzymatic hydrolysis is advantageous because of its low toxicity, low utility cost and low corrosion compared to acid or alkaline hydrolysis (Sun and Cheng, 2002; Taherzadeh and Karimi, 2007). In enzymatic hydrolysis the enzymes catalyze only specific reactions, and as result no other side reactions occur or byproducts are formed and hydrolysis has the potential to achieve higher yield of reducing sugars (Mukhopadhyay et al., 2011). Here cellulase and hemicellulase enzymes cleave the bonds of cellulose and hemicellulose respectively. Cellulase enzymes involve endo and exoglucanase and β-glucosidases. Hemicellulolytic enzymes are more complex and are a mixture of at least eight enzymes. Cellulase is hydrolysed to glucose whereas hemicellulose gives rise to several pentoses and hexoses (Sarkar et al., 2012).

Zymomonas mobilis has been intensively studied in ethanol fermentation. Zymomonas mobilis metabolizes sugar via the Entner-Doudoroff (ED) pathway, which produces less ATP and less biomass. More carbon sources are thus channeled to ethanol, resulting in an even higher ethanol yield than that found with the native ethanol fermenting yeast Saccharomyces cerevisiae. In addition, because of producing less ATP during ethanol fermentation, Z. mobilis maintains a higher glucose metabolic flux, normally three to five fold that of S. cerevisiae (Wirawan et al., 2012). The aim of this work was to evaluate the production of ethanol from different enzymatic hydrolysates from pretreated Eucalyptus globulus saw dust pulp.

2 Materials and methods

2.1 Microorganism and media

Zymomonas mobilis NRRL B-806 strain was provided by the Environmental Biotechnology Lab. of Biochemistry Engineering Faculty, Pontificia Universidad Catolica de Valparaíso, Chile (PUCV). Zymomonas mobilis NRRL B-806 was cultivated on M2 solid medium containing per liter: 100 g glucose, 5 g yeast extract, 2 g KH₂PO₄, 1 g MgSO₄ and 1.5 g (NH₄)₂SO₄ at 30 °C. Inoculum was prepared from the stock culture, using the same culture medium. The growth was carried out at 30 °C for 48 hours.

2.2 Eucalyptus globulus pretreatment

Eucalyptus globulus saw dust pulp pretreatment was carried out in a stainless steel reactor under the following conditions: H₂SO₄ 1% at 176 °C for 10 minutes followed by a quick decompression to atmospheric pressure. The solids were separated by filtering and washed with tap water to neutrality. The solid residue was dried in a forced-air oven at 105 °C.

2.3 Enzymatic hydrolysates

The study was carried out using three different enzymatic hydrolysates from pretreated Eucalyptus globulus saw dust pulp under the following conditions: (FPU:UI pNPG ratio and enzyme/sustrate relation). Enzymes used were of the series NS500 Novozymes (Bagsvaerd Denmark), cellulase (NS50013) and β-glucosidase (NS50010). Enzymatic hydrolysates compositions are shown in Table 1 obtained under the following conditions; 50 °C, with a stirring rate of 200 rpm during 72 h.

2.4 Hydrolysates fermentation process

Enzymatic hydrolysates were supplemented with nutrients of M2 medium at a pH 5.5 (without glucose). Experiments were carried out in 250 mL Erlenmeyer flasks, each containing 100 ml de hydrolysates. In the case of the hydrolysate E, hydrolysates C and D were mixed in a ratio 1:1 to obtain 75 ml of final volume. A control was studied containing M2 medium, using glucose with an initial concentration of 100 g L⁻¹. All the flasks were inoculated with 5 mL of cellular suspension (0.15 g L⁻¹). Incubation time was 51 h, at 30 °C with a stirring rate of 150 rpm.
2.5 Analytical methods

Carbohydrates concentrations, inhibitor concentrations and ethanol production were determined by HPLC (Agilent 1260 HPLC, IR Detector). A Biorad HPX-87-H column was used, enabling quantification of glucose, xylose, cellobiose, arabinose, formic acid, acetic acid, ethanol. Operational conditions were H₂SO₄ 5mM as mobile phase, at a flow rate of 0.6 mL/min, and 45 °C. All samples were centrifuged at 10,000 rpm for 5 min, and filtered and dilutes in HPLC water before being analyzed. Cellular growth was determined by measuring optical density of cells using a UV/Vis spectrometer (Cary 50Bio) at 660 nm and correlated with dry weight. All the analyses were performed in triplicate.

3 Results and discussion

Figure 1 shows glucose consumption, ethanol production and biomass growth in control reactor with Zymomonas mobilis NRRL B-806 using M2 medium at 30 °C. Glucose was totally consumed after 30 h and at this point maximum ethanol production and biomass growth was achieved with a 41.1 g L⁻¹ and 2.1 g L⁻¹ respectively, with an ethanol yield (Yₑ/Σ) of 0.46 g ethanol g⁻¹ glucose (90% in relation to theoretical value) and a productivity of 1.37 g L⁻¹ h⁻¹ (see Table 2). Growth curve had a correlation with glucose consumption, showing that after 30 h a stationary phase was reached, achieving a yield of 2.43 ×10⁻² g biomass g⁻¹ glucose (2.43 %). Low biomass production is normally observed in Zymomonas mobilis, and cell growth and fermentation are not linked (Parker et al., 1997). According to Rogers et al. (1982) approximately 2% of the carbon source is converted into biomass. This occurs due to Entner-Doudoroff pathway used by this microorganism. This pathway yields only a single mole of ATP per mole of carbohydrate fermented, giving Zymomonas the lowest molar growth yield reported for bacteria (Swings and De Ley, 1977).

Figure 2 shows glucose consumption and ethanol production with Zymomonas mobilis NRRL B-806 from different enzymatic hydrolysates of pretreated Eucalyptus globulus saw dust pulp (A, B and E) with medium M2 (without glucose) at 30 °C. Ethanol production with Zymomonas mobilis NRRL B-806...
using enzymatic hydrolysate A reached a maximum ethanol production of 39.8 g L\(^{-1}\) at 48 h, observing that glucose consumption rate increased after 20 h, contributing this to the long time required for total glucose consumption and to reach ethanol production stationary phase (48 h). Ethanol yield was 0.45 \(\eta_{\text{ethanol}}\) \(\eta_{\text{glucose}}\) \(\times 100\%\) in relation to theoretical value) and a productivity of 0.83 g L\(^{-1}\) h\(^{-1}\) (see Table 1). In the case of enzymatic hydrolysate B it was observed that glucose was consumed in less time and achieving a higher ethanol yield, with a maximum ethanol concentration of 37 g L\(^{-1}\) at 32 h, with no significant increase after 27 h, at this point glucose was almost totally consumed. Ethanol yield was 0.47 \(\eta_{\text{ethanol}}\) \(\eta_{\text{glucose}}\) \(\times 100\%\) in relation to theoretical value) with a productivity of 1.16 g L\(^{-1}\) h\(^{-1}\) (see Table 2).

In the case of enzymatic hydrolysate E, it can be observed that glucose was totally consumed after 32 h, obtaining a maximum ethanol concentration of 31.8 g L\(^{-1}\). Ethanol yield was 0.41 \(\eta_{\text{ethanol}}\) \(\eta_{\text{glucose}}\) \(\times 100\%\) in relation to theoretical value) and a productivity of 0.99 g L\(^{-1}\) h\(^{-1}\) (see Table 2). Low ethanol yield may be attributed to the high concentration of acetic acid present in the hydrolysate E (12.8 g L\(^{-1}\)), causing a partial inhibition of \(\text{Zymomonas mobilis}\) NRRL B-806 (Figure 2).

Kim et al. (2000) mentioned that acetic acid has a potential inhibitory effect over \(\text{Z. mobilis}\) (10.9 g L\(^{-1}\) at pH = 6.0), followed by vanillin (0.04 g L\(^{-1}\)), syringaldehyde (0.13 g L\(^{-1}\)) hydroxymethylfurfural (0.9 g L\(^{-1}\)) and furfural (0.3 g L\(^{-1}\)) (Rogers et al., 2007) Previous reports by our research group (Rios-Gonzalez et al., 2012), in relation to inhibitory effects of acetic acid in ethanol production by \(\text{Zymomonas mobilis}\) NRRL B-806 from pretreated \(\text{Eucalyptus globulus}\) saw dust pulp (enriched with glucose), showed that ethanol yield was 86 % and 4.7 % when acetic acid concentration was 6.8 g L\(^{-1}\) and 17.9 g L\(^{-1}\) respectively.

Table 3 shows xylose, arabinose and cellobiose concentration during fermentation process by \(\text{Zymomonas mobilis}\) NRRL B-806 from pretreated \(\text{Eucalyptus globulus}\) saw dust pulp. No significant changes in concentration for the three carbohydrates during fermentation process were observed. This is attributed to the limited range of carbohydrates that \(\text{Zymomonas mobilis}\) can use as carbon source, which convert only hexoses such as glucose, fructose and sucrose (Rogers et al., 2007).

<table>
<thead>
<tr>
<th>Kinetic Parameters</th>
<th>M2 Control</th>
<th>Hydrolysate A</th>
<th>Hydrolysate B</th>
<th>Hydrolysate E</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Y_{X/S})</td>
<td>0.0243</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(Y_{E/S})</td>
<td>0.46 (90)</td>
<td>0.45 (88)</td>
<td>0.47 (92)</td>
<td>0.41 (80)</td>
</tr>
<tr>
<td>EP</td>
<td>1.37</td>
<td>0.83</td>
<td>1.16</td>
<td>0.99</td>
</tr>
</tbody>
</table>

\(Y_{X/S}\) Bio mass yield \((\eta_{\text{biomass}}\) \(\eta_{\text{glucose}}\)).
\(Y_{E/S}\) Ethanol yield \((\eta_{\text{ethanol}}\) \(\eta_{\text{glucose}}\)).
EP Ethanol productivity \((\eta_{\text{ethanol}}\) L\(^{-1}\) h\(^{-1}\)).
Table 3. Xylose, arabinose and cellobiose concentrations during fermentation process by *Zymomonas mobilis* NRRL B-806 from pretreated *Eucalyptus globulus* saw dust pulp.

<table>
<thead>
<tr>
<th>Parameter (g L&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Initial concentration</th>
<th>Final concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Xylose</td>
<td>7.85</td>
<td>6.82</td>
</tr>
<tr>
<td>Arabinose</td>
<td>10.36</td>
<td>5.77</td>
</tr>
<tr>
<td>Cellobiose</td>
<td>11.55</td>
<td>7.06</td>
</tr>
</tbody>
</table>

Table 4. Main results reported in literature for ethanol production from lignocellulosic hydrolysates by strains of *Zymomonas mobilis*.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Conditions</th>
<th>Ethanol concentration</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane molasses</td>
<td><em>Zymomonas mobilis</em> MCC 2427 Substrate 216 g/L of total reducing sugar Temperature of 31 °C pH 5.13 Time 44 h</td>
<td>58.4 g/L</td>
<td>(Maiti et al., 2011)</td>
</tr>
<tr>
<td>Mahuala flowers</td>
<td><em>Zymomonas mobilis</em> MTCC 92 Substrate 100 g/L of mahuala flowers slurry Temperature of 30 °C pH 6.5 Time 96 h Cell concentration 10% (v/v)</td>
<td>38 g/L</td>
<td>(Behera et al., 2011)</td>
</tr>
<tr>
<td>Kitchen garbage</td>
<td><em>Zymomonas mobilis</em> 10225 Substrate 70 g/L of reducing sugar Enzyme load 100 U/g wet mass Temperature 30°C pH 6 Time 40 h Cell concentration 10% (v/v)</td>
<td>52 g/L</td>
<td>(Ma et al., 2009)</td>
</tr>
<tr>
<td>Sugarcane bagasse</td>
<td><em>Zymomonas mobilis</em> CP4 Substrate 80 g/L of glucose Enzyme load 25 FPU/g Temperature 30 °C pH 5 Time 36 h Stirring 150 rpm Cell concentration 4 g/L</td>
<td>60 g/L</td>
<td>(da Silveira dos Santos et al., 2010)</td>
</tr>
<tr>
<td>Carob pod extract</td>
<td><em>Zymomonas mobilis</em> PTCC 1718 Substrate 113.82 g/L of glucose Temperature 30 °C pH 5.2 Time 36 h Stirring 80 rpm Cell concentration 0.017 g/50 mL</td>
<td>40 g/L</td>
<td>(Vaheed et al., 2011)</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td><em>Zymomonas mobilis</em> NRRL-806 Substrate 79.5 g/L of glucose Temperature 30 °C pH 5.5 Time 32 h Stirring 150 rpm Cell concentration 0.15 g/L</td>
<td>38 g/L</td>
<td>(this work)</td>
</tr>
</tbody>
</table>

In table 4 are shown the most prominent results reported for ethanol production from lignocellulosic feedstocks by *Zymomonas mobilis* strains. As shown in this work and based on several reports (Maiti et al., 2011; Behera et al., 2011; Ma et al., 2009; da Silveira dos Santos et al., 2010; Vaheed et al., 2011) *Zymomonas mobilis* has the potential to revolutionize the fuel ethanol industry commercially; laboratory and pilot-scale operations indicate that it can generate nearly theoretical maximum yields from several feedstocks, including enzymatic hydrolyzate of wood-derived cellulose, such as *Eucalyptus globulus* saw dust pulp.

The main limitation of *Zymomonas mobilis* for a widespread industrial usage for ethanol production is its capacity to utilize only hexoses. Pentoses such as xylose and arabinose cannot be metabolized by *Zymomonas mobilis*, unless it is genetically manipulated (Yanese et al., 2005; Lawford et al., 1997). However as mentioned by da Silveira dos Santos et al. (2010) if only the cellulose fraction is used in a two-stream model process, non-modified *Zymomonas mobilis* strains can be a promising alternative for ethanol production on industrial scale.

**Conclusions**

Although in this study only acetic acid, formic acid were quantified, other inhibitory compounds
commonly found in lignocellulosic hydrolysates, may also be present in the medium, such as furfural, HMF, vanillin, syringaldehyde, and hydroxybenzoic acid, depending on the acid concentration, temperature and other conditions used for hydrolysis, and such compounds may also affect the metabolism of the microorganism used for fermentation. However, acetic acid is the most common fermentation inhibitor, causing a decrease in ethanol rate and yield. Its toxic effect is basically due to its undissociated form. Acetic acid present in different enzymatic hydrolysates from pretreated Eucalyptus globulus saw dust pulp caused a delay in ethanol production. High acetic acid concentration had adverse effect causing a delay in ethanol production efficiency, maximum ethanol production and glucose consumption.

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Nomenclature
\[ Y_{X/S} \] biomass yield (g biomass g\(^{-1}\) glucose).
\[ Y_{E/S} \] ethanol yield (g ethanol g\(^{-1}\) glucose).
\[ EP \] ethanol productivity (g ethanol L\(^{-1}\) h\(^{-1}\)).
\[ t \] time (h)

References


