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A life cycle assessment of pennycress (*Thlaspi arvense L.*) -derived jet fuel and diesel

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ABSTRACT

Field Pennycress (*Thlaspi arvense L.*) is a member of the mustard family and may be grown as a winter crop between traditional summer crops to produce renewable biomass for renewable diesel and jet fuel. This paper estimated total annual biofuel production potential of 15 million cubic metres from rotation between corn and soybeans on 16.2 million hectares in the Midwest without impact on food production. This study also investigated the life cycle greenhouse gas (GHG) emissions and energy balance of pennycress-derived Hydroprocessed Renewable Jet (HRJ) fuel and Renewable Diesel (RD). Both system expansion and allocation approaches were applied to distribute environmental impacts among products and co-products along the life cycle of each biofuel. The life cycle GHG emissions (excluding land use change) for RD and HRJ range from 13 to 41 g MJ^{-1} (CO_2 eq.) and −18 to 45 g MJ^{-1} (CO_2 eq.), respectively, depending on how the co-products are credited. The majority of the energy required for each biofuel product is derived from renewable biomass as opposed to non renewable fossil. The fossil energy consumptions are considerably lower than the petroleum fuels. Scenario analyses were also conducted to determine response to model assumptions, including nitrogen fertilizer application rate, nitrogen content in crop residues, and sources of H_2. The results show that pennycress derived biofuels could qualify as advanced biofuels and as biomass-based diesel as defined by the Renewable Fuels Standard (RFS2).

1. Introduction

1.1. Sustainable energy and transportation biofuels

The United States consumed 99.8 EJ of energy in 2009, of which almost forty percent was provided by petroleum [1]. Petroleum also serves as the dominant energy source for transportation sector, which was responsible for approximately 30% of total energy demand [1]. The current reliance almost exclusively on resources that will eventually be depleted is also another motivation to develop renewable forms of energy. In addition, domestic renewable energy can lower the trade deficit, help

Abbreviations: AITC, 2-propenyl allyl isothiocyanate (CAS 57-06-7); ATC, Allyl thiocyanate (CAS 764-49-8); CED, cumulative energy demand; dLUC, direct land use change; EA, energy allocation; EISA, Energy Independence and Security Act; FAME, fatty acid methyl esters; FED, fossil energy demand; GHG, greenhouse gas; GWP, global warming potentials; HRJ, hydroprocessed renewable jet; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; LCFS, Low Carbon Fuels Standard; LHV, lower heating value; LPG, liquefied petroleum gas; LUC, land use change; iLUC, indirect land use change; MVA, market value allocation; RD, renewable diesel; RFS, Renewable Fuels Standard; SMR, steam methane reforming; SPK, synthetic paraffinic kerosene; OZT, Oxazolidene-2-thione (CAS 5840-81-3).

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generate jobs and revenues [2], and reduce greenhouse gas (GHG) emissions [3]. Because of the strategic, economic, social and environmental benefits of biofuels compared to petroleum, the United States government has been promoting research leading to the increased use of biofuels. The Energy Independence and Security Act of 2007 (EISA) mandates the use of 136 million cubic metres of renewable transportation fuel by 2022 [4]. The European Emissions Trading Scheme (ETS) is also encouraging the international production of renewable jet fuel [5]. ASTM D7566 was approved on July 1st 2011, which allows blending of hydroprocessed renewable jet fuel (HRJ) (also referred to as SPK (synthetic paraffinic kerosene) from Hydroprocessed Esters and Fatty Acids, HEFA) up to 50% (volume fraction) with D1655 jet fuels [6], thus facilitating a commercial pathway to sustainable aviation fuels.

1.2. Field pennycress as an energy crop

Field Pennycress (*Thalaspi arvense L.*) is a winter annual native to Eurasia and now widely distributed throughout temperate North America [7]. It germinates in the fall and forms its early vegetative stage characterized by a low-growing rosette that protects it from low temperatures and drying winds as it overwinters. The plant flowers in the spring, sets seeds and is harvested before typical summer crops (soybean) are planted. Thus, it has the potential to be grown as a winter crop between traditional summer crops to produce renewable biomass for fuel production [8]. Pennycress is a prolific seed producer, with seed yields of 1.5 Mg ha^{-1} from test plots in North Dakota having been reported [9]. In Illinois, Isbell reported that wild type strains planted in prepared ground resulted in seed yields of 900 kg ha^{-1} to over 2352 kg ha^{-1} [10]. Current commercial strains with genetically improved research lines are now exceeding 2463 kg ha^{-1} [11] indicating that higher yields are possible. The harvested pennycress seeds contain oil up to a mass fraction of 36% of the seed, nearly twice the amount as soybeans [12] and comparable to other high yield oil producing plants such as camelina [13]. This high oil content (similar to other commercial renewable oils) and fatty acid profile (high contents of unsaturated fatty acids as shown in Table 1) make pennycress oil acceptable for biodiesel production [14] and a potentially attractive feedstock for conversion to drop-in hydrocarbon fuels. As useful applications for pennycress meal develop, the oil is a candidate to become a sustainable alternative for advanced biofuels production. The remaining de-oiled presscake has an inherently high energy content of 22.2 MJ kg^{-1}dry basis [12], suitable for direct combustion or gasification for energy production. The presscake has also been demonstrated to produce a uniquely stable bio-oil when subjected to thermochemical conversion using fast pyrolysis [12]. While traditionally considered unsuitable for animal feed due to the presence of glucosinolates [14,15], pennycress presscake contains only sinigrin which is present in several other food plants such as horseradish and brown mustard [16]. Sinigrin has little or no biological activity [17], but there is concern that enzymatic hydrolysis by myrosinase could produce the toxic compound 2-propenyl allyl isothiocyanate (AITC). However, temperatures produced in seed crushing denature myrosinase preventing AITC formation and by extension oxazolidene-2-thione (OZTs) known to cause nutritional problems in animals (Vaughn SF, USDA, personal comunication July 20, 2011). Majak et al. [18] considered the potential that glucosinolate hydrolysis by microorganisms of the rumen could produce AITC or allyl thiocyanate (ATC) in the absence of plant derived myrosinase. Sinigrin incubated for 2–6 h in bovine rumen fluid did not release detectable amounts of AITC or ATC. The authors [18] conclude that the sinigrin aglycone can only be generated by specific thioglucosidases of plant origin. In animal feeding studies, Shires [19] concludes that pennycress seeds cooked and extracted can be feed at relatively high levels without appreciable risk associated with glucosinoates. In fact, pennycress seed meal with its beneficial crude protein content of 31% [20] has been fed successfully to sheep [21]. The meal is also considered as animal feed by one group of Canadian researchers in their pennycress biorefinery strategy [22].

Table 1 – Fatty acid profile (mass fraction) of field pennycress oil, camelina oil and jatropha oil.

Fatty acid composition[a]	Field pennycress oil (%) [14]	Camelina oil (%) [23]	Jatropha oil (%) [24]
C14:0	0.1	0.1	0-0.1
C16:0	3.1	6.8	14.1-15.3
C16:1 9c	0.2	Trace	0-1.3
C18:0	0.5	2.7	3.7-9.8
C18:1 9c	11.1	18.6	34.3-45.8
C18:1 11c	1.5	1.1	
C18:2 9c 12c	22.4	19.6	29-44.2
C18:3 9c 12c 15c	11.8	32.6	
C20:0	0.3	1.5	0-0.3
C20:1 11c	8.6	12.4	
C20:2 11c 14c	1.6	1.3	
C22:0	0.6	0.2	0-0.2
C22:1 13c	32.8	2.3	
C22:2 13c 16c	0.7		
C22:3 13c 16c 19c	0.3		
C24:1 15c	2.9	Trace	

a for example, C18:1 9c means an 18 carbon fatty acid chain with one double bond located at carbon 9.

Field pennycress has a relatively early harvest date compared to other winter annual oil seed crops, which makes a two-crop rotation with soybean possible [25]. It is currently proposed to be grown as a winter annual in the Midwest (Zone 5A, 5B and 6A in Fig. 1) on unused land following the corn harvest and prior to the spring planting of soybeans. This means that farmers can continue to grow corn and soybeans in the traditional way but add this new crop in the winter allowing them to earn additional income with underutilized land and equipment assets. Approximately 16.2 million ha of land are available each year for the winter production of pennycress [26] under this strategy with no impact to the food supply or critical wildlife habitats. As an energy crop, pennycress has the potential to produce approximately 15 million cubic metres of liquid transportation fuels per year [27] while providing farmers with 4 billion US dollars($4*$10^9$) in extra revenue and creating 23,000 new jobs [26]. The pennycress cultivation strategy being implemented by the farmers across Illinois and the surrounding area is shown in the Fig. 2.

Western Illinois University [29] has conducted preliminary field trials examining the impact of the presence or absence of

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