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Life cycle assessment of feedstock supply systems for cellulosic biorefineries using corn stover transported in conventional bale and densified pellet formats

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A B S T R A C T

A major practical limitation of the logistics of cellulosic feedstocks, such as corn stover, for use in biorefineries is their low bulk density. This could be improved by densifying feedstock through methods like baling and pelletization, which also have environmental footprint. Thus, this study assessed the environmental impacts of three potential corn stover feedstock supply scenarios incorporating baling and pelletization for a cellulosic biorefinery of 114 million liters per year capacity in the U.S. Midwest. Scenarios included feedstocks transported in bale and pellet formats with and without storage at distributed storage and processing sites. For the three feedstock supply scenarios, the estimated ranges of global warming potential, acidification potential and resource depletion environmental impacts per ton of delivered biomass (at 0% moisture content) were 20–73 kg carbon dioxide equivalent, 0.1–0.2 kg sulfur dioxide equivalent, and 36–52 MJ surplus, respectively, with pelletization process contributing to higher emissions. For supply system with pellets, electricity required for pellet production was the major contributor to the overall emissions. For the geographic locations with higher share of renewable energy mix in the electricity grid (e.g., Western Electricity Coordinating Council grid, Norway), the emissions from all three scenarios were close. With technology advancement in future, larger capacity biorefineries with increased biomass supply area and transportation distance are possible. In such case, enhanced densification, such as pelletization, could further lower the environmental impacts of biomass feedstock supply systems.

1. Introduction

Limited petroleum sources with unpredictable prices and the increasing awareness about greenhouse gases (GHG) induced climate change have resulted in an increased interest in biomass for biofuels, and products (Berner, 2003). Biomass-derived bioenergy can be produced, stored and used in solid, liquid and gaseous forms for heat and electricity production, transportation, and cooking purposes. Integrating bioenergy systems with agriculture and forest systems along with management of emissions from industrial sources can substantially reduce environmental impacts (Wise et al., 2009). Bioenergy is projected to grow up to 35% of global primary energy by 2050 and 50% by 2100 (Rose et al., 2014). Thus, to promote bioenergy in the U.S., revised renewable fuel standard (RFS2) is implemented. RFS2 mandates the production of 136 billion liters of renewable biofuels, including 60 billion liters of cellulosic biofuels, by 2022. There has been a considerable development of ethanol from corn grain with facilities currently producing almost 57 billion liters per year of ethanol (RFA, 2015). However, development of cellulosic ethanol is lagging (RFA, 2015).

The recent Billion-Ton Report emphasizes that the U.S. can produce at least one billion dry tons of biomass resources annually without adversely affecting the production of food or other agricultural products (DOE, 2016). This amount of resources could produce enough bioenergy and bioproducts to displace approximately 30% of 2005 U.S. petroleum consumption (DOE, 2016). Several studies have also asserted the abundance of corn stover, which is a promising lignocellulosic feedstock source (Graham et al., 2007; Tilman et al., 2001; Zhang, 2008). Despite this enormous potential, commercial cellulosic biofuels production in U.S. is negligible (RFA, 2015). One of the major bottlenecks for the

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commercial success of cellulosic biofuels is the current biomass feedstock logistics, which is costlier and generates high emissions and is significantly impacted by lower biomass bulk density (Li et al., 2012; Rentizelas et al., 2009; Richard, 2010; Shah and Darr, 2016). The lower bulk density limits the amount of material to be transported in each truckload and thereby increasing the number of truckloads for transportation. Also, the distance between biomass production sites and biorefineries are often long and thus, increase the requirements for biomass transportation and storage (Rentizelas et al., 2009). Hence, technological and logistical development in this area leading to increased bulk density would help reduce the use of fossil fuels to handle, transport and store the biomass feedstocks for the biorefinery plant.

Biomass from agricultural residues, primarily corn stover, is currently densified in the form of bales, transported and utilized by the very few existing and operational cellulosic biorefineries (Shah and Darr, 2016). Bales are the common in-field densified form of biomass with a bulk density of 130–190 kg/m^3 (Sokhansanj and Fenton, 2006).

Densification techniques, such as pelletization, could be implemented in the feedstock supply system to increase the biomass bulk density by multiple times (Sokhansanj and Turhollow, 2004). Furthermore, biomass pellets have low and uniform moisture content which can be handled and stored cheaply and safely using well-developed systems for grains (Fasina and Sokhansanj, 1996). Hence, pelletization of the biomass feedstock could potentially decrease the costs and emissions during biomass feedstock transportation for the cellulosic biorefinery.

Biomass densification is poised to be a necessary step in biomass feedstock logistics systems where biomass resources need to be transported over longer distances. However, biomass densification step will also increase the emissions as it needs power/electricity and thus affect the overall environmental impacts of the logistics as well as the biorefinery systems (Li et al., 2012). Life cycle assessment (LCA) methodology could be used to identify the scenarios for biomass feedstock transportation incorporating densification technologies for the corn stover based cellulosic biorefinery with relatively lower environmental impacts. Limited LCA studies (Li et al., 2012; Lin et al., 2016; Magelli et al., 2009; Mani et al., 2005; Pa et al., 2012) for pelletization of different feedstocks sources are available. However, the studies focused on the biomass feedstock densification and transportation for corn stover based commercial-size cellulosic biorefinery are almost non-existent. For the bioenergy sector to grow as projected in the future, large number of higher capacity biorefineries based on cellulosic feedstocks need to be established (DOE, 2016). The higher capacity cellulosic biorefineries will have wider feedstock collection area and corresponding transportation distance to meet the feedstock demand of these biorefineries. In such case, enhanced densification of biomass could be a necessary step for reducing the feedstock logistics emissions. Several studies (Balan, 2014; Hamelin et al., 2014; Li et al., 2012; Magelli et al., 2009; Pa et al., 2012; Singh et al., 2010; Valente et al., 2011) have highlighted biomass logistics as one of the challenges for large-scale implementation of lignocellulosic biomass based biorefineries. The energy used for transportation could increase up to 26% for lignocellulosic biomass (Richard, 2010; Uslu et al., 2008). As the size of biorefinery increases, transportation of lignocellulosic biomass feedstock has diseconomy of scale which contrasts with economies of scale for conversion technologies (Richard, 2010; Slade et al., 2009; Zhang et al., 2015). This could further increase the fraction of energy used for transportation for larger biorefineries. Thus, there is a need to quantify the emissions from the biomass feedstock logistics for such cellulosic biorefineries. Thus, the objective of this study is to assess the environmental impacts of biomass densification in bale and pellet formats on three potential corn stover feedstock transportation scenarios for a cellulosic biorefinery in the U.S. Midwest. This include scenarios where the biomass is either transported directly to biorefinery in bale format; stored at distributed storage and processing sites (referred as 'depot' hereafter) and transported to biorefinery in bale format; or further densified to pellets at depots, stored and then transported to biorefinery. Further, this study also identifies the minimum biomass feedstock transportation distances for implementing densification techniques such as baling and pelletization with lower environmental footprint.

2. Methods

2.1. Goal and scope definition

The goal of this study is to compare the environmental impacts of feedstock supply logistics for a corn stover based cellulosic biorefinery of 114 million liters per year (MLPY) capacity with densification by baling and pelletization. This is achieved by comparing three feedstock logistic scenarios, (Fig. 1), which include: (1) where biomass is directly transported in the form of bales from the field edge to the biorefinery, (2) where the biomass is transported in bale format to depots, stored, and then transported to biorefinery, and (3) where the biomass is transported in bale format to depots, pelletized, stored, and then transported to biorefinery. The functional unit for this study is defined as 1 metric ton (t) of dry biomass at 0% moisture content delivered to the biorefinery gate. Allocation is avoided for this study as all the biomass from the field is transported to the biorefinery gate. The impact assessment has been conducted using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) method developed by U.S. Environment Protection Agency (EPA, 2012) based on its scope and regional relevancy. The results for the three scenarios are compared in terms of all the impact categories based on TRACI which includes global warming potential (GWP), acidification potential (AP), resource (fossil fuels) depletion (RD), eutrophication potential, ecotoxicity, human health impacts, photochemical smog, ozone depletion, and respiratory effects. However, GWP, AP, and RD are discussed in further detail as these are the most relevant categories with direct impacts from the feedstock supply systems (Sathaye et al., 2006). The geographical location considered for this study is the U.S. Midwest region. The data from field studies, the emission values, and the electricity grid (i.e. MRO grid) are considered for the Midwest region. However, the research approach and results from this study related to supplying feedstocks to cellulosic biorefineries could be directly included or be inputs to LCA studies focused on the overall biofuels production in other regions as well. The analysis of this study could be extended to other lignocellulosic biomass feedstock type, especially energy crops, which have high potential in the future.

2.2. Systems description, boundary, and scenarios

This study is focused on the environmental impact of biomass feedstock supply logistics, and thus the boundary for this study is from the field edge with stacked bales to the biorefinery yard gate from where the biomass feedstock is utilized in the biorefinery. Other processes in the biomass production chain such as biomass production and conversion are not considered in this study as they have a negligible effect on the comparison of biomass densification techniques. Fig. 1 shows the system boundary and the three distinct scenarios for transportation of corn stover feedstocks from field edge to the biorefinery gate, which could be potentially applicable for feedstock supply logistics of commercial cellulosic biorefinery (Shah et al., 2017). In scenario 1, the biomass bales are initially