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Life cycle assessment of butanol production

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ABSTRACT

The goal of this work was to analyse and compare the environmental impacts of three production methods of butanol. The first one is based on the oxo synthesis and the others use ABE (acetone, butanol and ethanol) fermentation. A life cycle assessment for all alternatives under study was carried out. The ABE fermentation using corn as substrate presents the highest environmental impact and the ABE fermentation using wheat straw is the one that presents the lowest environmental impact, when the allocation method was based on mass. Considering an economic allocation method, the relative weight of butanol raised which increased considerably the environmental impact value in ABE processes due to the lower economic value of gases.

A sensitivity analysis was performed for the production of butanol from the two ABE processes varying the data of lower quality to analyse how this would affect the environmental impacts. In the ABE process with wheat straw the variations performed within the scope of the sensibility analysis had no meaningful effect in the global impact (<4.0%) except when the production of gases was varied. In this case the reduction of 50% in the mass of gases produced could result in an increase of roughly 40% in the global impact. For the ABE process with the corn the variation of wastewater produced resulted in a decrease of global environmental impact lower than 1%.

1. Introduction

Nowadays energy is an issue of great importance to countries' development. Security of supply and the instability of prices and markets together with increasing concerns related to environmental impacts due to the use of fossil fuels have led to new energy policies. Climate change and depletion of resources are major problems that must be tackled in the short period. These concerns led to the promotion of renewable energy sources and alternatives ways of producing energy and fuels. The Renewable Energy Directive [1] and the Energy/Climate package in European Union and the targets established are stirring research and are key drivers for a more sustainable energy system. The national targets established by each Member State to renewable energy can be achieved by a combination of the use of renewable energy sources to produce electricity, heat/cooling and transportation [2]. International commitments such as the Kyoto Protocol reinforced the role of renewables and studies show that the EU should keep on increasing the share of renewable energy for lowering emission levels of CO_2 [3]. Renewable energy innovations are very important in energy sector and several studies have been conducted to determine the major factors that influenced it [4]. These environment and energy concerns are shared worldwide since many environmental problems can only be solved if considered globally and trade/market conditions are increasingly global questions. Recent studies have analysed the relation between CO_2 emissions and other variables such as real output, energy consumption, trade, etc. for several countries [5–9]. In many of the those studies the application of the environmental Kuznets curve (EKC) is verified [5–7,10,11]. Some authors give special attention to the relation between renewable and non-renewable energy sources and CO_2 emissions [10,11]. Energy consumption is very important for CO_2 emissions and conclusions emphasised the need for the implementation of energy efficiency policies [6,7] and the increase in investment for further development of renewable technology [9,11]. In addition it is recommended an increase in energy consumption from renewable sources [8–11].

In this scenario biofuels, including n-butanol, are presented as alternatives worthwhile exploring and developing, since they can be an ecological and economical option. Butanol is an alcohol with a 4-carbon structure and the chemical formula is $C_4H_{10}O$ and has four isomers namely n-butanol, 2-butanol, *iso*-butanol and *tert*-butanol [12,13]. This alcohol can be produce from biomass by fermentation (biobutanol) or from fossil fuels obtaining the similar

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chemical properties [14,15]. N-butanol has been pointed out as a substitute for gasoline [13].

The most currently used process for the production of n-butanol is the chemical production from petroleum sources especially by oxo synthesis [12,14]. However the formation of butanol in the microbial fermentation was first reported in 1861 [16], and through out the years the methods used for producing it changed due to science developments and economic reasons. In fact it started to be industrially produced, during World Wars I and II, using the ABE (acetone, butanol and ethanol) fermentation, using as substrates corn and molasses [17,18]. This solvent was made with a variety of substrates all over the world such as in United States of America, United Kingdom, China, Russia, South Africa and India. During the World War II this alcohol was produced with Clostridium acetobutylicum bacteria because it was cheaper to produce by this way in comparison with petrochemicals [18].

In the 50's, the butanol production decreased due to the increase of molasses' price and processes reliability problems and for those reasons the ABE fermentation with substrates was replaced by petrochemical process in the 80's [12,17].

In the 90's, the prices of the oil barrels increased through out the years and this raised the interest in other products and production methods. Some investigators started to improve the ABE fermentation with the implementation of new genetic engineering techniques, incorporation of more productive reactors and news methods to recover the solvent [12]. Different strains of bacteria were used and especially Clostridium beijerinckii BA101 presented high efficiency starch conversion into acetone and butanol [19]. Nowadays the interest for the butanol production increased again due to promotion of the use of renewable energy sources and the fact it can be used as fuel.

The oxo synthesis is based on the hydroformylation of propene, followed by the hydrogenation of the formed aldehydes. Catalysts such as Co, Rh or Ru are used [20].

In the ABE production method the following parameters should be considered:

- Type of substrates

Several types of substrate can be used, such as wheat straw, corn, sugarcane biomass, wastes from agriculture, molasses and other raw materials. Generally they can be classified in cellulosic (bagasse, wheat straw, corn stover, switchgrass) and non-cellulosic (glucose, sugarcane, corn) materials. The choice of substrate involves technical, economic and even social reasons, because materials that do not compete with food supply are more sustainable. Other raw materials such as glycerol (a by-product of biodiesel production) and algae are also being studied [21–23].

- Type of microorganisms

There are a great number of microorganisms that can be used in this process such as Clostridium acetobutylicum, Clostridium aurantibutyricum, Clostridium beijerinckii, Clostridium butyricum, etc. [24]. However the most important ones in butanol production using ABE fermentation are Clostridium acetobutylicum and Clostridium beijerinckii since they are high butanol producers [25].

- Fermentation processes

Fermentation can be performed in three different ways, fed-batch, batch and continuous [26]. In batch fermentation the substrate and nutrients are placed in the reactor and the inoculate added. Fermentation is carried out at 35–37 °C and after process is finished the solids are removed and the liquid can be sent to distillation. This process presents low productivities [27]. Fed-batch fermentation is used in processes where substrates can be toxic to microorganisms. Initially a small quantity of substrate is loaded to the reactor and more substrate is added during the process, always maintaining the substrate concentration below the toxic level. Usually the solvent is being extracted since butanol is toxic to bacteria. In this method the new recovery techniques are used allowing the simultaneous recovery of all products. In continuous fermentation the production can be optimized. The system can have a single stage or multiple. One of the main difficulties is the fluctuation in production levels [12].

- Recovery processes

The main downstream fermentation processes are liquid-liquid extraction, perstraction, pervaporation and gas stripping [24]. In the first process a solvent is added and since butanol is more soluble in the extractant it is removed. Then it can be recovered by back extraction or by distillation. Perstration also uses an extractant but there is no direct contact between the extractant and fermentation broth due to the existence of a membrane that allows diffusion of ABE. Pervaporation uses a selective membrane and there is a gaseous phase on the other side into which the volatiles are extracted. The volatiles are then condensed and recovered. In gas stripping nitrogen or the fermentation gases are continuously sparged into the reactor and the gases are channelled to a condenser. The volatile solvents are then recovered by cooling [24].

- Inhibitory processes

Inhibitory processes in ABE fermentation are one of the main drawbacks, since it contributes to low productivities. The substrate can be toxic to microorganisms and the products of fermentation (acetone, butanol and ethanol) are also toxic for most clostridial cultures. Maximum concentration is around 20 g/L which on the other hand imposes restrictions at the substrate level. A common solution to solve this problem is the continuous removal of solvents. Other solution concerns the development of new strains that present higher resistance. When lignocelluosic materials are used pretreatment and hydrolysis are necessary but that can originate other inhibitory components such as formic acid, acetic acid, levulinic acid, furfural, and hydroxymethyl furfural [28–30].

The economic viability of butanol production from ABE fermentation is highly affected by price of substrates, presence of inhibitors and inefficient recovery of products [28,31].

Life Cycle Assessment (LCA) evaluates the environmental impacts associated with a product or service throughout its life cycle, from extraction of raw materials to final disposal of waste. It analyzes the flow of materials and energy flow involved in all stages of the life cycle such as production, use and disposal. LCA is performed in four steps, according to norms ISO14040-44, namely goal and scope, inventory analysis, impact assessment and interpretation [32]. It has been used in the environmental analysis of biofuels [33]. In this work a life cycle assessment was carried out to analyse and compare the environmental impacts of three production methods of butanol. The first one is based on the oxo synthesis and the others use ABE (acetone, butanol and ethanol) fermentation.

2. Production of butanol

Three production processes were considered in this studied: the oxo synthesis and two ABE fermentation processes, one with wheat straw as substrate and the other one using corn. For the two ABE fermentation processes data for inventory analysis were