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Thermodynamic investigation and environment impact assessment of hydrogen production from steam reforming of poultry tallow

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ABSTRACT

In this research, various assessment tools are applied to comprehensively investigate hydrogen production from steam reforming of poultry tallow (PT). These tools investigate the chemical reactions, design and simulate the entire hydrogen production process, study the energetic performance and perform an environment impact assessment using life cycle assessment (LCA) methodology.

The chemical reaction investigation identifies thermodynamically optimal operating conditions at which PT may be converted to hydrogen via the steam reforming process. The synthesis gas composition was determined by simulations to minimize the Gibbs free energy using the Aspen Plus™ 10.2 software. These optimal conditions are, subsequently, used in the design and simulation of the entire PT-to-hydrogen process. LCA is applied to evaluate the environmental impacts of PT-to-hydrogen system. The system boundaries include rendering and reforming along with the required transportation process. The reforming inventories data are derived from process simulation in Aspen Plus™, whereas the rendering data are adapted from a literature review. The life cycle inventories data of PT-to-hydrogen are computationally implemented into SimaPro 7.3. A set of seven relevant environmental impact categories are evaluated: global warming, abiotic depletion, acidification, eutrophication, ozone layer depletion, photochemical oxidant formation, and cumulative non-renewable fossil and nuclear energy demand. The results are subject to a systematic sensitivity analysis and compared to those calculated for hydrogen production from conventional steam methane reforming.

The LCA results indicate that the thermal energy production process is the main contributor to the selected environmental impact categories. Improvement actions to minimize the reforming thermal energy and the transport distance are strongly recommended as they would lead to relevant environmental improvements.

1. Introduction

Hydrogen (H_2) is regarded as the fuel for next generation and extensive research is being pursued for search of new and efficient techniques for H_2 production. According to Romm [1] there are two important pillars upon which the H_2 economy rests on: pollution-free sources for the H_2 production, and fuel cells for converting the H_2 to useful energy efficiently. Unfortunately, 95% of the current H_2 production comes from steam reforming of non-renewable natural gas [2]. H_2 derived non-renewable fuels will be either carbon intensive or expensive because of carbon sequestration costs. The expected increased demand for H_2 for fuel cell applications, however, dictates the development of new methods for eco-friendly H_2 production, especially from bio-renewable feedstocks. Therefore, the USA, Japan, China, India, and several European countries have established research and development programs focused on renewable H_2 production and fuel cell technology to solve the energy problem and the high dependence on fossil fuels.

Currently, the industrial practices have led to the generation of an enormous amount of crude fatty materials (CFM) as waste, and these materials are difficult to treat and valorize [3]. One such material is tallow from slaughterhouses, meat industry and food industry waste. Tallow is a rendered form of beef, poultry or mutton fat, processed from suet. Like vegetable oils (VO), tallow is primarily composed of triglycerides, with minor amounts of mono and diglycerides. A triglyceride consists of a three-carbon glycerol head groups conjugated to three fatty acid chains [4]. All triglycerides have the same basic structure, and the differences in properties and use of commercial triglycerides depends entirely on the degree of unsaturation, length and other chemical modifications to the fatty acid chains [4]. The fatty-acid carbon-chain lengths vary between 4 and 24 carbon atoms with up to six double bonds.

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Nomenclature

ADP	abiotic depletion potential
AP	acidification potential
CED	cumulative non-renewable fossil and nuclear energy demand
CFM	crude fatty materials
COPROX	carbon monoxide preferential oxidation
EP	eutrophication potential
FU	functional unit
GWP	global warming
HTS	High Temperature Shift
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LTS	Low Temperature Shift
LHV	Lower Heating Value
m	mass flow
ODP	ozone layer depletion
P	pressure
PEI's	potential environmental impacts
PEMFC	proton exchange membrane fuel cell
POFP	photochemical oxidant formation
PT	poultry tallow
PT-to-H_2	poultry tallow to hydrogen
Q	heat duty
SB	system boundaries
SG	synthesis gas
SMR	steam methane reforming
ST	steam reforming
S/C	steam to carbon ratio
TBD	tallow-based biodiesel
VO	vegetable oil
WGS	water gas shift
$\eta_{Thermal}$	thermal efficiency
$\alpha_{H2,\ renewability}$	hydrogen renewability ratio

As an overview of the world's statistic, a total of 24.64 million tones of animal/oils (i.e. butter, lard, tallow, grease and fish oil) were produced in 2007 [5]. Considering this huge amount, the valorization of these renewable and cheap fatty materials remains necessary. The use of tallow as a food additive is declined due to changing feeding habits of people and the soap industry cannot take up all the excess animal fat produced. In the last years considerable attention has been paid to the use of tallow for the production of biodiesel and other oleochemicals [6–10]. Biodiesel fuels produced from tallow and VO have comparable compositions [11]. However, there are some differences; the main one is that the tallow-based biodiesel (TBD) contains more saturated fatty esters [11]. Tallow as a biodiesel feedstock has some advantages and disadvantages. TBD has a higher cetane number than VO biodiesel, which means that TBD is cleaner and burns more efficiently in diesel engines [4]. However, TBD has a higher cloud point because of the high levels of saturated fatty acids. Its higher cloud point means that TBD tends to crystallize out at low temperatures, creating problems in engines. Used pure (100%) TBD would not meet the European standards. However, when blended at about 5% into conventional diesel, the mixture meets the relevant fuel quality standards [12].

This paper explores an innovative application for valorization of poultry tallow (PT) for H_2 production via steam reforming (SR) process. In fact, we believe that PT is a promising feedstock for producing renewable H_2 because the O_2 content is low and the potential yield of H_2 is high. Moreover, tallow is a potential alternative for H_2 production due to the highly centralized generation in slaughter processing facilities and historically low prices; this may have energy, environmental, and economic advantages that could be exploited. H_2 obtained from tallow has been proposed to be a low-risk end use for tallow from livestock that are removed from the food chain [13,14].

Currently, life cycle assessment (LCA) is considered a systematic tool evaluating the environmental impacts occurring throughout the entire life cycle of a process, product, or activity [15–17]. LCA leads to insight into the overall system performance and the relative contributions of the different stages in its lifetime with the so-called cradle-to-grave approach. The results of LCA can be helpful for promoting sustainable development policy and increasing environmental awareness in public [18]. In recent years, LCA methodology has been specifically used in environment assessment of new technologies for bioenergy including bioethanol [19,20], biomethanol [21], biomethane [22,23], biohydrogen [24,25]. Moreover it has been proven to be a valuable tool for analyzing energy and environmental considerations of CFM valorization. Dufour and Iribarren [26] performed a LCA of four biodiesel production systems including esterification–transesterification of waste VO (used cooking oil) and animal fats (beef tallow, poultry fat), and in situ transesterification of sewage sludges. They showed that biodiesel from waste VO potentially entailed the most favorable environmental performance and concluded that actions aimed at minimizing thermal and electric energy demands would lead to relevant environmental improvements. Morais et al. [27] compared the potential environmental impacts (PEI's) of three process design alternatives for biodiesel production from waste VO that are: the conventional alkali-catalyzed process including a free fatty acids pre-treatment, the acid-catalyzed process, and the supercritical methanol process using propane as co-solvent. They showed that the supercritical methanol process using propane as co-solvent is the most environmentally favorable alternative. The acid-catalyzed process generally shows the highest PEI's, in particular due to the high energy requirements associated with methanol recovery operations.

Djomo and Blumberga [25] applied the LCA methodology to quantify and to compare the energetic and environmental performances of H_2 from wheat straw, sweet sorghum stalk, and steam potato peels. They concluded that the energy ratios and the greenhouse gas emissions (GHG) of BioH_2 compared favorably with diesel and other fossil H_2 production pathways and the co-product yield is an important parameter when selecting a BioH_2 feedstock. Koroneos et al. [28] investigated the environmental aspects of H_2 production. They compared H_2 production methods with steam methane reforming (SMR) and five different renewable ways, which were solar energy using photovoltaic for direct conversion, solar thermal energy, wind power, hydropower and biomass. They cited that the use of wind, hydropower and solar thermal energy for the production of H_2 were the most environmental benign methods. Further investigation of hydrogen production system via LCA methodology was recently reported by Susmozas et al. [29]. The authors evaluated the environmental performance of H_2 production via indirect gasification of poplar biomass. They reported that the gasification-derived BioH_2 is generally a promis-