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Research paper

Technoeconomic analysis of camelina oil extraction as feedstock for biojet fuel in the Canadian Prairies

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ABSTRACT

This study presents a technoeconomic analysis of commercial extraction of camelina oil as an aviation fuel feedstock. An engineering economic model was designed in Superpro Designer® to quantify capital investment, scale, production cost, and profitability for a 120,000–1,500,000 tonnes annum^{-1} solvent extraction plant. The corresponding estimated capital investment was $24.7 - $155 million. Feedstock cost ($0.29–0.40 kg^{-1}), seed yield (1400–2100 kg ha^{-1}), oil content (38–47%), scale, and camelina meal revenue are key factors in the break-even selling price (BESP) and competitiveness of camelina oil as a feedstock. Feedstock represented 81–90% of operating cost. The BESP ranges from $0.43 -$1.22 L^{-1}. Larger plants have lower BESP compared to smaller plants which require higher breakeven prices. This suggests better economies of scale associated with higher plant scale. Camelina can be introduced into underutilized summerfallow land of semiarid Canadian Prairies of Saskatchewan. Swift Current is an ideal extraction plant location. These results can guide R&D and investment decisions for advancing camelina as an industrial feedstock within the innovation value chain.
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1. Introduction

There is significant public sector interest in Canada aimed at the development and commercialization of *Camelina sativa* (L.) Crantz, Brassicaceae ("camelina") as a dedicated biorefinery feedstock for production of high value bioproducts [1–5]. In fact, there is global interest in the development of camelina as a feedstock for the production of renewable aviation fuels such as hydroprocessed esters and fatty acids (HEFA) as demonstrated by the recent Federal Aviation Authority (FAA) certification of camelina derived aviation fuels [6]. This has been accompanied by industry level commercialization interest, including test flights by several of the world's major airlines, aircraft manufacturers, fuel developers and suppliers; coupled with memorandum of understanding between 14 major airlines to purchase camelina derived renewable jet fuel and diesel from potential feedstock suppliers [7]. A key driver relates to significant environmental concerns vis-à-vis the use of conventional jet fuel, a multi-component hydrocarbon fuel associated with significant rising levels of greenhouse gas (GHG) emissions [8]. A recent forecast by the International Civil Aviation Organization estimates an increase in global international aviation emissions by 300–700% by 2050 [9]. In Canada, GHG emissions from aviation increased from 11.80 million tonnes of CO_2-equivalent in 1990 to 15.57 million tonnes in 2011, representing a 31.9% increase over this period.

Consequently, the aviation sector has established goals to reduce GHG emissions and the aviation carbon footprint [10], including a global approach by the International Air Transport Association (IATA) to reduce GHG emissions by 50% by 2050 compared to 2005 levels. In this regard, camelina has been recognized as a feedstock for biojet fuel because of its potential to reduce the carbon footprint, as demonstrated in recent studies in Canada and the US showing that camelina-based biojet fuel reduces CO_2 emissions by 75–85% compared to traditional petroleum-based jet [10–12]. The commercial interest in camelina by the aviation industry is further spurred by legislated limits placed on the use of

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food-grown crops such as soybean, palm oil, and canola for biofuel production in large markets such the EU [13,14]. In particular, the EU's Renewable Energy Directive (RED) implemented in 2010 sets forth targets for the EU to achieve a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector [15]. Under RED, the EU has also limited biofuel production from food crops (e.g., soybean, canola, palm oil) to 7%. These major food crops account for over 90% of biodiesel feedstocks in major biodiesel producing regions such as Europe, US, Canada, and Brazil. This means dedicated non-food crops like camelina will play an increasingly important role in meeting increased demand for aviation fuel. In Europe, an EU-funded project called Initiative Towards sustAinable Kerosene for Aviation (ITAKA), targets camelina as the best sustainable feedstock converted into drop-in aviation fuel through the HEFA (Hydro-processed esters and fatty acids) pathway [16]. ITAKA is the mechanism for the implementation of the EU's European Industrial Bioenergy Initiative (EIBI), a key component of the EU Flight Path target of 2 million tonnes of sustainable biofuels used in European civil aviation by 2020 [14,17,18]. Clearly, these events, along with successful test flights (commercial and military) by a wide range of airlines (e.g. Japan Airlines, KLM, Lufthansa) and the US military using camelina biojet fuel [19] represent significant market pull for the development of camelina as dedicated feedstock for this sector.

In this regard, the Canadian Prairie province of Saskatchewan has been targeted as a potential supplier of camelina feedstocks. The opportunity includes growing camelina and crushing the seed in the province, and subsequently shipping the crude oil to key markets to meet increasing demand for camelina oil as a feedstock for aviation fuel. Camelina has agronomic advantages which favour arid regions of the Canadian prairies, in particular, Saskatchewan [2]. Camelina is a broadleaf oilseed flowering plant of the *Brassicaceae* family (canola, rapeseed, mustard, and crambe). Its agronomic advantages for commercial production include: short growth cycle and early maturity; low input requirements (e.g. water, nitrogen, and other nutrients); high adaptability to adverse environmental conditions due to its high tolerance to cold temperature and drought conditions; resistance to common crucifer pathogens and pests [2,4,20,21]. In addition, camelina also possesses several important fatty acid attributes. It has high seed oil content of 38–45% in Canada (twice the oil content of soybean (18–22%) [2,5,20] and over 90% unsaturated fatty acids, significant amounts of linolenic acid (30–40%) [22], low erucic acid (C22:1) content (3–4%) [23]; and low glucosinolate content (13–36 μmol g^{-1} dry seed) in the seed meal relative to other crucifers [24]. These attributes make camelina an ideal non-food biorefinery feedstock for industrial applications (jet fuel, biodiesel, and lubricants) and animal feed (poultry, swine and ruminants). In terms of animal feed, camelina meal has high protein content of around 400 g kg^{-1} similar to that of canola meal [25]. The application of camelina meal protein has been demonstrated in poultry, fish, and dairy cattle, based on its abundance in arginine, cysteine, lysine, methionine, and threonine amino acids [26–28]. In 2009, the US Food and Drug Administration (FDA) approved the use of camelina meal in diets of feedlot beef and broiler chicken up to 10% of the weight of total ration. The application of camelina meal in animal feed was approved in Europe by Act [EU] No. 575 in 2011. In 2015, the Canadian Food Inspection Agency (CFIA) approved cold-pressed non-solvent extracted camelina meal as a feed for boiler chickens at up to 12% inclusion. Overall, in terms of its on-farm adoption, camelina offers farmers in the marginal arid region a viable rotation-crop option and the potential to eliminate nearly one million hectares of summerfallow in the arid region of the Canadian prairies, representing a positive land use change, as discussed in more detail in Section 2 of this paper.

In spite of these prospects, the development of a camelina feedstock-based biorefinery concept in the Canadian Prairies of Saskatchewan requires significant investment in logistics and infrastructure in order to respond to market-pull demand within the context of a camelina value-chain. In various engagements between AAFC camelina researchers and the bio-jet fuel industry, feedstock cost has been identified as a significant constraining factor in the technoeconomics of biojet fuel production because feedstock accounts for a very high proportion of processing cost, thereby representing a significant market-pull constraint to the development of an integrated feedstock supply chain. In this sense, characterizing the configuration of Saskatchewan camelina oil extraction infrastructure is an important first step in developing viable business models for guiding research and development (R&D) and investment decisions. Hence, the overall objective of this study is to assess the technoeconomics and business case for establishing a camelina oilseed crushing plant in Saskatchewan as part of the infrastructure required to support the development of a camelina feedstock supply chain for the production of camelina oil as a dedicated feedstock to jet fuel production.

2. Methods

2.1. Location of camelina oilseed production

In terms of agronomic adaptation, AAFC breeders are targeting camelina to the arid Brown soil zone of Saskatchewan, which includes major locations such as Swift Current [29,30]. Saskatchewan accounts for over 40% of Canada's 67.5 million ha of farmland [31], and produces 85% of Canada's durum wheat, 74% of mustard, and 50% of canola [32], making it a major adopter of agricultural technologies. Overall the Prairie Provinces (Alberta, Manitoba, and Saskatchewan) account for 82% of Canada's farm land [31]. Camelina is still in the early phase of adoption, with adoption expected to be ramped up over the next few years as an integral part of the crop's R&D innovation chain.

The Prairie region typically characterizes production regions in terms of soil zones which correspond to variability in soil texture. The five distinct soil zones (with their crop reporting numbers in parenthesis and elucidated further in Section 2.2.3) are: Brown (3AN, 3BN, 3BS, 4A, 4B, 7A); Dark Brown (2A, 2B, 6A, 6B, 7B); Black (1A, 1B, 5A); Dark Gray (9A, 9B); and Gray (8A). Production capabilities are different and influenced by the presence of organic matter and weather conditions. The Brown soil zone comprises 6.3 million ha and is mostly situated in the southwest of the province, with approximately 70% cultivated. This region is typified by relatively warm temperature, low moisture (average 150 mm), and organic matter (20 g kg^{-1}, an attribute of marginal or nutrient deficient soils). This has restricted agricultural activities to small grains and grass pastures for livestock. By contrast, the Dark Brown soil zone, located on the northern and eastern side of the Brown soil zone, is typified by clay soils (30 g kg^{-1} organic matter), making it the most intensively cultivated zone, with nearly 82% of the areas under cropping. Above the Dark Brown soil zone lie the Black, Gray and Dark Gray soil zones whose soils have an even much higher (over 60%) organic matter content. Approximately 73% of its 7.52 million ha is cultivated, and is characterized by cooler temperature and high moisture, enabling farmers to adopt more diverse cropping choices, but with a much shorter growing season.

2.2. Camelina yield and production cost

2.2.1. Camelina seed and oil yield

Earlier studies in Saskatchewan by AAFC researchers [2] showed that camelina yields are comparable to other Brassica species such

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