Resources, Conservation & Recycling 134 (2018) 156–164

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full length article

Technoeconomic and environmental assessment of a process for biodiesel production from spent coffee grounds (SCGs)

I.K. Kookos[a,b,*]

[a] Department of Chemical Engineering, University of Patras, 26504, Patras, Rio, Greece
[b] INVALOR: Research Infrastructure for Waste Valorization and Sustainable Management, Caratheodory 1, University Campus, GR-26504, Patras, Greece

ARTICLE INFO

Keywords:
Spent coffee grounds
Renewable raw materials
Technoeconomic assessment
Life cycle assessment

ABSTRACT

The valorization of the spent coffee grounds (SCGs) has attracted a lot of attention recently from both the academia and industry. The development of an economically attractive and environmentally sustainable process based on available experimental data on the SCGs valorization has not been investigated in the open literature. This is clearly a very important issue and is the subject of the present work. Evidence is presented to support the conclusion that the economic performance of the process can be acceptable only at large production capacities realized at centralized facilities. In addition, it is shown, using a "gate-to-gate" Life Cycle Assessment (LCI), that the environmental performance of the process is acceptable and the process can be considered sustainable. Further research is necessary in the area of efficient recovery of the bioactive compounds available in SCGs. These compounds have a significant added value that can render the process economically attractive at capacities that are low enough to be practically realizable.

1. Introduction

Coffee is among the most valuable agricultural export commodities and represents one of the key export and cash crops. About 125 million people depend on coffee production in more than 68 tropical and subtropical countries (ICO, 2017). The total world production for the year 2013 (the most recent year for which complete data are available from the ICO) was $9{\cdot}10^6$ t green coffee beans, with an estimated market value of more than $20 billion (based on the price paid to growers). World coffee production over the last 5 years has fluctuated from 8.92 to $9.23{\cdot}10^6$ t green beans. World coffee consumption matched that of its production in 2013, of which about 30% was consumed domestically in coffee-exporting countries and 53.1% in the countries reported in Table 1 that include most of the world's developed countries. Finland has the highest per capita coffee consumption (11.90 kg coffee per capita), followed by Norway, Denmark and Austria. The countries that are included in Table 1 have in total 17% of the world's population and 60% of the world's Gross Domestic Product or GDP (IMF, 2017).

Several residues are obtained in vast amounts during coffee production and processing including residues from the coffee fruit (> 50% of the fruit mass) and spent coffee grounds (SCGs) which is the residue obtained during the brewing process (Campos-Vega et al., 2015). Despite the fact that SCGs contain compounds with established ecotoxicity (polyphenols, tannins) they are currently disposed of in sanitary landfills (Cruz et al., 2012). Most major food companies have announced their plans to reduce waste streams produced by the coffee industry by utilizing them as renewable sources for the production of chemicals and/or energy (see for instance http://www.nestle.com/csv/case-studies/allcasestudies/recycling-coffee-grounds-fuel). Spent coffee grounds, in particular, contain large amounts of organic compounds (i.e. anti-oxidants, fatty acids, lignin, cellulose, hemicellulose, and other polysaccharides) that can be exploited as a source of value-added products (Kourmentza et al., 2018). Thus, coffee residue has been investigated for SCGs oil (and subsequently biodiesel) production, as source of fermentable sugars, precursor for activated carbon production, compost and as sorbent for metal ions removal (Murthy and Naidu, 2012; Esquivel and Jiménez, 2012; Campos-Vega et al., 2015; Kourmentza et al., 2018; Janissen and Huynh, 2018).

As the number of alternative routes for the valorization of the SCGs is constantly increasing, due to the large interest from both the industry and the academia, there is a pressing need to direct research in the field towards the most promising technologies. It is important to note at this point that the evaluation of the alternative technologies must be based on multiple criteria involving at least economic and environmental performance criteria. Any promising technology must offer distinct advantages when compared to potential alternatives in order to be developed further. However, its industrial implementation necessitates

* Corresponding author at: Department of Chemical Engineering, University of Patras, 26504, Patras, Rio, Greece.
E-mail address: i.kookos@chemeng.upatras.gr.

https://doi.org/10.1016/j.resconrec.2018.02.002
Received 13 December 2017; Received in revised form 1 February 2018; Accepted 1 February 2018
0921-3449/

Table 1
Most important coffee consuming countries (2013 data, International Coffee Organization).

European Union	kt/y	kg coffee per capita
Finland	65.70	11.90
Denmark	49.32	8.60
Austria	74.94	8.58
Belgium/Luxembourg	89.16	7.42
Sweden	70.50	7.11
Germany	562.68	6.85
Belgium	74.70	6.54
Greece	66.06	5.92
Netherlands	97.50	5.72
Italy	338.04	5.69
Croatia	23.22	5.54
Estonia	7.20	5.50
Slovenia	11.04	5.31
France	342.42	5.27
Portugal	50.40	4.88
Cyprus	5.34	4.53
Spain	210.06	4.53
Lithuania	11.82	4.09
Slovakia	19.68	3.61
Czech Republic	38.22	3.60
Bulgaria	25.14	3.55
Malta	1.32	3.07
Latvia	5.70	2.92
Romania	53.46	2.73
Poland	100.14	2.62
United Kingdom	169.68	2.56
Ireland	11.76	2.47
Hungary	10.62	1.09
TOTAL EU	**2600.28**	**5.45**
Norway	45.78	8.63
Switzerland	67.38	7.95
USA	1405.02	4.33
Japan	446.10	3.50
Tunisia	25.74	2.23
Russian Federation	218.88	1.52
Turkey	47.34	0.59
Total	**4,767.42**	**4.04**

further developments at the social and political level in order to be adopted by the industry and to be implemented at large-scale. Step-changes take place only when a promising and sustainable technology reaches a level of maturity that reduces the level of risk for all stakeholders.

The goal of this work is to present a detailed evaluation and assessment of the SCGs valorization for the production of SCGs oil and its transformation to biodiesel. This process looks rather appealing to the research community as it encompasses most of the elements of a sustainable consumption and production process. It aims at the valorization of a by-product stream that is currently considered as a waste stream, is produced at significant quantities and is rich in carbohydrates, bioactive compounds, proteins and fats. Its potential uses are diverse and include the production of bio-gas, composites, oil and biodiesel, ethanol, polyhydroxyalkanoates (PHAs), bio-oil and biochar. However, as it is shown in the present work, extracting the oil from the SCGs using liquid solvents and subsequently converting oil to biodiesel can be an unattractive option as inherent characteristics of the SCGs limit the annual production levels that can be achieved. The simultaneous extraction of high added value products such as bioactive compounds is deemed necessary in order to achieve the elusive target of economic sustainability. The structure of the work is as follows: the characteristics of the SCGs are presented first followed by the description of a skeleton process flow diagram for biodiesel production. Standard technoeconomic and environmental assessment methodologies are then applied and then the results are presented and analyzed.

2. Material and methods

2.1. SCGs characteristics, chemical analysis and economic potential

It is estimated that 0.65 kg of dried spent coffee grounds (DSCGs) are produced from each kg of green coffee beans. Green beans smell green-earthy and they undergo a heat treatment, called roasting, that results in a profound increase in their volume and loss in weight (mainly due to decrease in their moisture content). Their specific gravity falls from approximately 1.2–0.6 and their color changes from green to brown (green beans sink in water while brown beans float). Although extensive changes are observed in the protein content and amino acid composition of the beans, the lipid fraction appears to be particularly stable (Belitz et al., 2009). Taking into consideration that the annual production of green beans is $9{\cdot}10^6$ t it then follows that the roasted coffee produced is approximately $5.85{\cdot}10^6$ t/y.

Spent coffee grounds is the solid residue which is obtained after the roasted coffee brewing process that takes place domestically, in coffee shops chains (such as Starbucks) or at industrial level (such as Nestle or Jacobs). The residue is currently incinerated or disposed of in landfills, a practice that is considered unsustainable and potentially dangerous for both humans and the ecosystem. This is due to the fact that SCGs contain significant amounts of compounds with established toxicity. The SCGs contain significant moisture that may exceed 65% by mass (Cruz et al., 2012; Vardon et al., 2013; Somnuk et al., 2017).

DSCGs contain significant amounts of polymerized sugars (cellulose and hemicellulose) that correspond to almost 50 wt% of the DSCGs and can be hydrolyzed using dilute acid hydrolysis to produce a medium rich in fermentable sugars (Mussatto et al., 2012; Burniol-Figols et al., 2016). Burniol-Figols et al. (2016) report a yield of 0.22 g ethanol/g DSCGs using *Saccharomyces cerevisiae* as biocatalyst and pretreated DSCGs (chlorogenic acids had been removed using liquid solvents prior to hydrolysis). DSCGs contain 0.1-0.8 wt% chlorogenic acid (CGA) and the same authors report a 32% recovery of the phenolics in DSCGs (0.032–0.256 g CGA/100 g of DSCGs).

DSCGs contain also 10–15 wt% lipids (called SCGs oil in the following). The lipids composition vary according to the source of the green beans. The SCGs oil (lipids) consists mainly of linoleic (C18:2), palmitic (C16:0), stearic (C18:0), oleic (18:1) and linolenic (C18:3) acids (Campos-Vega et al., 2015). Obruca et al. (2014) have demonstrated that SCGs oil can be used for the production of polyhydroxybutyrate (PHBs). Obruca et al. (2014) report a yield of 0.82 g PHB/g of SCGs oil using *Cupiavidus necator* as biocatalyst. Most published work on SCGs oil extraction and subsequent valorization aim at the production of biodiesel. Biodiesel production is achieved in a three step process in which SCGs are first dried to remove moisture, oil is then extracted using common solvents (hexane, isopropanol, ethanol, methanol, etc.) and finally biodiesel is produced through transesterifaction (Abdullah and Bulent Koc, 2013; Vardon et al., 2013; Kourmentza et al., 2018). To avoid the oil extraction step, in-situ transesterification of DSCGs has also been investigated but have been criticized for excessive energy consumption for recovering the unreacted methanol (Tuntiwiwattanapun et al., 2017). The yield of oil to biodiesel is approximately 1 g of biodiesel/g DSCGs oil.

The DSCGs after the oil extraction are called defatted spent coffee grounds (DFSCGs) and have a heating value of approximately 20 MJ/kg. It can be combusted directly to replace conventional (fossil) fuels or can be upgraded to bio-oil (a liquid fuel with HHV = 27 MJ/kg) and biochar (that can be used as soil amendment or solid fuel with HHV = 28.3 MJ/kg) (Vardon et al., 2013).

We have, at this point, identified a network of potential processes for the complete valorization of DSCGs. The next step is to determine the economic potential of a possible process for the complete valorization of SCGs. The summary of the calculations is presented in the form of a block flow diagram (BFD) in Fig. 1. 2857 kg of raw SCGs that contain 65 wt% moisture when dried produce 1000 kg of DSCGs. The