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Novel front end processing method of industrial beet juice extraction for biofuels and bioproducts industries

Anand Kumar Pothula [a], *C. Igathinathane* [a,*], *T. Faller* [b], *R. Whittaker* [c]

[a] *Department of Agricultural and Biosystems Engineering, North Dakota State University, 1221 Albrecht Boulevard, Fargo, ND 58102, USA*

[b] *North Dakota Agricultural Experiment Station, North Dakota State University, 1230 Albrecht Boulevard, Fargo, ND 58102, USA*

[c] *Heartland Renewable Energy, 926 Grandview Avenue, Muscatine, IA 52761, USA*

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ABSTRACT

Conventional raw beet juice extraction in food-grade crystal sugar production is a highly involved and energy intensive process, which includes beets washing, thawing of frozen beets, cossettes slicing, and high temperature denaturation and diffusion. Industrial beets, a new feedstock bred for non-food industrial use, processing for biofuel and bioproducts applications can use less stringent quality requirements and simplify the juice extraction process. A novel simplified front end processing (FEP), which is less expensive, energy efficient, and involved only common equipment (hammer mill and basket press), was developed and tested. The hammer mill pulverized the beets and basket press extracted the juice. Four beet conditions (fresh, frozen, thawed and fresh-frozen) and four presses with water addition were tested for juice extraction. The juice concentration had decreased with the increased number of presses, and the fitted exponential equations ($R^2 \geq 0.97$) determined the juice concentration as a function of number of presses. Frozen beets consistently produced significantly high concentration juice followed by fresh-frozen, thawed, and fresh beets. Freezing had a beneficial effect in increasing the cumulative approximate sugar extracted. Two presses for fresh (92%) and three for frozen (97%) beets extracted the most available sugars. Future research may focus on water temperature, beet particle size, juice for extraction, microbial stability, energy economics, and products utilization. This new FEP efficiently extracts industrial beet juice and has direct scope in industry deployment as well as enhances the potential of the fuel generated being recognized as an advanced biofuel by the renewable fuel standards.

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1. Introduction

Depletion of fossil fuel reserves and concerns over greenhouse gas emissions have raised interest in alternative energy sources “mainly ethanol” worldwide [1]. In the US, with an aim to improve automobile fuel economy and to reduce dependency on fossil fuel, the Energy Independence and Security Act of 2007 (EISA) mandates an annual production of

* *Corresponding author*. Tel.: +1 701 667 3011; fax: +1 701 667 3054.
E-mail addresses: Igathinathane.Cannayen@ndsu.edu, igathi@gmail.com (C. Igathinathane).
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136 hm^3 of biofuels by 2022 [2]. Corn is the prevalent ethanol feedstock, which is also the major food grain crop in the US. In the US, over 95% of ethanol was produced from corn during the year 2011 [3]. Increased demand for corn from ethanol producers is one of the factors that drives up the corn prices, even though the corn prices were momentarily low at present. The persistent debate on food *vs* fuel also encourages the ethanol producers to find alternative feedstock to corn [4].

Industrial beets, also known as energy beets or sugar beets, represent one such alternative and can be readily considered an industrial feedstock. Industrial beets are specifically bred for the renewable energy or bioproducts production initiative. Regular sugar beets, were grown in fertile and mostly irrigated regions to cater the food-grade sugar industries. In comparison, industrial beets were grown both on dryland and irrigated regions with good yield potential in both cases [5]. In 2012, industrial beet trial results conducted by North Dakota State University at various locations in North Dakota showed an average root yield ranging from 72.6 to 109.7 Mg ha^{-1} (sugar mass fraction of fresh weight was 16.7%–19.7%) in irrigated land and 49.4–82.0 Mg ha^{-1} (sugar mass fraction of fresh weight was 18.1%–21.2%) in dryland, respectively [6]. Thus, industrial beets are being considered as an ethanol and bioproducts industrial feedstock that can be grown on varied regions to support industrial development and rural employment generation.

Sugar beet provides easily fermentable sucrose, unlike fermentable liquor derived from cellulosic sources, and clearly forms a potential source of feedstock for ethanol production [7,8]. Panella [7] also conducted life cycle analysis on sugar beet depending upon the environmental conditions in central European countries, where the most commercial ethanol production from sugar beet occurs. It was further reported that the greenhouse gas (GHG) emissions from sugar beet ethanol production were reduced comparably or superiorly to corn or sugarcane. According to EISA [2], "advanced biofuel means any renewable fuel derived from other than corn starch that has lifecycle GHG emissions less than at least 50% of the baseline GHG emissions." Therefore, with the reduced GHG emissions, sugar beet crop qualifies as advanced biofuel feedstock under EISA mandate [4]. France is the major ethanol producer using sugar beet as feedstock [4,9]. Although production of food grade sugar crystals from sugar beets is an established commercial industrial process, the biofuel and bioproduct applications of sugar beets are relatively new in the US. Thus, in the US, the research on industrial beets preprocessing, biofuel and bioproducts production, and industrial commercialization is in the initial stages, and the literature on these aspects are not available.

Molasses, the byproduct of food grade sugar production from sugar beets, is the common raw material for the ethanol production. Also a thin beet juice concentrate obtained by membrane filtration was successfully used as high yielding fermentation feed for ethanol production [8]. Research on ethanol production from whole sugar beet and sugar beet pulp has been reported [10]. Further, raw beet juice with about 15%–20% of dry solids (mostly sugar) and 85%–90% of purity is found profitable as input material for the ethanol production when compared to the cost of other intermediates [11–14].

The conventional method for extracting juice from sugar beets includes beet washing, slicing the beets into cossettes, and thermal denaturation followed by diffusion [15–17]. Beet washing requires large amounts of water because dirt and small rocks stick to the harvested beets. Making cossettes increases the surface area of beets exposed to water in diffuser for better sugar extraction. In the diffuser tank, hot water at about 70 °C is used for about an hour to denature (rupture/destruct) the cell membranes of the beet tissue and to extract the juice (sugars and non-sugars) simultaneously [15,18]. Thermal denaturation is a highly energy consuming process and also changes the inner chemical structure of cell walls through hydrolytic degradation, thereby increasing the impurities such as pectin, amino compounds etc., in the extracted juice [18].

After harvesting, beets are generally stored in the outside field or in the storage area nearby the processing plant to take advantage of the cold weather in winter for freezing. Thawing of these frozen beets using warm water before slicing not only consumes high energy but also causes sugar loss due to leaching [19]. Beet slicing into cossettes is a precise operation and the machinery involved requires high maintenance. Direct slicing of frozen beet without thawing for any application has not yet been reported. Also no literature has been found for the extracting beet juice without first making cossettes and then involving diffusion process. Frozen beets are likely to be too hard for the knife system designed for softer tissues of fresh or thawed beets.

To address the energy concerns with thermal denaturation, several studies have been conducted on the feasibility of cold extraction using pulsed electric field method of denaturation of the cell membrane, which is usually followed by pressing sliced cossettes for the production of high purity juice [20–27]. Purity of the raw juice extracted is highly important in sugar industry as non-sugar impurities increase the operational cost of juice purification as well as affecting the filtration process before crystallization of sugar [15,18]. Whereas for ethanol industry, the purity of raw juice is not much of a concern as ethanol can be produced from any of the intermediates in sugar industry; except for the cost involving in the preparation and handling of that intermediate will be higher based on the quality of the input material.

To qualify for advanced biofuel, it is central for the entire process to have reduced energy consumption and production cost so that it meets specific proportional limits. This advanced biofuel qualification for biofuels from industrial beets satisfies the EISA requirement of fuels in that category with better incentives to processing industries, thus further promoting such industries. New methods of alternative technologies have also been proposed by researchers for cold extraction of juice that eliminates thermal denaturation, such as pulsed electric field assisted pressing [26]. Seeing the difficulties, high energy inputs, and maintenance cost involved in extraction of juice from sugar beet, an alternative less energy intensive and less expensive beet juice extraction methodology has very good potential for the emerging beet ethanol industry in the US.

Mechanical pressing as a solid liquid expression technique is very common in food processing industries [25]. Using mechanical means to pre-process beets will be a simpler process and less energy intensive, as thermal processes are not involved. It is also essential that the preprocessing is