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Hydrogen production by dark fermentation from pre-fermented depackaging food wastes

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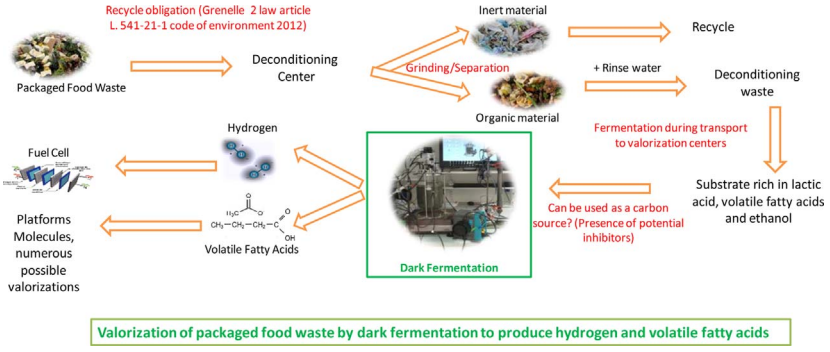
GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a specific fraction of food waste, i.e. depackaging waste, was studied as substrate for hydrogen production by dark fermentation. During storage and transport of this liquid mixture, inhibitory compounds like acids or alcohol might be produced by endogenous flora. A factorial fractional design based on the composition of the substrate was used to determine the best condition to convert this substrate into hydrogen. First results indicated that the consortium used might convert high quantity of lactate into hydrogen. A batch culture confirmed that lactate was used as the main carbon source and a global yield of 0.4mol_{H2}·$mol_{lactate}^{-1}$ was obtained. This study demonstrated the ability of the consortium tested to convert different carbon sources (carbohydrates or lactate) with good efficiency. These data represented an important parameter in the prospect of using an industrial substrate whose composition is liable to vary according to the conditions of storage and transport.

1. Introduction

The present fossil fuel-based production of energy has led to large-scale industrial expansion. However, the dependence on fossil fuels trains to the gradual depletion of natural resources and to an increase of greenhouse gases emissions with negative effects on the global climate.

It is then essential to develop innovative processes to produce renewable energy sources. Biohydrogen is a promising alternative clean energy carrier with a high energy content (142 MJ/kg), twice that of natural gas (Singhania et al., 2012). Upon the combustion of H_2, H_2O is the only major by-product. In the coming years, their use will be generalized with development of fuel cell in many domain, mainly in automotive industry but also in aerospace, multimedia and civil engineering (Dayhim et al., 2014; Santoro et al., 2017). In recent decades,

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several biological routes to produce H_2 were investigated for the attractive and renewable characteristics of this energy carrier. Dark fermentation (DF) with mixed culture represents an interesting way for hydrogen production and allows the recycling of many types of waste. The main advantage of performing DF with mixed culture is the ability of anaerobic bacteria to degrade many complex substrates such as agricultural residues, lignocellulosic biomass, wastes, industrial and domestic effluents (Eker and Sarp, 2017; Slezak et al., 2017; Urbaniec and Bakker, 2015; Yun et al., 2017; Gonzales et al., 2016). Moreover, the VFAs (Volatiles Fatty acids) co-produced during the culture correspond to high added value building blocks that have many industrial applications (Béligon et al., 2016; Singhania et al., 2012).

Food waste represents an important resource for hydrogen production by dark fermentation with 1.3 billion of tons of food waste generated annually (Uçkun Kiran et al., 2014; Zhang et al., 2007). Currently, one quarter of food waste is lost in the food supply chain (Kummu et al., 2012). This substrate has high energy content with 85–95% of volatile solids. Biological hydrogen potential (BHP) of this substrate presents large variations between 3 and 290 $mL_{H2}{\cdot}g_{vs}^{-1}$ depending of nature of the food wastes. The average BHP is 60 $mL_{H2}{\cdot}g_{vs}^{-1}$ twice the one reported for agricultural wastes (Guo et al., 2010).

In European Union, food wastes were estimated at 89.3 million of tons in 2005. This value will reach 93 million in 2020 (European commission 2011). An European study estimated that 173 kg of food waste are produced by person and by year in food chain (Stenmarck et al., 2016). The European directive 2008/98/CE encourages the various European players to recycle food wastes (Redlingshöfer et al., 2017). In France since 2016, Grenelle law 2 (article L. 541-21-1 du code de l'environnement 2012) forces food producers to recycle their wastes if they generate more than 120 tons/years.

Several studies have already been carried out on the ability to produce hydrogen from food waste. The authors generally determined an average composition of food waste and worked from a model mix. The originality of this work is to study a particular fraction of food waste i.e. depackaging waste obtained after removing the packaging from food residues in deconditioning units. The resulting product is a liquid soup containing organic matter with a high energy potential which represents a promising carbon source for dark fermentative and hydrogen production. However, depackaging wastes (DWs) are carbohydrate-rich and are rapidly fermented during storage and transport. Potential inhibitors of hydrogen production can then be produced, in particular lactic or acetic acids. The aim of this study is to investigate the possibility of perform dark fermentation from this industrial pre-fermented substrate. The depackaging wastes were first analysed to determine if potential inhibitors were present. Then, an experimental design was conducted in various conditions to determine the hydrogen potential of this substrate. The best conditions obtained were then used to realize a batch culture on bioreactor and to explore the metabolic pathways used for acids conversion to H_2.

2. Materials and methods

2.1. Inoculum

The microbial consortium was derived from sewage treatment plant sludge. The collected sample was incubated in complete medium (Béligon et al., 2016) with addition of 2-bromoethanesulfonate (10 mM) (Bulock and Kristiansen, 1987) to remove methane producing Archeae. Five subcultures (10% v/v) were carried out to stabilize the consortium until a same hydrogen production is achieved in 16 h. The analysis of the consortium was previously described in detail (Noblecourt et al., 2017).

2.2. Depackaging wastes

Depackaging wastes (DWs) were supplied by Methelec Company, a methanisation unit (Ennezat, France). Three samples were taken at different times during delivery on the methanisation unit to analyse the variability of substrate. The substrate was sieved at 0.5 mm to eliminate the largest particles in suspension.

Table 1
Factorial fractional experimental design matrix defining pH (X_1), heat treatment (X_2), inoculum (X_3), medium culture addition (X_4), reduction (X_5) and deconditioning waste dilution (X_6).

Run	Parameters					
	X_1	X_2	X_3	X_4	X_5	X_6
1	7	−	−	−	−	1
2	7	+	+	+	−	1
3	7	−	−	+	+	1/2
4	X	+	−	−	−	1/2
5	X	−	+	−	+	1
6	X	−	+	+	−	1/2
7	7	+	+	+	+	3/4
8	7	+	+	−	+	1/2
9	X	+	−	+	+	1

2.3. Experimental design

Optimization conditions were designed according to a fractional factorial design. The results were fitted by a linear model with software JMP 9.0 (JMP® SAS). The responses were i) hydrogen and VFAs yields which were expected to be as high as possible, ii) propionate yield which was expected to be as low as possible because its synthesis is made through a competitive pathway of hydrogen production and iii) the monitoring of the ratio Butyrate/Acetate to determine a potential correlation with the hydrogen production. To optimize these responses, six factors were tested.

The nine tested conditions were shown in Table 1. Each condition was performed in duplicate with a standard deviation less than 5%.

2.4. Bioreactor culture

2.4.1. DWs batch culture

The culture was carried out in a 2.5 L bioreactor (GPC-Bio, Périgny, France) with 2 L of working volume. 200 mL of inoculum was added in bioreactor (10% v/v) after 30 h of incubation at 37 °C. In bioreactor, the other parameters were temperature 35 °C, stirring rate 200 rpm, pH regulated at 7 by KOH (5 $mol{\cdot}L^{-1}$) and/or H_2SO_4 (4 $mol{\cdot}L^{-1}$) addition.

2.4.2. Glucose batch culture

The glucose batch culture was performed with the same bioreactor and inoculum than DWs batch culture with complete medium ***(part 2.1). The culture parameters were glucose initial concentration of 60 $g{\cdot}L^{-1}$, 35 °C, stirring rate 200 rpm, pH regulated at 6 by KOH (5 $mol{\cdot}L^{-1}$) and/or H_2SO_4 (4 $mol{\cdot}L^{-1}$) addition.

2.5. Analytical methods

2.5.1. Gas phase analysis

Biogas volume and flow rate were measured with a drum-type gas meter (Ritter TG05). RIGAMO® software was used for analysis and real-time monitoring. Biogas composition analysis was carried out with a micro-GC (Agilent 3000) equipped by two channels and a thermal conductivity detector (TCD). The composition in hydrogen, oxygen, nitrogen and methane was determined from the first channel with a molecular sieve column (5 Å). Argon was used as a vector gas at a pressure of 30 psi, the injector and oven temperatures were respectively 80 and 90 °C. Carbon dioxide and hydrogen sulfur were determined by the other channel with a Pora plot U (PPU) column. Hydrogen was the vector gas at a pressure of 30 psi, the temperatures of the injector and of