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Integrated bioethanol production from triticale grain and lignocellulosic straw in Western Canada

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ABSTRACT

Triticale is an emerging bioenergy crop in Canada, with potential as a feedstock for the production of ethanol and co-products from both its grain and straw. This study evaluates the commercial potential of introducing triticale as an industrial feedstock crop in the Brown agroecological soil zone of the Canadian Prairies, a semi-arid area which accounts for the highest share of underutilized summerfallow in the region. The study approach includes determination of location parameters (potential triticale land area, feedstock collection radius, and transportation distance), on-farm triticale yield, on-farm production cost, and feedstock chemical composition. Subsequently, SuperPro® Designer was used to develop and simulate two processes using both grain and straw: a) integrated process that ferments both pentose and hexose (Process I); b) single process involving fermentation of hexose sugars only, while pentose sugar is diverted for biogas production and then combined with lignin for power generation (Process II). Triticale on-farm yield is analyzed for the range 5.1–6.8 t ha^{-1} (which corresponds to 74–126 thousand ha of triticale area). Triticale on-farm production cost is \$473 ha^{-1} with corresponding on-farm profit of \$570–\$1150 ha^{-1} from grain and straw sale. The integrated grain and straw processing model is developed and simulated for a 200–550 million L $annum^{-1}$ ethanol biorefinery, with corresponding total capital investment cost of \$140–\$240 million. Fermenting both grain and straw and using hydrothermal pretreatment for straw resulted a lower equipment purchase cost per litre of ethanol (\$0.12–\$0.14 L^{-1}) compared with cellulosic ethanol production using other pretreatment methods (\$0.60–\$1.24 L^{-1}). The process involving fermentation of both pentose and hexose (Process I) is more profitable compared with a hexose-only process (Process II). Ethanol selling price, plant capacity, and feedstock cost all have high impact on net present value. All plants generate negative net present value at ethanol prices of \$0.60 L^{-1} or less, while a price of at least \$0.80 L^{-1} is required for plants with capacity higher than 250 million L to generate positive net present value. This study provides a basis for further articulation of Canada's triticale biorefinery concept beyond the near-term goal of producing ethanol, namely, sustainable production of a wide array of bioproducts (bioenergy, biofuels, biomaterials, biochemicals, and biologics) to enhance the profitability of the triticale biorefinery and contribute to Canada's environmental goals for a bio-based economy.

1. Introduction

Triticale (×*Triticosecale*) is being developed as Canada's industrial cereal crop and biorefinery feedstock in the context of the government's clean energy and bioproduct strategies for agri-based feedstocks that minimize competition with food and livestock feed use (AAFC, 2014). Triticale could support near term goals for sustainable production of ethanol currently dominated by food crop feedstocks such as wheat (*Triticum aestivum*) and corn (*Zea mays*). It could also contribute to the attainment of environmental targets for abating greenhouse gas (GHG) emissions from fossil fuels, especially from the transportation sector which is Canada's second largest contributor of GHG emissions (after the oil and gas sector), accounting for 23% of total national emissions (Environment and Climate Change Canada, 2011, 2016).

Within this context, triticale has several advantages. First, it is a non-food crop and hence would directly substitute current uses of corn and wheat for ethanol and co-product production. Second, Canadian breeding and agronomic research to advance this crop (Beauchet et al.,

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2013; Beres et al., 2013a; Beres et al., 2013b; Collier et al., 2013; Goyal et al., 2011; McKenzie et al., 2014; McKenzie et al., 2007) has demonstrated triticale's agronomic attributes including low grain protein concentration and high grain and biomass yield compared with wheat and other cereals in western Canada, desirable traits in biorefinery processes that currently utilize wheat as feedstock (Beres et al., 2010; Goyal et al., 2011). Its higher yield relative to Canadian wheat varieties provides greater competitiveness with weeds (Beres et al., 2010), while other research has demonstrated that triticale has resistance to biotic and abiotic stresses including drought and pest tolerance compared with wheat and other widely grown cereals in Canada (Beres et al., 2010; Goyal et al., 2011; McKenzie et al., 2014). Globally, triticale is an established crop. World triticale production for 2016 was 15.2 million tonnes, an increase from 13.7 million in 2012 (FAOSTAT, 2018). Triticale is cultivated in over 30 countries, with Poland, Germany, Belarus, France, and the Russian Federation representing the top five producers, accounting for almost 80% of world production. Canada's 2016 triticale production was 54 thousand tonnes, an increase from 24 thousand in 2015. Although this is less than 1% of world production, the increase reflects current Canadian sector initiatives to advance triticale as a dedicated industrial feedstock for supplying both grain and straw for biorefinery applications. The triticale straw to grain ratio is approximately one (Li et al., 2012). Hence, in general, 15.2 million tonnes of triticale grain production yield approximately an equivalent amount of straw. The estimation of straw production by region requires parameters specific to a given geographic location (Li et al., 2012). In the Canadian Prairies where grain production is dominant, straw availability is typically estimated at 52% of total grain production, taking into account biomass retained on the field for soil conservation as well as loss during handling and storage, as demonstrated by Dassanayake and Kumar (2012).

Recently, Beres et al. (2013a) conducted a study to benchmark the relative performance of triticale versus wheat classes utilized for ethanol production, while McLeod et al. (2010) analysed changes in ethanol production potential due to species, cultivar, and location on the Canadian prairies, demonstrating the potential of triticale as a feedstock for ethanol production. Significant research by Agriculture and Agri-Food Canada (AAFC) and collaborators has advanced triticale as an ethanol crop through the development of varieties such as Sunray and Brevis which possess higher starch content hence higher suitability for ethanol production (Beres et al., 2012; McLeod et al., 2012). Triticale is also considered to provide agronomic and environmental benefits due to its suitability for semiarid marginal farming regions of the western prairie agroecological zone (McKenzie et al., 2014). This suggests that non-traditional small grains such as triticale have potential to be introduced in these semiarid regions covering over 2 million ha based on available hectares that are not in competition with land required for the production of food grains and oilseeds (Gan et al., 2012; Smith et al., 2016; Zentner et al., 2001).

Triticale also represents potential for the dual use of its straw in an integrated ethanol plant to contribute even further to ethanol output in a sustainable way. Studies show that triticale's high grain yield also generates over 30% more straw per hectare compared with wheat and barley (*Hordeum vulgare*), and that triticale cultivars with higher straw yield can be selected without compromising grain yield (Beres et al., 2013a; Beres et al., 2013b; Goyal et al., 2011; Larsen et al., 2012). Triticale straw provides a valuable second-generation (2G) (cellulosic biomass) feedstock that would support further development of 2G technologies on the Prairies. From an investor vantage point, over 90% of ethanol plants in Canada as shown in Table 1 (Renewable Industries Canada, 2016) are first generation (1G) technologies. These 1G technologies have lower capital costs and simpler processes (grain grinding, starch separation, and saccharification) in comparison with 2G technologies that require more complex capital intensive processes to pretreat the recalcitrant lignocellulosic biomass (Baeyens et al., 2015; Mupondwa et al., 2017a; Mupondwa et al., 2017b; Solomon et al., 2007; Tao et al., 2011) and large-scale operations with typical capacities of more than 150 million litres (L) year^{-1} and initial investment outlays of over $200 million (Eggeman and Elander, 2005; Gnansounou and Dauriat, 2010; Kaylen et al., 2000; Kazi et al., 2010).

It has therefore been suggested that an integration of 1G and 2G feedstocks provides viable options for reducing overall downstream ethanol production costs while facilitating the evolution of 2G cellulosic biorefinery concepts, through the incorporation a sugar-rich stream from grain and a higher ethanol concentration (Erdei et al., 2010; Joelsson et al., 2016). In fact, the triticale biorefinery concept as promoted by AAFC includes the optimization of the crop to produce biopolymers, biochemicals, and bioenergy (AAFC, 2014) through genomics as well as development of fractionation technologies to optimize the production of a diverse set of monosaccharides, oligosaccharides, lignins, and other high-value compounds from DDGS such as sterols, phenolic compounds, and β–glucan (Badea et al., 2011; Beauchet et al., 2013; Diedhiou et al., 2012; Eudes, 2015; Gibreel et al., 2011; Hills et al., 2007; Hosseinian and Mazza, 2009; Laroche et al., 2015; Pronyk and Mazza, 2010, 2011, 2012; Pronyk et al., 2011; Ross et al., 2012; Ton-That and Li, 2015; Wierenga et al., 2010; Xu et al., 2011; Zaidi et al., 2012). For instance, Pronyk and Mazza (2012) used hydrothermal processing to fractionate triticale straw and recover cellulose and other extracts rich in oligo-saccharides which potentially contain more acetyl and uronic substituents for high-value food applications as prebiotic compounds. Other research being investigated as part of AAFC's Canadian Triticale Biorefinery Initiative explored triticale starch vis-à-vis its thermoplastic properties for the development of triticale starch-based materials with improved properties, including the manufacture of 100% biobased blown film within the triticale biorefinery concept (Li et al., 2011). Mihai and Ton-That (2017) explored novel polylactide triticale straw biocomposites and showed that triticale straw acts as a good reinforcement in thermoplastic composite applications in construction, common goods, and transportation industries. Other related research under the same network includes Abokitse et al. (2010) who explored potential for the bioproduction of ferulic acid from triticale bran. Ferulic acid has been identified as one of the two top aromatic acid building blocks from lignocellulosic biomass (Dodds and Gross, 2007; Werpy et al., 2004). It is best recognized as an antioxidant in food preservation and active ingredient in cosmetics (Ou and Kwok, 2004). Ferulic acid can also be enzymatically converted to other value-added products including vinyl guaiacol and vanillin, well known as flavouring agents in foods, beverages, or perfumes (Mathew and Abraham, 2006).

In spite of triticale's demonstrated potential as a dedicated bioenergy crop, there are no studies that provide an ex ante analysis of the potential integration of triticale into Canada's industrial feedstock crop supply chain. A majority of studies have provided valuable insights in terms of stand-alone ethanol production platforms from feedstocks such as corn/wheat starch (Kwiatkowski et al., 2006; Lin et al., 2011; Wood et al., 2014), sugarcane (Huang et al., 2016; Khatiwada et al., 2016), corn stover (Aden and Foust, 2009; Aden et al., 2002), and crop residues (Kumar and Murthy, 2011), with the exception of recent studies such as Erdei et al. (2010) that have integrated technoeconomic analysis of ethanol production from both the grain substrate and straw substrate (in the context of wheat). The objective of this study is to provide an ex ante analysis of the potential integration of triticale into Canada's industrial feedstock crop supply chain, based on integrated use of triticale grain and straw to advance the triticale biorefinery in a rural western Canadian region. These ex ante results are important in the context of AAFC research and Canada's clean energy/bioproducts strategy within the biorefinery concept in providing information that can be contemporaneously used to facilitate go-no-go decisions, re-design of R&D, and commercialization strategies at various stages in the triticale innovation chain. This case study of triticale also further illustrates the need to formalize the link between agriculture and the agricultural biomass-to-biorefinery concept for the production of