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Evaluation of energy consumption and greenhouse gas emissions from poly(phenyllactic acid) production using sweet sorghum

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ABSTRACT

The extensive use of fossil-based plastics has raised concerns regarding the depletion of fossil resources and the deterioration of the environment. Phenyllactic acid (PhLA), fermented from renewable resources, could be used to produce high-performance bio-plastics able to replace the fossil-based engineering plastics (FBEPs) in many applications. In order to evaluate the environmental performance of poly(PhLA) produced from sweet sorghum, a cradle-to-factory-gate life cycle assessment was performed for two impact categories, namely fossil energy consumption and greenhouse gas (GHG) emissions per kilogram of poly(PhLA). These two impact categories were compared with those of the FBEPs, and with those of the bio-based polylactides (PLA) and poly(hydroxyalkanoate) (PHA). The fossil energy consumption for poly(PhLA) is 24.2 MJ/kg, which is lower than that of the FBEPs and the bio-based PLA and PHA. However, the GHG emissions are 6.2 kg CO_2 eq/kg using the current technology; these are higher than those of the FBEPs and bio-based PLA and PHA. The results of a sensitivity analysis show that the GHG emissions become less than those of FBEPs when increasing the efficiency of separation and purification to more than 90.3%, the PhLA yield to more than 20.6%, the sugar extraction rate to 96%, the Brix of sorghum juice to more than 19.4%, and the sorghum yield to more than 79.2 t/ha. These results show that using the poly(PhLA) produced from sweet sorghum to replace the FBEPs has the potential to reduce fossil energy consumption and GHG emissions.

1. Introduction

Global plastics consumption is expected to reach 297.5 million tons by 2015 (GIA, 2013). Currently, most industrial plastics are produced from non-renewable resources such as oil or gas, which has raised public concern regarding the depletion of fossil resources. Furthermore, large amounts of greenhouse gases (GHGs) are released when plastics are produced. For example, the emissions rates for conventional manufacturing processes are 7.5 kg CO_2 eq/kg for polycarbonate (PC) and 4.9 kg CO_2 eq/kg for polybutylene terephthalate (PBT). In addition, because of their resistance to microbial decomposition, conventional fossil-based plastics are a serious concern for the environment. These environmental concerns may be mitigated if biodegradable plastics, derived from renewable resources such as biomass, could be commercialized (Gross and Kalra, 2002; Karana, 2012).

Poly(hydroxyalkanoate) (PHA) and polylactide (PLA), derived from renewable resources, are two of the leading candidates to replace conventional plastics on a large industrial scale (Alvarez-Chavez et al., 2012; Papong et al., 2013; Pool, 1989). However, the process of fermenting PHA from renewable agricultural feedstock consumes a large amount of energy, which has been demonstrated to result in the overall release of more GHGs than does conventional petrochemical polymer production (Gerngross, 1999). Consequentially, PLA seems to be the only plant-based plastic that

Abbreviations: FBEPs, Fossil-based engineering plastics; GHG, Greenhouse gas; IDEA, Inventory Database for Environmental Analysis; LCA, Life cycle assessment; LHV, lower heating value; PA, polyamide; PBT, polybutylene terephthalate; PC, polycarbonate; PHA, poly(hydroxyalkanoate); PhLA, Phenyllactic acid; PLA, Polylactide; POM, Polyacetal; PPS, Polyphenylenesulfide; SS, Sweet sorghum.

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could possibly become competitive with conventional plastics (Gerngross and Slater, 2000). However, because of the poor thermal and mechanical properties of the biodegradable plastic that can be produced from PLA derived from biomass, PLA would be able to replace only a small percentage of the current demand for plastics (Kaneko et al., 2006). Therefore, numerous obstacles need to be overcome in order to replace the conventional plastics with the bio-based plastics.

The incorporation of phenyl groups into PLA or PHA can dramatically change their thermal and mechanical properties (Shen et al., 2014; Tobin and O'Connor, 2005). In addition, the aromatic ring is a convenient platform for the introduction of additional functionalities that can be exploited to give more elaborate polymer architectures and provide desirable properties such as the ability to crosslink the polymers (Simmons and Baker, 2001). Phenyllactic acid (PhLA) is a lactic acid in which one of the hydrogen atoms of the methyl group is substituted by a phenyl group. PhLA fermented from renewable resources could potentially produce high-performance bio-plastics capable of replacing fossil-based engineering plastics (FBEPs) in a large number of applications. High molar mass poly (PhLA) was successfully prepared by direct polycondensation of PhLA (Nguyen et al., 2011). The activation energy of thermal degradation for poly (PhLA) (200 kJ/mol) is higher than that for PLA (158 kJ/mol), and its resistance to chemical reagents is better than that of the polymers that are in general use today (Tsuji et al., 2008). In addition, the aromatic polymers are distinguished by their considerable thermostability and remarkable strength. The mechanical performance of poly (4-hydroxycinnamic acid-co-3,4-dihydroxycinnamic acid) rivals that of the engineering plastic derived from fossil resources. For example, poly (4-hydroxycinnamic acid-co-3,4-dihydroxycinnamic acid) was found to have a bending strength of 63 MPa, a Young's modulus of 16 GPa, and a maximum softening temperature of 169 °C (Kaneko et al., 2006). The engineering plastic derived from fossil resources has a strength of more than 50 MPa, a Young's modulus of more than 2.5 GPa, and a softening temperature of more than 100 °C.

Currently, PhLA is produced from a nonrenewable and expensive resource using lactic acid bacteria (LAB), or non-LAB strains (Mu et al., 2012). A fermentation process to produce PhLA from glucose, using *Escherichia coli (E. coli)* genetically modified by phenylpyruvate reductase, was developed and produced approximately 29.2 g PhLA/L (Fujita et al., 2013; Konishi and Takaya, 2012). However, the need for a renewable and inexpensive carbon source could not be met.

The integration of agro-energy crops and biorefinery manufacturing technologies offers the potential for creating a cost-effective supply of sustainable biomaterials (Ragauskas et al., 2006). Sweet sorghum is a promising industrial feedstock for value-added fermentation products such as PhLA because of its higher content of fermentable sugars and yield of green biomass, short growth period, drought tolerance and high efficiency in water usage, low requirements for fertilizer, and the ability to grow under a wide range of climate and soil conditions (Paterson et al., 2009; Pennisi, 2009; Sun et al., 2010). The juice obtained from the sweet sorghum stem has a high content of the sugars glucose, fructose, and sucrose that can be easily converted to glucose and fructose. Therefore, sweet sorghum juice has great potential as a carbon source for the production of biopolymers such as poly(PhLA) at an industrial scale (Tanamool et al., 2013).

A life cycle assessment (LCA) on the environmental performance of a new technology for poly(PhLA) production is needed before significant resources can be dedicated to the development of the technology. However, there are currently no LCA studies available in the literature on poly(PhLA) production from sweet sorghum. Therefore, the objective of this study is to assess the "cradle-to-factory-gate" life cycle energy consumption and GHG emissions of the production of poly(PhLA) using sweet sorghum.

2. Methodology

We performed the LCA using the following five steps. First, we conducted a literature search for the technologies that are currently under consideration. Secondly, we developed a set of process flow diagrams (PFDs) to describe the technologies. Thirdly, we developed a simulation model of the process with Microsoft Excel and calculated a mass and energy balance for the arrangement of the equipment in the PFDs, using the available experimental data. Fourthly, we calculated the GHG emissions, using the method of emission factor (Yu and Chen, 2008). Fifthly, we conducted a sensitivity analysis and proposed ways to improve the process.

2.1. Process description

Based on our literature search, we propose a system for producing poly(PhLA) from sweet sorghum juice. The process flow is shown in Fig. 1. First, sweet sorghum is chop-harvested by a forage harvester, and the sugar-containing juice is extracted from the chopped plants. The juice is fermented to PhLA using *E. coli* genetically modified by phenylpyruvate reductase (Fujita et al., 2013). The method of solvent extraction is used to separate and purify the PhLA. In the present study, the poly(PhLA) was synthesized using the method of Fujita et al. (2013). The PhLA fermentation process, the separation and purification process, and the polymerization process require steam and electricity, which can be provided by various primary energy sources, including biomass or fossil fuels. Since the bio-based polymer production using fossil fuel sources provided no greenhouse gas advantage over fossil-based polymers (Kurdikar et al., 2001), we have assumed here that the required electricity and steam of the overall process of poly(PhLA) production can be provided by a cogeneration system using the

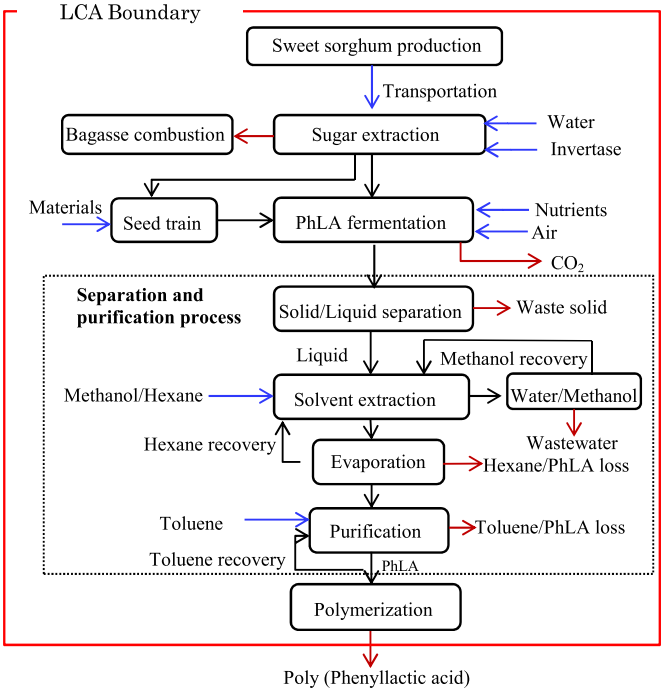

Fig. 1. Simplified flow diagram of the overall process.

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