Renewable and Sustainable Energy Reviews 88 (2018) 151–159

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Thermochemical conversion of sugar industry by-products to biofuels

Thibault Nicodème, Thomas Berchem*, Nicolas Jacquet, Aurore Richel

University of Liège, Gembloux Agro-Bio Tech, Laboratory of Biomass and Green Technologies, Passage des Déportés, 2, B-5030 Gembloux, Belgium

ARTICLE INFO

Keywords:
Sugarcane bagasse
Sugar beet pulp
Biofuel
Fischer-Tropsch
Gasification
Thermochemical pathway

ABSTRACT

Replacement of petroleum by other energy sources is one of the principal challenges of contemporary engineering. One of the most promising substitutes for petroleum is biomass, chemically converted into fuel. For instance, as the world's biggest producer of sugarcane, Brazil generates large quantities of agricultural residues from sugarcane cultivation which could be used to produce biofuels for transportation and aviation (i.e. jet fuel) without much difficulty. Furthermore, sugar beet industry generates important amount of waste that could be valorized into biofuels. The purpose of this article is to review the different technologies currently available for the production of biofuels via a thermochemical pathway using sugarcane bagasse and sugar beet pulp as feedstock, with specific interest in using feedstock gasification and subsequent conversion of the synthetic gas into fuel. Gasification is a longstanding process of conversion of carbonaceous material into a gaseous compound (syngas) and a solid output, called char. Several kinds of gasifiers are described, as well as the syngas cleaning-up process, and the characteristics of several processes through which syngas is converted into synthetic fuel are detailed, including Fischer-Tropsch (FT), Methanol-to-gasoline (MTG), Methanol-to-olefins (MTO) as well as pyrolysis.

1. Introduction

An important issue concerns the availability of fuels in the coming years. Oil reserves depletion and scarcity of petroleum lead transport industry to look after new fuels [1]. Moreover, petroleum is a great contributor to CO_2 emissions and thus is implicated in global warming [2]. Those considerations about the non-renewable aspect of petroleum are not recent. Indeed, in the early 1970, the Club of Rome expressed concerns about an exponential growth of population combined with finite hydrocarbon-based energy sources like petroleum [3]. So replacement of petroleum is one of the greatest challenge of the 21st century. Solutions exist but assistance from governments is needed, for example with financial contribution or by implementing policy that supports biofuel technology and production [4].

Aviation industry has shown its determination to reduce its environmental impact. Therefore, aviation industry has engaged itself in the ambitious challenges of being carbon neutral in 2020 and reducing CO_2 emissions to 50% of 2005 level in 2050. In order to achieve these objectives, improvements are expected in several ways: more efficiency of fuels with improved turbines, design of airplanes and advanced airspaces management [5]. Biofuels can be another solution in order to reduce CO_2 emissions. Sustainable biofuels dedicated to aviation industry had to be "drop-in" fuels. "Drop-in" fuels define biofuel that, when blended with conventional jet fuel up to a ratio defined by a fuel specification, can use the same supply infrastructure and do not require any adaptation of aircrafts or engines.

The production of biofuels can be divided into three generations. This distinction is mainly based on the origin and the type of biomass used to produce the biofuel.

First generation biofuels are elaborated typically from the storage organs of the plants, containing mainly sugars, starch and oil. These resources enable to produce biofuel through relatively cheap and rapid techniques (microbial fermentation of carbohydrates and transesterification of oils) [6]. However, first generation biofuel is now commonly recognized as a threat for the food security since their development could greatly influences the land use dedicated to a single energetic use and, therefore, the world food prices. Then, it seems difficult to conciliate the increasing demand of both food and biofuels [7].

This review focuses on second generation biofuel, using byproducts from agrofood industries, especially sugar industry (sugar beet pulp and sugarcane bagasse). The use of such products allow to keep the first purpose of the feedstocks in the human food sector, without inducing any disruption in the cultures in term of land use or destabilization of the market of the products that already exist.

The third generation relies on the algal biomass. Certain species of microalgae's can have a very high oil content that acts as the starting compound for the fuel synthesis [8]. Microalgae's show a rapid growth

* Corresponding author.
E-mail addresses: thibault.nicodeme@ulg.ac.be (T. Nicodème), thomas.berchem@ulg.ac.be (T. Berchem), Nicolas.Jacquet@ulg.ac.be (N. Jacquet), A.Richel@ulg.ac.be (A. Richel).

https://doi.org/10.1016/j.rser.2018.02.037
Received 20 December 2016; Received in revised form 4 September 2017; Accepted 27 February 2018

rate and a high production capacity of lipids. They also do not compete with food or feed production since they can be grown on non-arable lands or in saline water. These advantages depict the third generation biofuels as a complementary way of energy production to the second generation rather than a competing technology.

1.1. Sugarcane and sugar beet industries

In the last decades, sugarcane culture has been largely developed in Brazil for the production of sugar and bioethanol, but its potential is not being fully realized. Indeed, the lignocellulosic wastes of the sugarcane (i.e the bagasse and the straw) can successfully be converted into biofuel since bagasse and the straw account for two third of the total energy of the plant [9].

Sugarcane cultivation is relevant especially to Brazil, which generates 670 million tons of sugarcane in 2015–2016, or one third of the world's total output [10]. After being processed, this crop yields almost 200 million tons of bagasse and 220 million tons of straw (wet basis) per year as by-products [9]. For a long time, sugarcane bagasse has been burnt to supply electricity to the factories and to the national grid. Estimations show that currently almost 90% of bagasse from sugar ethanol production plants are used to make electricity and heat by cogeneration [11]. In 2008, about 3% of total electricity consumed in Brazil came from this "bio-electricity" [12]. Moreover, from an environmental point of view, power generation is a key-element considering his high potential in CO_2 emission reduction [13]. Sugarcane wastes are also used in others applications such as pulp and paper industry, chemicals and metabolites (alcohols, enzymes) manufacturing. In Brazil, roughly half of the sugarcane straw is left on the field to prevent soil erosion, for the conservation of its agronomic characteristics related to its chemical content (C, N, P, K, Ca, Mg and S) and for the maintenance of soil microbiota [9]. The other half is either burned to generate electricity or converted to metallurgical coke. In addition, recent improvements of harvesting techniques provide large amount of straw usable for co-generation or ethanol production [9].

The lignin, cellulose and hemicellulose contents of several biomasses are summarized in Table 1. Sugarcane bagasse is mainly composed of cellulose (40–50%), hemicellulose (20–30%), lignin (20–25%) and 2–4% ashes (dry basis) [14,15]. Ashes content is similar to sugar beet pulp but is quite low compared with alfalfa, wheat straw or rice husk with 7–9%, 7–10% and 15–20% respectively. Moreover, thanks to its high crop yield (80 tons/ha/year), sugarcane is also considered as a great solar energy reservoir compared with wheat (1 ton/ha/year) and trees (20 tons/ha/year) [16–18]. Combustion and gasification of sugarcane bagasse can be seen as carbon neutral processes because the amount of CO_2 generated is the same consumed during the plant growth [15].

Sugar beet industry is well developed in Western Europe (France, Germany and Belgium) with a production of about 190 million tons in 2014 [19]. Sugar refineries generate an important amount of by-products such as pulps, leaves and crowns. Beet pulp is the main waste proceeded by this industry. Concretely, one ton of sugar beet gives more or less 500 kg of pulp at 10% dry matter which is equivalent to 55 kg at 90% dry matter. Beet pulp is especially used to feed cattle but other valorisation pathways exist. For example, sugar beet pulp is rich in pectins that are used in cosmetic sector as surfactants. Pulp and paper industry also uses compressed or dried beet pulp as an alternative component. Lastly, this waste can be burned or spread on the fields. The second interesting by-product of sugar beet industry is molasses. It is used as fermentation medium for yeast or alcohol manufacturing. Finally, leaves and crown are also considered as cattle food [20].

Table 1
Cellulose, hemicellulose, lignin and ashes content (referred on a dry basis) of different biomasses [15, 17, 18].

Biomass type	% Cellulose	% Hemicellulose	% Lignin	% Ashes
Sugarcane bagasse	40–50	20–30	20–25	2–4
Sugar beet pulp	20	32	1–2	4–6
Alfalfa	30	12–17	12–14	7–9
Wheat straw	34–40	21–26	11–23	7–10
Rice husk	40–50	20–25	25–30	15–20

Thanks to its appropriate climate and the quality of the soil, Belgium is a favourable land to sugar beet culture. Indeed, in 2014, sugar beet production has reached 5,121,524 tons leading to approximately 431,744 tons of crown and 281,684 tons of dehydrated pulps [21]. The important amount of waste encourages researchers to focus on the valorisation of pulp, leaves and crown by thermochemical pathway. Beet pulp pyrolysis has for example already been investigated [22,23].

Moreover, with the sugar quotas abolition in 2017, sugar beet industry will face economic challenges and shall find solutions to ensure a financial sustainability of all sugar beet industry stakeholders. Biofuel production from sugar beet waste could be a way of valorisation.

1.2. Bioethanol and "Proalcool" program

During the oil crisis of the 1970′s, Brazil's government founded the "ProAlcool" Program to develop ethanol production as an alternative to fossil fuels [11]. Thanks to this program, Brazilian automotive market is dominated by so-called flex-fuel cars which are able to run either on gasoline, hydrated ethanol, or any proportional mixture of the two fuels. The initial mandate of this program was to blend gasoline with 5% ethanol but has since increased to 22% [24]. Presently bioethanol is blended in gasoline to a concentration of about 30% (v/v) of gasoline and yet increasing demand is forecast for the next 10 years.

The hundred million tons of sugarcane bagasse harvested annually and used for electricity generation seems to be the most promising source of carbon to make cellulosic ethanol [11].

Initially bagasse was converted to ethanol biochemically, through enzymatic hydrolysis and fermentation of sugar but recent work have demonstrated that a thermochemical process (i.e. gasification followed by the Fischer-Tropsch process) offers several advantages over the conventional biochemical methods [25,26]. The thermochemical pathway derives a greater benefit from economies of scale due to its large capital costs and its capacity to process dry and compacted raw materials [27]. In order to be economically competitive, an important point is the combined generation of biofuel, electricity and specific chemicals. Combining gasification of biomass and the Fischer-Tropsch process is a promising way to make biofuel and it deserves a special focus (Fig. 1).

This article is part of this approach and reviews the different thermochemical conversion technologies currently available for the production of biofuels using sugarcane bagasse and sugar beet pulp as feedstock, with specific interest in using feedstock gasification and subsequent conversion of the synthetic gas into fuel.

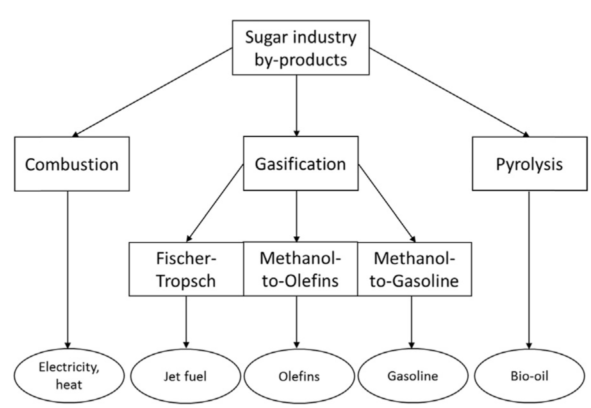

Fig. 1. Overview of biofuel production by thermochemical pathway.