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Environmental impact assessment of soybean oil production: Extruding-expelling process, hexane extraction and aqueous extraction

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ABSTRACT

Expelling and hexane extraction are two typical processes for soybean oil production used in industry. The main issues for these two processes are the low efficiency and hazardous chemical problems respectively. Enzyme assisted aqueous extraction process (EAEP) was proposed to increase the efficiency without using organic solvent, which is replaced by water. The environmental impact analysis of these three processes are based on their mass flows, energy consumption and global warming potential. For mass flows, the environmental impact indices were calculated based on material flow of input and output components. Energy consumption was used to evaluate the carbon dioxide, other greenhouse gas (GHG), and criteria pollutants emissions by GREET models. According to our results, hexane extraction has the highest environmental impact due to the application of organic solvent. Expelling has the highest GHG and criteria pollutants emissions because of the high energy requirement for heat pressing processes. EAEP has similar environmental impacts to the expelling process, but it also lowers GHG and criteria pollutants emissions. EAEP has the potential to be a green process adopted by industry although a high energy intense pretreatment to produce finer soybean flakes for increasing oil recovery is still a challenge.

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1. Introduction

The US is the largest soybean producer in the world; around 34% of soybean production takes place in the US (Soystats, 2016). Due to its high oil content (Bernardini, 1983), soybean is the main oilseed used in edible oil production. In industry, the mechanical pressing-expelling, and hexane extraction are two typically used processes. However, lower oil recovery from expelling, and safety and environmental issues (Li et al., 2004; Oliveira et al., 2013) resulted from hexane extraction are the main flaws in the soybean oil industry. For improving the oil yield and mitigating the safety and environment related problems caused by expelling and hexane extraction, the enzyme assisted aqueous extraction process (EAEP) has been developed and might be a proper method for industrial application (Rosenthal et al., 1996).

Before pressing and extraction in mechanical expelling process, a series of pretreatment including cleaning, cracking, dehulling, and conditioning is required (Fig. 1). These treatments are mainly used to clean crops and reduce particle size to increase the oil recovery (Lamsal et al., 2006). During the extraction step (Fig. 1), heat and pressure are applied in the expelling process to denature the oleosins and to break the structure of oil body to release oil. The solubility of hexane and oil is the principle for the solvent extraction to extract oil from crushed soybean, and the desolvenization is applied to recover free oil and soybean meal. Further degumming and refining processes are needed for both expelling and hexane extraction to remove phospholipids and other impurities.

As to aqueous extraction (Fig. 1), contrary to solvent hexane extraction, water is used as the solvent and the insolubility of water oil is applied. During the process, the oil in water emulsion is formed. Consequently, the demulsification is conducted to separate the oil from the emulsion. The protein is extracted and dissolved in the aqueous fraction as well, therefore the further degumming process can be exempted (Johnson and Lucas, 1983; Jung et al., 2009; Sekhon et al., 2015). Thus, the safety and environmental related problems derived from chemical usages can be avoided. Additionally, this leads to a higher oil recovery than the mechanical expelling process.

In addition to technical improvement and feasibility, the environmental sustainability is another critical factor to evaluate the feasibility of the process. As to oil extraction, electricity is the main energy used in facility operations; steam is the heating resource which is mainly generated from a natural gas boiler built in the plant (Li et al., 2006). Besides energy consumption of the operation, the fossil-derived chemical addition is another critical issue for environmental impact evaluation, especially for hexane extraction. For EAEP, water is used as the solvent which could mitigate the environmental impact when compared to solvent extraction. However, the demulsification has been regarded as a critical step for oil recovery in aqueous extraction due to its high energy requirement, especially on physical (Hagenmaier et al., 1972; Harada and Yokomizi, 2000; McClements, 2005) and chemical methods (Menon and Wasan, 1985).

Based on the characteristic of different extraction processes, the environmental impact assessment (EIA) has been used to investigate the potential environmental impact resulted from the process. The mass balance, mass flow, and energy consumption are the main objectives used to evaluate the energy efficiency, greenhouse gas (GHG) and pollutants emissions from the processes (Salomone and Ioppolo, 2012). Heinzle et al. (1998) proposed the quantifying approach to evaluate the environmental impacts derived from chemical processing by calculating all input and output components. Also, the Organization for Economic Co-operating and Development (OECD) proposed the environmental indicator to assess the sustainability of industrial processing in 2001.

There are many computation models which can be used for GHG and air pollutant emission estimation such as Aspen Plus (Morais et al., 2010) and Simapro (Kiwjaroun et al., 2009). The GREET model (the greenhouse gases, regulated emissions, and energy use in transportation model, Argonne National Laboratory) was introduced to evaluate the GHG and criteria air pollutants emissions. Although the GREET model has the restriction for only investigating biofuels used in transportation sector, the soybean oil has been regarded as a critical resource for biodiesel production. Therefore, the GHG and air pollutants emissions of soybean oil production can be extracted from the soy-based biodiesel GREET model. However, there were few studies mainly focused on soybean oil production, especially comparing different processes and the alternative extraction methodology.

This study mainly focuses on the comparison among these three extraction processes. The EIA is divided into two sections including environmental impacts derived from material flows of the process and the GHG and air pollutants emissions from the oil extraction processes. The environmental impacts will be quantified based on material balance of the whole process, especially from input and output components. The total energy consumption, heating agent, and mass flow were used to build up an oil extraction pathway via the GREET model. The GHG and criteria air pollutants emissions were investigated by the GREET model. According to these criteria, the environmental feasibility of these three processes could be obtained and compared.

2. Materials and methods

2.1. Boundary definition

The assessment boundary of soybean oil extraction includes oilseed pretreatment, extracting processes, oil degumming, and coproducts handling. The transportation, however, was not considered (Fig. 2). Additionally, the land use and the generations of primary energies were not considered in this EIA. Steam (assumed to be produced by the natural gas boiler within the plant) and natural gas were used as the primary source of heat energy. Therefore, the whole boundary can be defined as the operation within the plant as well. Also, these three oil extraction processes are investigated under pilot scale operations, which are 23.3, 31.5, and 15.4 million ton of annual soybean oil production from the expelling process, hexane extraction, and EAEP respectively.

2.2. Environmental impact

Material flow is the basic factor for evaluating the environmental impact. The mass flow is separated into input and output components. The data of the expelling process and hexane extraction were collected according to the research from Haas et al. (2006), Cheng (2017), and Cheng and Rosentrater (2017); and, the EAEP was evaluated based on de Moura's research (2011). The mass flow of input components, output components, and the main product are shown in Table 1 and they are the basis for the further environmental indices calculations.

2.2.1. Component classification

For input and output components, there are four impact groups for each component individually including the material property, potential thermal risk, and toxicity. Also, there are several categories which are assigned to each impact group (Heinzle et al., 2006). The hierarchical diagram of EIA is shown in Fig. 3.

As the hierarchy of environmental components shows, groups and categories are built and the impact categories are allocated into three classifications (A, B and C) based on the level of potential risk and toxicity of a component in the process (Table 2). The highest class in the referred impact categories defines the classification of the impact category for each impact group.

In impact category classification, critical chemical and complexity are evaluated based on Ullmann's Encyclopedia of Industrial Chemistry (Ullmann, 1985); thermal risk and