Applied Energy 136 (2014) 14–22

Contents lists available at ScienceDirect

Applied Energy

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

Castor plant for biodiesel, biogas, and ethanol production with a biorefinery processing perspective

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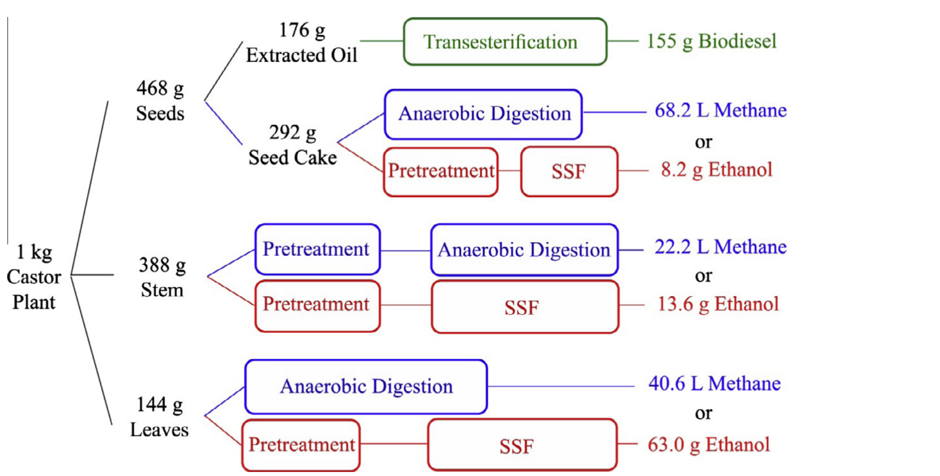
HIGHLIGHTS

- Castor plant as a whole was used for biofuels production.
- The optimum biodiesel yield was 88.2% which was obtained at 0.4:1 methanol to oil mass ratio at 40 °C for 90 min.
- Castor plant residues—stem, seed cake, leaf—were used to produce ethanol and biogas.
- Pretreatment using NaOH at 100 °C for 60 min maximized ethanol production yield.
- Alkali pretreatment of castor stem boosted up the methane production yield.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 June 2014
Received in revised form 2 September 2014
Accepted 3 September 2014
Available online 29 September 2014

Keywords:
Alkaline pretreatment
Biodiesel
Biogas
Castor plant
Ethanol

ABSTRACT

Whole parts of castor plant, as a non-edible energy crop, were used for multiple biofuels production. Extracted castor oil was used for biodiesel production by transesterification, whereas the castor plant residues, i.e., stem, seed cake, and leaves, were employed for ethanol and biogas production. Effects of operating conditions, including methanol to oil ratio, temperature, and reaction time on biodiesel production yield were investigated. The optimum biodiesel yield was 88.2%, obtained at 0.4:1 methanol to oil mass ratio at 40 °C for 90 min. This yield corresponded to 155 g biodiesel per kg castor plant. In addition, pretreatment using 8% w/v NaOH at 0 and 100 °C for 30 and 60 min was applied to improve ethanol and biogas yields. The best results for both enzymatic hydrolysis and ethanol production by simultaneous saccharification and fermentation (SSF) were obtained after alkali pretreatment at 100 °C for 60 min for all plant residues. The highest ethanol production yield achieved from pretreated castor stem was as high as 82.2%, corresponding to 63 g ethanol per kg castor plant. In the case of biogas production, alkali pretreatment enhanced the methane production yield from castor stem; however, it could not improve the production yield of castor seed cake and leaves. Furthermore, untreated castor seed cake had the highest methane production yield of 252.1 ml/g VS, equal to 68.2 L per kg of castor plant.

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http://dx.doi.org/10.1016/j.apenergy.2014.09.005
0306-2619/

1. Introduction

Increasing energy demand and fossil fuel prices together with environmental concerns have motivated scientists to find alternative energy sources such as biofuels. Biofuels are renewable and biodegradable sources of energy with acceptable environmental impacts [1,2]. Ethanol, biodiesel, and methane are the common types of biofuels [3].

Biodiesel is a mixture of monoalkyl esters of vegetable oils or animal fats, which may be produced via a transesterification reaction [4–6]. Currently, more than 95% of the world biodiesel is produced from edible vegetable oils [7] such as rapeseed [8,9], soybean [10,11], palm [11,12], and sunflower oils [11,13]. Biodiesel production in a large scale raises great concerns due to food–fuel competition in the long term [14,15]. Therefore, using nonedible vegetable oils like *Jatropha curcas* [16,17] and castor oil [18] not only can skip the food–fuel concerns, but also decreases the final biodiesel cost which is rigorously affected by the feedstock type [19].

Ethanol and biogas are other biofuels that are industrially produced from easily degradable biomass resources, i.e., sugars and starchy materials. This usually leads to food–fuel conflict [20]. Due to limited resources of starch- and sugar-based materials, lignocellulosic materials, an inexpensive and affluent resource, have been considered as an alternative feedstock of ethanol and biogas production [21]. An acidic or enzymatic hydrolysis followed by a fermentation step, generally by *Saccharomyces cerevisiae*, is used for ethanol production [22], while biogas is produced through anaerobic digestion [23]. Although lignocellulosic materials have a considerable amount of carbohydrates, which can be converted to biogas and bioethanol, their recalcitrant structure is an obstacle in their direct conversion to the desired products [24]. Thus, a pretreatment process is a pivotal stage necessary to reduce the recalcitrance of the materials, i.e., reduce cellulose crystallinity, increase accessible surface area, and remove lignin and hemicelluloses [25,26]. After the pretreatment step, either the pretreated materials are subjected to anaerobic digestion for biogas production or they are hydrolyzed to convert lignocelluloses' carbohydrates to fermentable sugars that can be used by microorganisms for ethanol production. Several pretreatment methods have been developed to alter the structure of lignocellulosic materials, including physical, chemical, physicochemical, and biological methods. Alkaline pretreatment using sodium hydroxide is one of the most effective chemical processes, which can enhance the ethanol production yield from lignocelluloses [20]. Moreover, the alkaline pretreatment was shown to improve biogas production [20,21,27]. Nieves et al. [27] showed that pretreatment using 8% NaOH solution for 60 min significantly improves biogas production from oil palm empty fruit brunches (OPEFB). Salehian et al. [21] used an alkaline pretreatment with 8% w/w NaOH solution at 100 °C for 10 min to improve the biogas production yield from pine wood by 181.2%. Likewise, Salehian and Karimi [20] used the same alkaline solution at 0 °C and 100 °C for 60 and 10 min, respectively, and pretreated different parts of pine tree, i.e., needle leaves, branches, cones, and bark. They reported significant improvement in biogas and ethanol yields in most cases.

Castor is an important non-edible oil crop that can tolerate various weather conditions [28]. Castor seeds contain about 47–49% oil, which is constituted mainly of ricinoleic acid [29]. The average yield of castor seeds in the world is around 1.1 t ha^{-1} although a very favorable cultivation condition can lead to 4–5 t castor oil ha^{-1}. Considering 90% extraction yield, an average productivity of 460 kg castor oil ha^{-1} or a maximum of 2000 kg castor oil ha^{-1} can be achieved. Therefore, castor plant represents a high oil yield potential [30]. Moreover, the plantation cost of castor is significantly less than other plants such as jatropha, soybean, and rapeseed [7]. Rather than the feedstock, alcohol content, catalyst, reaction temperature and pressure, reaction time, the contents of free fatty acids and water are the main factors affecting the biodiesel production [31]. Several studies were investigated the effect of these parameters on the biodiesel production yield from castor oil [18,32–37]. For instance, in separate studies, De Oliveira et al. [32] and Da Silva et al. [33] surveyed the effect of some parameters such as temperature, catalyst concentration, and ethanol to oil ratio on biodiesel production from castor oil using Taguchi experimental design and response surface methodology (RSM), respectively. These authors [32,33] represented completely different operating conditions in order to maximize the biodiesel production yield. Berman et al. [38] studied some properties of biodiesel produced from castor oil through transesterification reaction for 1 h at 50 °C using 6:1 methanol to oil molar ratio and KOH (50 g kg^{-1} oil) as an alkaline catalyst. They found that kinematic viscosity and distillation temperature of B100 (pure biodiesel) are the only properties not meeting the appropriate ASTM standard limits; however, the B10 blend sample met all the specifications [38].

Castor plant is used as an urban decorating plant; however, seeds and seed cake of this plant are highly poisonous and limit their use for various applications, particularly as human and animal feed [28]. Therefore, castor wastes, which include stem, seed cake, and leaves, are potentially applicable as feedstocks for ethanol and biogas production, while castor oil is useful for biodiesel production.

To our knowledge, limited studies have been done on producing multiple bio-based products from all parts of a plant and there is no research on the castor plant in this field; however, some studies have been done on biodiesel production from castor oil. Moreover, a comparison between the effectiveness of pretreatment on enzymatic hydrolysis, ethanol, and biogas production from castor plant residue has not been presented in the literature.

2. Experimental section

2.1. Raw materials

Castor oil plant was collected from local land in Khomeinishahr, Isfahan, Iran. After the oil extraction step, different parts of the plant residues including stem, seed cake, and leaves were milled and screened to achieve particles with a size between 0.177 mm (mesh 80) and 0.841 (mesh 20). The dry weight of substrates was measured by drying in an oven at 105 °C until constant weight [20].

2.2. Oil extraction and preparation

Prior to oil extraction, the seeds were heated in an oven at 70 °C for 72 h in order to eliminate excess moisture [38]. The oil was extracted by a Soxhlet extractor for 8 h using n-hexane as a solvent [39]. The solvent was then recovered by vacuum rotary evaporator, and the extracted oil was filtrated by a 80 mesh sieve to remove the solid particles. The neat oil was heated at 80 °C in an oven to eliminate the remaining moisture before biodiesel production.

2.3. Biodiesel production

The transesterification process was conducted in a 500 ml reactor equipped with reflux condenser at 400 rpm in the presence of 1.5 g KOH/kg oil as an alkaline catalyst. The reaction was performed at different mass ratios of methanol to oil (0.1–0.5), reaction temperatures (30–70 °C), and reaction times (30–120 min).

After the reaction, a separating funnel was utilized to separate ester layer (upper layer) from glycerol layer (lower layer) [19]. The mixture was left overnight to completely separate the phases.