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A multi-objective superstructure optimization approach to biofeedstocks-to-biofuels systems design

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ABSTRACT

This paper describes a biofeedstock-to-biofuel superstructure (BBSS) and a multi-objective optimization scheme to suggest processing paths for a given biofeedstock. The BBSS uses feedstock compositional data to estimate the mass balance for each of the seventeen production paths in the four categories of transesterification to biodiesel, hydrolysis fermentation to ethanol, gasification to syngas, fast pyrolysis and catalytic upgrading to liquid hydrocarbons, and anaerobic digestion to biogas. An ideal biofuel production process would have low cost, low carbon emissions, and high energy recovery from the feedstock. These three objectives are used in a multi-objective network flow optimization of the BBSS. In order to make biofuels feasible, no part of an energy crop/plant should go to waste, so the optimization assigns a combination of processes to treat different fractions of the feedstock. The results of the optimization for three representative biofeedstocks, rapeseeds, corn, and switchgrass, are discussed in detail with emphasis on how the importance assigned to a given objective impacts the optimal solution. Optimization results indicate that switchgrass should be treated with gasification or anaerobic digestion rather than ethanol fermentation. Rapeseed should be processed using transesterification though the results were too sensitive to make a distinction between different transesterification methods. Results for corn grain confirm that fermentation is probably the best processing method and suggest using anaerobic digestion as treatment for the non-starch fraction.

1. Introduction

As concern grows over the future scarcity of petroleum reserves, there is renewed interest in finding an alternative source for transportation fuels [1]. Biomass has fairly high energy content, and its abundance and wide distribution could allow for local energy independence. However, to meet the needs of a transportation fuel, biomass needs to be converted into an energy-rich biofuel [2]. A wide variety of technologies have been proposed and some of them have been implemented to produce biofuels, originating from diverse sources of biomass. A search of the Compendex and Inspec databases for "biofuel production" returns well over three thousand papers published since 2007 alone. Clearly, this volume of information is too large to be examined at once by those attempting to gauge progress and identify research gaps. A more systematic approach is desirable.

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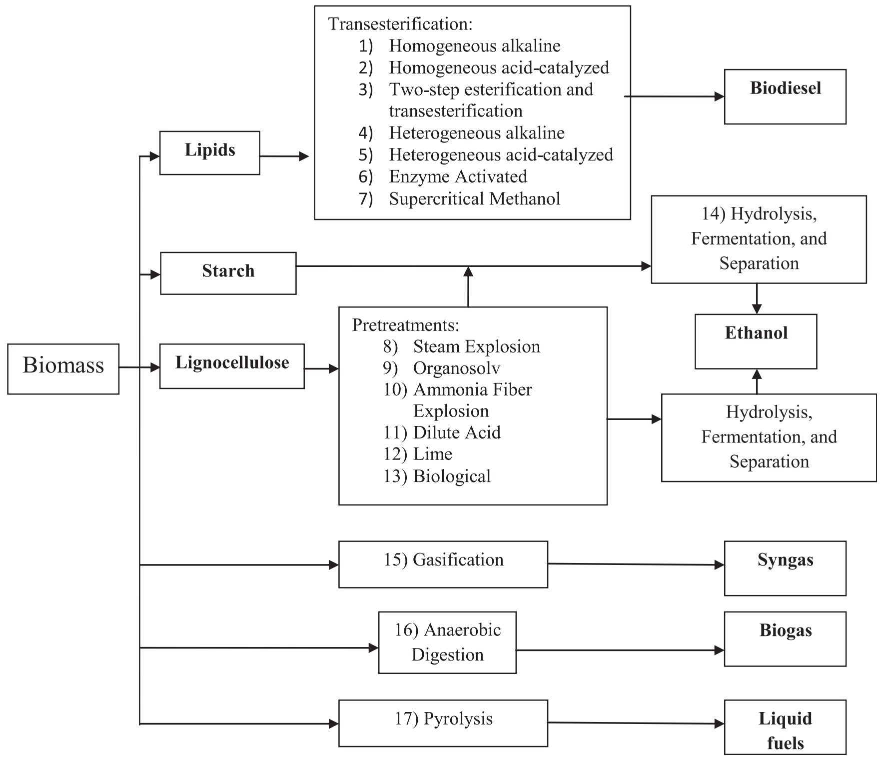

Fig. 1 – Biofeedstock-to-biofuels superstructure.

Previous efforts have used modeling and optimization to address several aspects of biofuel production. Cundiff et al. [3] modeled and optimized biofeedstock production, harvesting, storage, and transportation strategies. Gassner and Maréchal [4] applied multi-objective optimization strategies to synthesize feasible process flow sheets for a gasification-based biorefinery. Their methodology was extended to include environmental performance and applied to lignocellulosic feedstock combined fuel and power plant in Gerber et al., 2011 [5]. While these works have often focused on optimizing a specific type of biofuel production technology, very little work has been done to systematically compare technologies in a broader context. de Wit et al. [6] modeled the expected utilization of several biofuels in European markets based on economic considerations including technological learning. Santibañez-Aguilar et al. [7] proposed a superstructure for the planning of a biorefinery given the economy and available crops in central Mexico and optimized this superstructure to maximize profit and minimize environmental impact. However, studies considering a wide range of technologies in a general, non-location-specific context are lacking in the literature.

This paper presents an approach to systematically compare production routes via a biofeedstock-to-biofuel superstructure, a network representation that links different biomass components to biofuel products via all possible production technologies. The biofeedstock-to-biofuels superstructure (BBSS) can be seen as the roadmap of biofuel production, containing information about mass and energy flows through each process. In this work, we developed a multi-objective linear optimization problem using the BBSS superstructure and three performance metrics – processing cost minimization, CO_2 emission minimization, and product energy maximization– for the biofuel processing paths. The objective of the optimization problem is to minimize the processing cost and CO_2 emissions and to maximize energy recovery. The next section provides an overview of the technologies included in the BBSS, followed by their implementation in the model and the optimization formulation. Finally, the results of three case studies for selected biofeedstocks are presented with a discussion of their significance.

2. Technology overviews

This section will provide an overview of each of the seventeen specific processing paths included in the BBSS. The general approach to producing each fuel product will be discussed followed by an explanation of specific processing alternatives that define each path in the BBSS (Fig. 1). The technologies considered in the BBSS (Fig. 1) may be placed into five general categories: transesterification, starch-based fermentation, cellulosic fermentation, gasification, pyrolysis, and anaerobic digestion.

2.1. *Transesterification technologies*

Biodiesel is produced from lipids through a transesterification reaction with an alcohol, usually methanol [8]. The product of this reaction, fatty acid methyl esters (FAME), has a significantly lower viscosity than the raw triglycerides, which is