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Development of a mathematical methodology to investigate biohydrogen production from regional and national agricultural crop residues: A case study of Iran

Nooshin Asadi [a,*], Masih Karimi Alavijeh [b], Hamid Zilouei [a,**]

[a] Department of Chemical Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran
[b] Department of Chemical and Petroleum Engineering, Sharif University of Technology, Azadi Avenue, Tehran, Iran

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ABSTRACT

This study aims to construct a quantitative framework to assess biological production of hydrogen from agricultural residues in a country or region. The presented model is able to determine proper crops for biohydrogen production, its possible applications and use as well as environmental aspects. A multiplicative decomposition method was designed to forecast future production and Monte Carlo simulation was employed in the model to evaluate the risk of estimations.

From 2013 to 2050, the hydrogen production capacity could increase from 53.59 to 164.41 kilotonnes (kt) in Iran. The highest contribution to biohydrogen production (52.1% in 2013 and 73.3% in 2050) belongs to cereal crops including wheat, barley, rice and corn and the share of horticultural products including apples, grapes and dates is the lowest (2.7% in 2013 and 2.2% in 2050). For possible variations in the quantity of collectable residue and biohydrogen yield, the production may change in the range of 40.16% and 209.48% of the base value in 2013 and 41.64% and 233.18% of that in 2050. Ammonia production as nitrogen fertilizer and the area could be cultivated by that for each crop were calculated. The amount of natural gas saving and reduction in greenhouse gas (GHG) emissions using biohydrogen were discussed. Development of hydrogen fuel cell vehicles and their impacts on the environment and consequent social costs as well as the quantity of gasoline would be saved were estimated by 2050.

Introduction

Opening the door to modern technologies based on harnessing biomass energy as the third largest primary source of energy in the world [1] has led to a promising perspective to tackle environmental issues and to supply global energy demand. Agricultural residues as one of the major sources of biomass have a heating value of about 12.56 × 10^6 kJ t^{-1} (equivalent to approximately 50% and 33% of that of coal and

* *Corresponding author*. Fax: +98 3133912677.
** *Corresponding author*. Fax: +98 3133912677.
E-mail addresses: nooshin.asadi.che@gmail.com (N. Asadi), hzilouei@cc.iut.ac.ir (H. Zilouei).

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Nomenclature

A	area harvested, ha
a	the lowest value parameter of cumulative probability function
A_{CH_3OH}	quantity of methanol from biohydrogen, t
A_{H_2}	potential amount of produced biohydrogen, kg
$A_{H_2,T}$	total potential amount of produced biohydrogen, kg
A_{NH_3}	quantity of ammonia from biohydrogen, t
b	the most likely value parameter of cumulative probability function
c	the highest value parameter of cumulative probability function
CA	cultivable area by ammonia fertilizer (thousand ha)
C_T	annual production of crop, t
DS_t	deseasonalized series
F_C	field cover factor, t ha^{-1}
F_{CR}	fraction of collectable residue
FE_{CV}	average fuel economy of conventional vehicles, mile l^{-1}
F_{GHG}	amount of GHG emissions by process or end-use vehicles, kg CO_2 eq
F_{H_2}	annually required hydrogen for fueling hydrogen fuel cell vehicles, kg
FE_{HFCV}	average fuel economy of hydrogen fuel cell vehicles, mile kg^{-1} H_2
F_{SCC}	total social cost of carbon, $
F_t	forecast in year, t
h_h	yield of hydrolysis of biopolymers to hexoses
h_p	yield of hydrolysis of biopolymers to pentoses
I_t	irregular component in year t
l_h	loss of hexoses during operation
l_p	loss of pentoses during operation
M	seasonal length
MMA_t	M-step Moving Average
MI	average annual passenger car mileage, mile $vehicle^{-1}$
N_m	number of matching seasonal factors
N_{PC}	total passengers cars
NR	crop nitrogen requirement rate, kg N ha^{-1}
N_S	time-series length
P	cumulative probability
R^2	coefficient of determination
r	portion of total required hydrogen fuel supplied by biohydrogen, %
r_c	cellulose recovery after pretreatment
r_h	hemicellulose recovery after pretreatment
R_C	annual collectable quantity of residue, t
R_M	maximum available residue, t
RPR	residue to product ratio
R_T	annual production of residue, t
SCC	social cost of carbon, $ t^{-1} CO_2 eq
S_{CF}	quantity of conventional fuel saved using hydrogen fuel cell vehicles, l
S_{CH_4}	amount of natural gas could be saved using the total biohydrogen, kg
SF_t	seasonal factor in year, t
SI	seasonal index
SS_R	residual sum of squares
SS_T	total sum of squares
S_t	seasonal component in year t
t	time, year
t_0	first year in time-series data
t_f	last year in time-series data
T_t	trend component in year, t
$WTW_{CF,mi}$	average well-to-wheel GHG emissions factor of conventional vehicles, kg CO_2 eq $mile^{-1}$
WTW_{H_2}	average well-to-wheel GHG emissions factor of biohydrogen production, kg CO_2 eq kg^{-1} H_2
$WTW_{H_{2,mi}}$	average well-to-wheel GHG emissions factor of hydrogen fuel cell vehicles, kg CO_2 eq $mile^{-1}$
x_c	mass fraction of cellulose in native residue
x_h	mass fraction of hemicellulose in native residue
y_h	conversion yield of hexoses to biohydrogen
y_p	conversion yield of pentoses to biohydrogen
Y_C	crop yield, t ha^{-1}
Y_{CH_3OH}	amount of hydrogen required for each tonne of methanol, kg H_2 t^{-1} CH_3OH
Y_{CH_4/H_2}	methane consumption per hydrogen production in a steam reforming process, kg CH_4 kg^{-1} H_2
Y_{H_2}	biohydrogen yield from crop residue, kg t^{-1} residue
Y_{NH_3}	amount of hydrogen required for each tonne of ammonia, kg H_2 t^{-1} NH_3
Y_t	time-series data
α	contribution of hydrogen fuel cell vehicles to passenger car fleet, %
Δ_{GHG}	reduction in GHG emissions, kg CO_2 eq
Δ_{SCC}	reduction in social costs of carbon, $

diesel, respectively) and a fuel value of 1.86×10^6 kJ t^{-1} (equivalent to approximately 6.28×10^6 kJ bbl^{-1} of that of diesel) [2]. In 2011, it was estimated that 11 billion tonnes of agricultural biomass were produced in around the world [3]. Geographical distributions of crop residues are more scattered in comparison to fossil reserves accumulated in limited regions of the world [4]. Owing to the limited amount of fossil fuels, being non-renewable, and greenhouse gases (GHG) emissions, extensive efforts are underway to exploit and manage biomass energy in many different countries. In the United States from 2000 to 2015, the production of this energy increased about 61% and in 2015, it accounted for 46.56% of total renewable energy and 5.64% of the total US primary energy production [5]. From 2004 to 2014, the biofuels production was increased from 2035 to 11,683 million tonnes of oil equivalent (Mtoe) in Europe and Eurasia, 6488 to 31 252 Mtoe in North America, 7311 to 20,294 Mtoe in South and Center America and, overall, 16,445 to 70,792 in the world [6]. In

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