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Comparison of pyrolysis and hydrolysis processes for furfural production from sugar beet pulp: A case study in southern Idaho, USA

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ABSTRACT

Furfural is an organic compound that is widely used in the chemical industry for manufacturing various products, such as pharmaceuticals, pesticides, and solvents. Furfural production from biomass feedstocks can be achieved through various conversion pathways (e.g., pyrolysis or hydrolysis), however, it requires further investigation to reduce the total cost and meet the market needs. This study proposes a multi-objective decision making framework to compare techno-economic and environmental aspects of pyrolysis and hydrolysis technologies for furfural production from sugar beet pulp. Life cycle assessment method is applied for investigating the environmental impacts of converting organic materials to intermediate bioproducts (e.g., bio-oil) on-site, near collection area, using a portable refinery unit. The techno-economic assessment employs an optimization model for minimizing the upstream and midstream costs (e.g., collection, transportation, and production). Sustainability assessments are conducted on a real case study in southern Idaho, USA, to evaluate and verify the methodology and demonstrate the application of this study. The results show that the total cost for furfural production, using pyrolysis and hydrolysis, are approximately $846 and $980 per metric ton, and total emission is 267 and 1095 kg CO_2 eq. per metric ton, respectively. Therefore, the pyrolysis pathway results in lower emissions and costs due to the high-water demand and low energy-density feedstock transportation associated with the hydrolysis pathway. It is concluded that portable operations near collection sites can reduce the total costs and emissions, and consequently stimulate sustainable furfural production by addressing upstream and midstream challenges.

1. Introduction

1.1. Motivation and challenges

Furfural has a myriad of industrial uses (e.g., solvents and precursor chemicals) in various sectors (e.g., healthcare and basic materials) (Chandel et al., 2018); however, the major challenge is the low production process yield, which subsequently increases the production cost (Nhien et al., 2016; Yemiş and Mazza, 2017). Mariscal et al. (2016) provided an in-depth overview of the state of the furfural industry, including discussions of the chemistry and multiple production techniques, reporting that the price of furfural can be approximately $1500 per ton. Furfural is a platform chemical, with a carbonyl function group and a furan ring, which can be used directly or indirectly to make over 80 chemicals and fuels (Rodríguez Montaña et al., 2020). In 2019, global furfural production was a $551 million (USD) industry, and is projected to be worth over $700 million by 2024 (Rodríguez Montaña et al., 2020). Furfural can be produced from 5-carbon sugars known as pentoses (Chandel et al., 2018). The wide range of products from furfural makes it a chemical of interest for not only the energy industry, but also agrochemical and pharmaceutical manufacturing. Furfural can be synthesized from petrochemical sources, but it can be friendly to the environment, using renewable resources, such as sugar beet pulp (SBP). The major cost-driver for furfural production from biomass feedstocks is midstream operations, including conversion and upgrading processes (Mariscal et al., 2016). Particularly, the conversion of lignocellulose to green chemical products is hampered by immature, underdeveloped technology (Chandel et al., 2018), which can render petrochemical

Abbreviations: GHG, greenhouse gas; GWP100, 100-year global warming potential; LCA, life cycle assessment; RMCGP, revised multi-choice goal programming; SBP, sugar beet pulp; TC, total cost; TEA, techno-economic assessment; TGHG, total GHG emissions.

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technologies more cost-effective than biomass processing technologies (Hansen and Mirkouei, 2018, 2019). In addition to midstream operations, extra upstream required steps (e.g., harvesting, collection, and transportation of low energy density feedstocks) can increase the total cost for green chemical production (Erickson et al., 2011; Mirkouei et al., 2016).

1.2. Background

Furfural production from xylose (wood sugar) was pioneered by the Quaker Oat company in the 1920s. The process used by Quaker treated oat hulls with dilute sulfuric acid (H_2SO_4) to increase the process yield of furfural production (Binder et al., 2010). In 2013, it was reported that about 98% of furfural produced from feedstocks were sourced from either corncobs or bagasse (Cai et al., 2013), owing to the relative abundance, low cost, and high pentosan content of these materials. Pentosan is a five-carbon polysaccharide found in lignocellulose, which is especially conducive to furfural production. Wheat straw can be used to generate furfural (Liu et al., 2014), and there has been promising research on the use of water hyacinth (*Eichhornia crassipes*), which is rich in pentosan and has high water content (Poomsawat et al., 2019). Tomaszewska et al. (2018) identified SBP as an increasingly promising material for furfural production, citing improving market conditions. Table 1 provides a comprehensive classification of recent research studies on furfural production from various biomass feedstocks, considering at least one of the following factors conducted in this study:

- Environmental assessment. Earlier studies have conducted environmental impact assessments of furfural production from different feedstocks, such as wood and oat hulls (Binder et al., 2010), corncob and bagasse (Nhien et al., 2016), and Baru (Dipteryx alata) residue (Rambo et al., 2020). Binder et al. (2010) suggested furfural produced from xylose as an alternative to petrochemicals for reducing the environmental impacts. They also studied the use of Lewis acids to improve furfural yields. Nhien et al. (2016) studied furfural production from corncob and bagasse, using hydrolysis, and reported that environmental and economic objectives are not mutually exclusive, and the optimization of heat integration and process intensity can fulfill both aspects. Rambo et al. (2020) studied the sustainability of furfural production from Baru residues, using pyrolysis technology, reporting that Baru could be a good source for furfural production due to high process yield and low moisture content.
- Techno-economic assessment (TEA). Several studies have conducted cost analysis for furfural production from biomass feedstocks in the Netherlands (Kühnel et al., 2011), South Korea (Nhien et al., 2016), India (Chandel et al., 2018), and Argentina (Casoni et al., 2018). Kühnel et al. (2011) reported that biochemical processing of SBP for furfural production could be economically viable. Silva et al. (2017) performed an economic analysis on furfural production from sugarcane bagasse, using a Rosenlew reactor, which had lower energy demands than conventional distillation processes. Casoni et al. (2018) conducted a techno-economic study for furfural production from sunflower seed hulls, and found that the price of levoglucosenone, a co-product of furfural during pyrolysis reactions, was the key variable in determining profitability. Chandel et al. (2018) studied lignocellulose biorefinery technologies, including furfural production from agricultural and forestry residues. They resulted that the furfural industry is in a nascent stage, requiring further technological advancements to be truly economically viable. Gómez Millán et al. (2020) performed a TEA for furfural production using hydrolysis technology, and reported a 5-year return on investment.
- Pyrolysis process. Pyrolysis is a thermochemical process for converting biomass to intermediate products (i.e., pyrolysis oil, char, and gas) in the absence of oxygen under 400–600 °C and 15–20 psi (Hersh and Mirkouei, 2019; Struhs et al., 2020, 2021). One of the main parameters for cost reduction is conversion processes yield, and

Table 2
List of sugar beet processing facilities in southern Idaho (Amalgamated Sugar, 2020).

Address	Sugar Beet Processed Daily U.S. tons (metric tons)
50 S 500 W, Paul, ID, 83347	17,000 (15,419)
138 W Karcher Rd, Nampa, ID, 83687	12,000 (10,884)
2320 Orchard Dr. E, Twin Falls, ID 83301	6800 (6168)

Table 1
Recent economic and environmental studies on furfural production from biomass feedstocks.

Study	Objectives		Product	Technology		Resource	Method	Case Study
	1	2	Furfural	3	4			
Binder et al. (2010)	✓	×	✓	×	✓	Wood & oat hulls	Experimental	×
Kühnel et al. (2011)	×	✓	✓	×	✓	SBP	Experimental	×
Mao et al. (2012)	×	×	✓	×	✓	Corn cobs	Experimental	×
Liu et al. (2014)	×	×	✓	×	✓	Wheat straw	Experimental	×
Nhien et al. (2016)	✓	✓	✓	×	✓	Corn cob & bagasse	HYSYS model	×
Wang et al. (2016)	✓	×	✓	✓	×	Corn Stalk	LCA	✓
Mariscal et al. (2016)	×	×	✓	×	×	–	Overview	×
Kamzon and Abderafi (2017)	×	×	✓	×	✓	SBP & bagasse	COFE model	✓
Silva et al. (2017)	×	✓	✓	×	×	Bagasse	TEA	✓
Chandel et al. (2018)	×	✓	✓	✓	×	Forest/agricultural residues	TEA	✓
Kim et al. (2019)	✓	×	✓	✓	×	Goat excreta	Experimental	✓
Poomsawat et al. (2019)	×	×	✓	×	✓	Water hyacinth	Experimental	×
Cieciura-Włoch et al. (2019)	×	×	✓	×	✓	SBP	Experimental	×
Hossain et al. (2019)	×	✓	✓	✓	×	Corn Stover	TEA	×
Cao et al. (2020)	×	×	✓	✓	×	Corn husks	Experimental	×
Rodríguez Montaña et al. (2020)	×	×	✓	×	×	–	Review	×
Rambo et al. (2020)	✓	×	✓	×	✓	Baru	Experimental	×
Gómez Millán et al. (2020)	×	✓	✓	×	✓	Birch	TEA	×
Zang et al. (2020)	×	✓	✓	×	✓	Switchgrass	TEA	×
This Study	✓	✓	✓	✓	✓	SBP	TEA & LCA	✓

1: Environmental; 2: Economic; 3: Pyrolysis; 4: Hydrolysis.

Mao et al. (2012) found that furfural yield dropped significantly as temperatures rose to above 190 °C. Pyrolysis technology can be used in conjunction with H_2SO_4 to fully utilize biomass feedstocks for furfural production. Santos et al. (2018) reported a 64% process yield for furfural production with pyrolysis technology. Cao et al. (2020) reported that pretreatment with 3% H_2SO_4 solution (by weight) allows the occurrence of reduction in the temperature of pyrolysis process (from 500 °C to 300 °C), and subsequently reduces the production cost.

➢ Hydrolysis process. Hydrolysis is a chemical process where hot water or steam is used to extract furfural directly from biomass feedstocks (Cieciura-Włoch et al., 2019). Mao et al. (2012) found that furfural yields were increased by using ferric chloride ($FeCl_3$) and acetic acid (CH_3COOH) to aid in the hydrolysis of corn husks. Liu et al. (2014) reported that Lewis acids (e.g., $FeCl_3$ or $AlCl_3$) could be effective catalysts for furfural production, however, recycling chemical hazard wastes (e.g., acids) remain the main environmental challenges. Nhien et al. (2016) conducted a design and optimization study, and resulted that optimizing the distillation process can reduce the energy consumption and cost of furfural production. Kamzon and Abderafi (2017) compared the hydrolysis yields of SBP with bagasse, and resulted that SBP can produce marginally greater yields of furfural and other desirable chemicals. Cieciura-Włoch et al. (2019) studied furfural production from SBP by employing hydrolysis process and applying dilute solutions of H_2SO_4 or hydrochloric acid (HCl). They reported approximately 65% process yields, although lower temperatures were required for maximum yield when HCl pretreatment was used. Modelska et al. (2020) conducted a study for furfural production from sugar beet pulp and leaves in Poland (one of the leading producers of sugar beet in Europe) via acidic hydrolysis

1.3. Objectives and scope

The main contributions of this study are: (i) the proposed multi-objective decision making framework, including TEA and LCA studies to compare pyrolysis and hydrolysis pathways for furfural production from SBP (Fig. 1), (ii) the integrated sustainability ideology and technological aspects to explore the commercial feasibility of furfural production, using mixed-mode (i.e., portable and fixed) conversion technologies, and (iii) the presented case study in southern Idaho, USA for demonstrating the application of the methodology and verifying the models. The decision making framework evaluates the use of portable pyrolysis refinery units to convert SBP to intermediate products (e.g., bio-oil and biochar) on-site and transfer high-energy density products to upgrading facilities that can alleviate transferring low-energy density SBP. LCA and TEA studies conducted herein evaluate global warming potential (GWP) and total cost of SBP-to-furfural production, including collection, grinding, drying, conversion, storage, and transportation. The multi-objective decision making framework investigates optimal solutions that can simultaneously minimize the total cost and environmental impacts (Mirkouei and Haapala, 2014, 2015, 2015; Mirkouei and Kardel, 2017). Ultimately, the case study examines the sustainability benefits of the conversion pathways in regions with high production volumes of SBP.

2. Materials and methodology

This study compares the market opportunity and sustainability benefits of furfural production from SBP, employing either hydrolysis or pyrolysis conversion pathways. The developed methodology in this study includes LCA for environmental impacts analysis and mathematical optimization modeling for TEA to evaluate GHG emissions and total cost of furfural production (Fig. 2).

For comparison purposes, both conversion pathways encompass four steps: collection/transportation, pretreatment, conversion, and separation (Fig. 3). SBPs are collected and transported either to the portable pyrolysis refinery unit near the collection site or to hydrolysis refinery facility. Pretreatment operations include two steps for pyrolysis process: (i) size reduction, using a Peterson 5710C horizontal grinder and (ii) drying, using a drier (running at 100 °C for several hours), along with pyrolysis char and gas that are byproducts of pyrolysis process. The portable pyrolysis refinery unit is simulated and scaled-up of our built in-house pyrolysis rig, operating under 15–20 psi and 550 °C. Nitrogen is used as an inert gas to move biomass to the free-fall pyrolysis reactor. Then, the intermediate products of pyrolysis process are transported to either bio-oil upgrading facility for furfural production or biochar distribution center. More details about the pyrolysis and separation processes are provided in earlier studies (Cao et al., 2020; Struhs et al.,

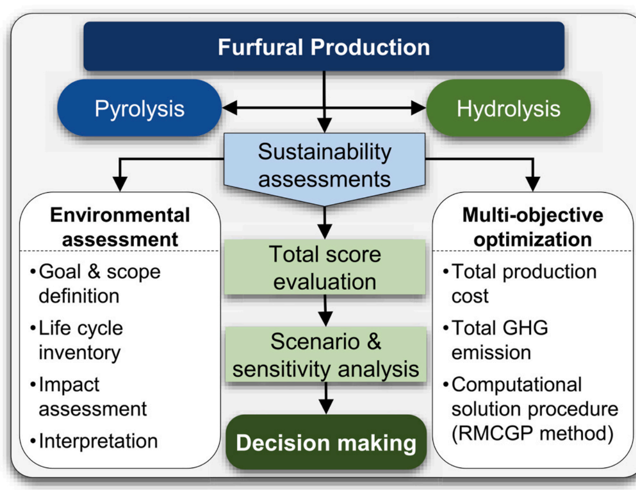

Fig. 2. Multi-objective decision making framework for sustainability assessments.

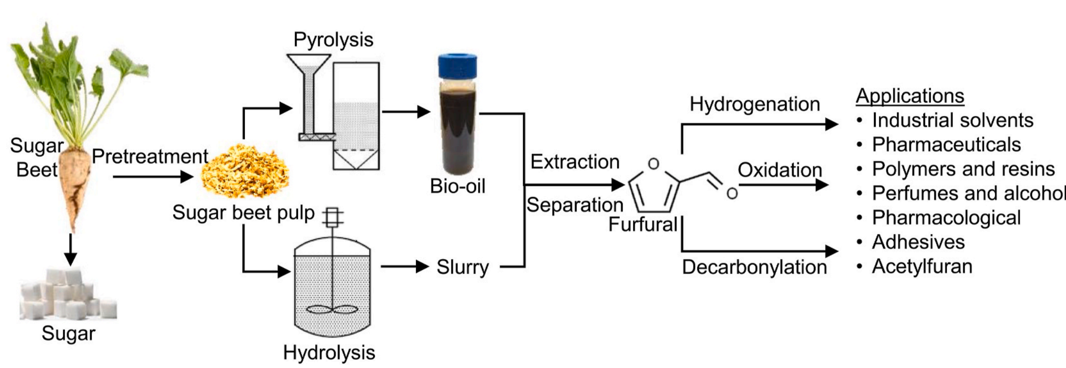

Fig. 1. Furfural production from sugar beet pulp, using pyrolysis and hydrolysis technologies (Danon et al., 2014; Mao et al., 2012).

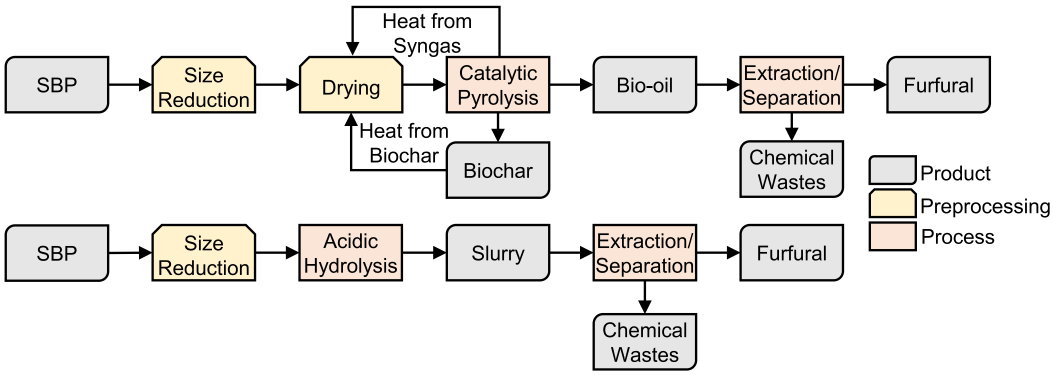

Fig. 3. Process flow schematics for pyrolysis (top) and hydrolysis (bottom).

2020). For hydrolysis, pretreatment includes only grinding operations. Pretreatment and conversion operations are on-site (near collection area) for the pyrolysis pathway, however, all operations (pretreatment, conversion, and separation) are in the separation facility for hydrolysis pathway. Hydrolysis process performs in a pressurized reactor at a temperature around 160 °C, mixing biomass with water and sulfuric acid. Separation process employs an autoclave under 290 psi at a temperature around 90 °C, using Pd/Al_2O_3 catalyst. Further details about hydrolysis and separation processes are provided in an earlier study (Modelska et al., 2020).

2.1. Environmental impacts assessment

This study investigates GHG emissions (i.e., CO_2, CH_4, and N_2O) and global warming potentials for a 100-year time horizon (GWP_{100}), which considers the potential global warming impact relative to CO_2 over a specified interval (U.S. Environmental Protection Agency, 2017). Particularly, different gases degrade at different rates, so the time allowed is a significant consideration. GWP of CO_2 for any time horizon is one, and GWP_{100} of N_2O is approximately 265, while GWP_{100} of CH_4 is reported between 28 and 36 (IPCC, 2007). In other words, 1 kg of N_2O in the atmosphere has a 100-year impact on global warming as 265 kg CO_2 eq./kg N_2O; thus, GWP_{100} of N_2O is 265. LCA conducted herein includes four phases: goal and scope definition, life cycle inventory, life cycle impacts assessment, and interpretation, which are described below.

Goal and scope definition. Environmental impacts of furfural production from SBP via pyrolysis pathway need to be explored in comparison with hydrolysis pathway. The general scope of this study for both hydrolysis and pyrolysis pathways encompasses two main segments and several operations: (i) upstream segment, including SBP collection and transportation; and (ii) midstream segment, involving pretreatment, conversion (hydrolysis or pyrolysis), and separation, and storage. The above-described scope considers a gate-to-gate system boundary, and for both pathways, the functional unit is set as one metric ton of furfural (Fig. 4).

Life cycle inventory. To accurately evaluate the SBP-based furfural production, data was obtained from multiple studies and reports (EPA, 2014; Nugent and Oliver, 2009; OpenLCA, 2019). Equipment used for SBP collection includes a loader and single-trailer truck. For pyrolysis pathway, the upstream inputs are SBP, diesel-based energy, and lubricants required by the machinery, and the outputs are GHG emissions from collecting and hauling of SBP to portable pyrolysis units, located 10 km away from the sugar factory. The midstream operations start by loading SBP to an on-site grinder and then into a dryer for pretreatment purposes. Pretreatment inputs are raw SBP and diesel-based energy, and outputs are ground/dried SBP and GHG emissions from water vapor and fuel combustion. After pretreatment, dried SBP enters the portable pyrolysis unit, requiring N_2 and heat. Electricity is produced by a diesel generator. Pyrolysis inputs are pretreated SBP, nitrogen, and diesel to produce electricity, while outputs consist of biochar, bio-oil, pyrolysis gas, as well as emissions from pyrolysis and diesel combustion. The produced biochar and pyrolysis gas are used for drying, and the rest is transferred to the distribution center, using diesel trailer trucks. The produced bio-oil is transported by diesel tanker trucks to a separation facility. Separation inputs are bio-oil, polyurethane, and electricity for furfural extraction and separation, and outputs are furfural and chemical wastes, as well as emissions. Hydrolysis pathway is modeled with a collection phase similar to pyrolysis, with SBP transported by diesel trailer trucks to hydrolysis conversion and separation facilities. SBP pretreatment requires only griding and occurs in the same manner as modeled for pyrolysis. After grinding, SBP enters the conversion stage, which requires water, heat, and sulfuric acid. Energy is generated by a diesel generator. After conversion, furfural is separated from the collected slurry before being stored.

Life cycle impact assessment. Impact analysis of competing product systems is performed using data from the case study in the Magic Valley region of southern Idaho. Pyrolysis and hydrolysis conversion pathways are converted to a product system, using OpenLCA (an open-source LCA

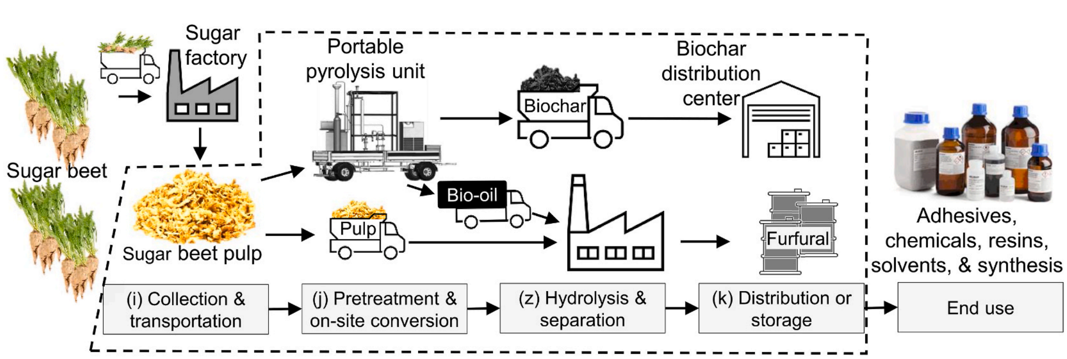

Fig. 4. A gate-to-gate system boundary (dotted line) for SBP to furfural life cycle assessment.

software). Life cycle impacts assessment was conducted using the CML-IA baseline method, created by the University of Leiden (version 1.5.5) and Eqs. 1–16.

- For pyrolysis pathway. Total upstream (collection and transportation) emission factors and GWP are calculated, using Eqs. (1) and (2). Midstream (grinding, drying, and pyrolysis) emission factors and GWP for biochar and bio-oil production are calculated, using Eqs. (3) and (4). Biochar and bio-oil transportation emission factors and GWP are calculated, using Eqs. (5)–(8). Separation emission factors and GWP for furfural production are calculated, using Eqs. (9) and (10).

$$\eta_{up} = R_{CO2} \times \eta_{up,CO2} + R_{CH4} \times \eta_{up,CH4} + R_{N2O} \times \eta_{up,N2O} \tag{1}$$

$$GWP_{up} = M_{beet} \times \eta_{up} \tag{2}$$

$$\eta_{mid} = R_{CO2} \times \eta_{mid,CO2} + R_{CH4} \times \eta_{mid,CH4} + R_{N2O} \times \eta_{mid,N2O} \tag{3}$$

$$GWP_{mid} = M_{beet} \times \eta_{mid} \tag{4}$$

$$\eta_{trans\text{-}char} = R_{CO2} \times \eta_{trans\text{-}char,CO2} + R_{CH4} \times \eta_{trans\text{-}char,CH4} + R_{N2O} \times \eta_{trans\text{-}char,N2O} \tag{5}$$

$$GWP_{trans\text{-}char} = M_{char} \times \eta_{trans\text{-}char} \times D \tag{6}$$

$$\eta_{trans\text{-}oil} = R_{CO2} \times \eta_{trans\text{-}oil,CO2} + R_{CH4} \times \eta_{trans\text{-}oil,CH4} + R_{N2O} \times \eta_{trans\text{-}oil,N2O} \tag{7}$$

$$GWP_{trans\text{-}oil} = M_{oil} \times \eta_{trans\text{-}oil} \times D \tag{8}$$

$$\eta_{sep} = R_{CO2} \times \eta_{sep,CO2} + R_{CH4} \times \eta_{sep,CH4} + R_{N2O} \times \eta_{sep,N2O} \tag{9}$$

$$GWP_{sep} = M_{oil} \times \eta_{sep} \tag{10}$$

- For hydrolysis pathway. Total upstream (collection and transportation) emission factors and GWP are calculated, using Eqs. (11) and (12). Midstream (grinding and hydrolysis) emission factors and GWP for pentose (C5H10O5) production are calculated, using Eqs. (13) and (14). Separation emission factors and GWP for furfural production are calculated, using Eqs. (15) and (16).

$$\eta_{up} = R_{CO2} \times \eta_{up,CO2} + R_{CH4} \times \eta_{up,CH4} + R_{N2O} \times \eta_{up,N2O} \tag{11}$$

$$GWP_{up} = M_{beet} \times \eta_{up} \tag{12}$$

$$\eta_{mid} = R_{CO2} \times \eta_{mid,CO2} + R_{CH4} \times \eta_{mid,CH4} + R_{N2O} \times \eta_{mid,N2O} \tag{13}$$

$$GWP_{mid} = M_{beet} \times \eta_{mid} \tag{14}$$

$$\eta_{sep} = R_{CO2} \times \eta_{sep,CO2} + R_{CH4} \times \eta_{sep,CH4} + R_{N2O} \times \eta_{sep,N2O} \tag{15}$$

$$GWP_{sep} = M_{pentose} \times \eta_{sep} \tag{16}$$

Interpretation. GWP_{100} (CO_2 eq. emissions) and water usage for pyrolysis and hydrolysis are the main environmental impacts that are studied herein. The provided information and results of the defined pathways help to identify the key factors for sustainable furfural production from various biomass feedstocks. Sensitivity and Pareto analyses were performed to compare the results through the lens of sustainability. GHG emissions from SBP-based products (e.g., bio-oil and biochar) are considered as part of the natural cycle (biogenic) that will be absorbed by new feedstocks. The largest contributor of GWP for both hydrolysis and pyrolysis product systems is the conversion process.

2.2. Techno-economic and multi-objective assessments

General optimization model: A general optimization model is formulated to integrate all processes for producing furfural through pyrolysis and hydrolysis pathways. The environmental objective (Eq. (17)) minimizes the sum of the environmental impacts from the process. The economic objective (Eq. (18)) minimizes the total cost for furfural production, including the costs from all activities. g_a is the cost evaluation function for activity a, which depends on the value of continuous variables y_a and binary variables x_a. Continuous variables can be applied for quantities of material and transportation flows. Binary variables can be used for the selection of facility location. Equation (19) ensures that the process output is dependent on the decisions in all activities, where $f_{a,p}$ is the evaluation function for process p and activity a depending on decisions in activity a. Equation (20) ensures that the output of the process must satisfy the demand. Capacity constraint (Eq. (21)) ensures that there is a sufficient capacity for the process. Equations (22) and (23) are the non-negative constraint and the binary constraint, respectively. The detailed model formulation is provided in Supplementary Materials.

$$Min\ Obj_{environment} = \sum_p \eta_p Y_p \tag{17}$$

$$Min\ Obj_{economic} = \sum_a g_a(x_a, y_a) \tag{18}$$

$$Subject\ to:$$

$$Y_p = \sum_a f_{a,p}(x_a, y_a) \quad \forall_p \in P \tag{19}$$

$$Y_p \geq \theta_p \quad \forall_p \in P \tag{20}$$

$$Y_p \leq Cap_p \quad \forall_p \in P \tag{21}$$

$$Y_p, y_a \geq 0 \quad \forall_p \in P \tag{22}$$

$$x_a \in \{0,\ 1\} \quad \forall_a \in A \tag{23}$$

General revised multi choice goal programming model (RMCGP): A general revised multi-choice goal programming (RMCGP) method is applied to combine objectives and finding the desired solutions for enhancing sustainability benefits (Chang, 2008). The RMCGP problem is formulated as follows (Eq. (24)):

$$Min \sum_{h=1}^{n} \left[W_h\left(d_h^+ + d_h^-\right) + a_h\left(e_h^+ + e_h^-\right)\right] \quad (General\ revised\ multichoice\ goal\ programming\ model) \tag{24}$$

$$Subject\ to:$$

$$h_s(X) = (\leq or \geq)0 \quad s = 1, 2, \ldots, q$$

$$f_h(X) - d_h^+ + d_h^- = A_h \quad h = 1, 2, \ldots, n$$

$$A_h - e_h^+ + e_h^- = g_{h.min} \quad h = 1, 2, \ldots, n$$

$$g_{h.min} \leq A_h \leq g_{h.max} \quad h = 1, 2, \ldots, n$$

$$d_h^+, d_h^-, e_h^+, e_h^- \geq 0 \quad h = 1, 2, \ldots, n$$

where $h_s(X)$ represent system constraint s, $f_h(X)$ is goal constraint h, $g_{h.max}$is the upper bound of the hth aspiration level, $g_{h.min}$is the lower bound of the hth aspiration level, $A_h$is the continous variable with a range of $g_{h.min} \leq A_h \leq g_{h.max}$, $d_h^+$and d_h^- are positive and negative deviations from $|f_h(X) - A_h|$and $w_h$is the weight of the hth goal. $e_h^+$and e_h^- are positive and negative deviations from $|A_h - g_{h.min}|$and $a_h$is the weight of the sum of deviations of $|A_h - g_{h.min}|$. The details of RMCGP method and computational solution procedure (LINGO codes) can be found in Supplementary Materials.

3. Case study

Recent studies from the U.S. Department of Agriculture (USDA) reported that the state of Idaho is second in sugar beet production (after the state of Minnesota), producing approximately 6.5 million tons of sugar beets annually, with over 170,000 acres cultivated (USDA, 2020). Cassia, Minidoka, and Bingham counties in southern Idaho produce over 58% of the state's production (Fig. 5). A real case study was conducted for furfural production from SBP in southern Idaho to compare the different production pathways, verify the models, and demonstrate the application of the proposed methodology.

The following assumptions are made, using data from prior studies and USDA reports (Fig. 6):

1. The time horizon in this study is one year.
2. The type of equipment and tools (e.g., portable refinery, grinder, dryer, and loader) are known and assumed to have an effective lifetime of 10 years.
3. All dollar amounts used in this paper are U.S. dollars (USD).
4. Diesel is considered for SBP, bio-oil, and biochar transportation.
5. On-site grinding is considered for SBP size reduction, using a grinder and diesel for both pyrolysis and hydrolysis pathways.
6. Loader, grinder, dryer utilization rates for collection, sized reduction, and drying are 60,000, 37,500, and 40,000 tons per year, respectively (Struhs et al., 2020).
7. SBP has 70–90 wt% moisture content (Hueze et al., 2019).
8. Pyrolysis process requires drying; however, hydrolysis process does not require drying.
9. Energy demand for drying SBP (to below 7 wt% moisture content) is assumed approximately 9 kWh per 100 kg of wet SBP with 70–90 wt% moisture content (Kudra and Mujumdar, 2009).
10. Pyrolysis conversion process requires 0.93 kg of N_2, and the yields for biochar, bio-oil, and syngas are assumed 30%, 55%, and 15%, respectively (Struhs et al., 2020).
11. This study assumes that GWP_{100} value for CH_4 is 28, and the GWP_{100} of N_2O is 265 (IPCC, 2007).
12. Pyrolysis refinery unit is assumed to have 50 dry tons capacity per day, and works 328 days for 12 h per day (Mirkouei, 2016; Mirkouei et al., 2017).
13. During hydrolysis process, 1 kg of SBP is treated with 5 kg of water and 0.005 kg H_2SO_4 at a temperature of 180 °C (Cieciura-Włoch et al., 2019).
14. Hydrolysis process is assumed to have 20 g furfural yield per 1 kg of wet SBP that enters into the hydrolyzer (Cieciura-Włoch et al., 2019).
15. Pyrolysis pathway is assumed to have 77 g furfural yield per 1 kg of dried SBP that enters into the pyrolyzer.
16. After processing at the portable refinery site in Paul, Idaho, bio-oil is transported by tanker trucks to the separation sites in Salt Lake City, Utah. The on-way distance is assumed 300 km (ArcGIS, 2019).
17. Biochar is transported to Bingham distribution center, Idaho, and the one-way distance is assumed 160 km (ArcGIS, 2019).
18. Pretreated SBP transported to the hydrolysis site in Salt Lake City, Utah, and the one-way distance is assumed 300 km (ArcGIS, 2019).
19. Separation process employs an autoclave under 290 psi at temperature around 90 °C, using Pd/Al_2O_3 catalyst. More details about separation process is reported in (Modelska et al., 2020).
20. Approximately 6 million metric tons of SBP are available annually in southern Idaho (Table 2).
21. This study does not consider GHG emissions from chemical wastes.
22. This study does not consider sustainability benefits of biochar in the economic and environmental performance of furfural production.

4. Results, sensitivity analysis, and discussion

Several studies investigated various feedstocks, including SBP (Cieciura-Włoch et al., 2019), water hyacinth (Poomsawat et al., 2019), and corncobs (Nhien et al., 2016) for furfural production. Production parameters have also been studied, including temperature (Mao et al., 2012), and the use of CO_2 (Kim et al., 2019) or acid (Binder et al., 2010)

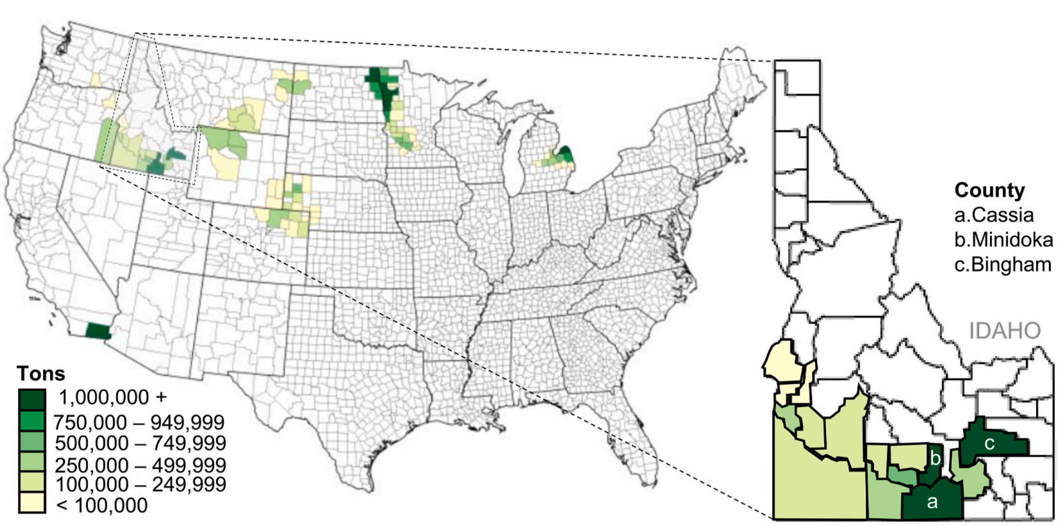

Fig. 5. Sugar beets production by state and county in the United States (left) and three main Idaho counties (a, b, and c) with over 1 million tons of sugar beets, considered in our case study (USDA, 2018).

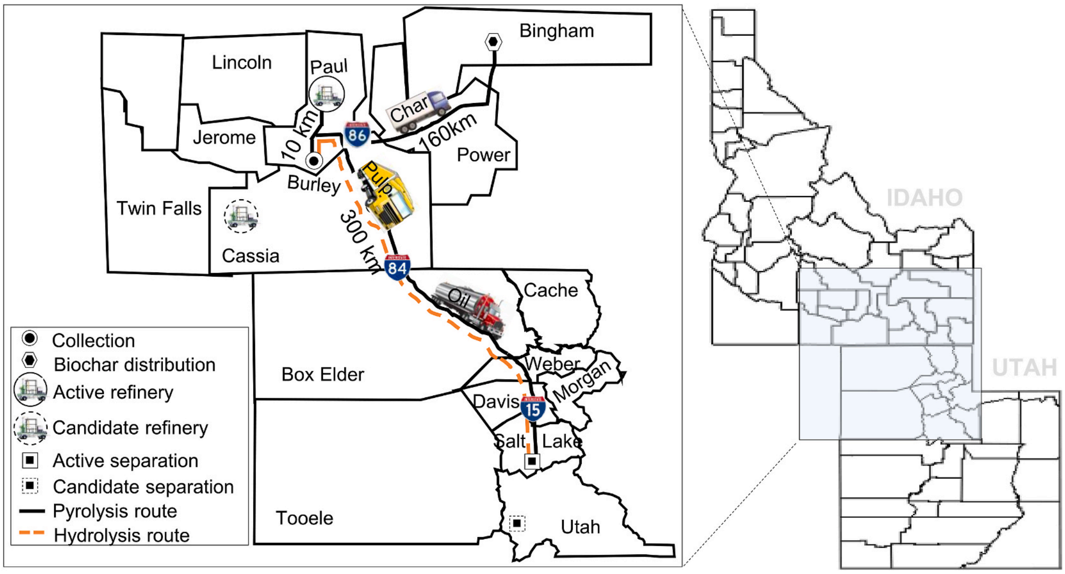

Fig. 6. Shortest paths between collection, portable refinery, separation, and distribution sites.

Table 3
Total emissions for one metric ton furfural production from SBP.

Pathway	Pyrolysis (kg)				Hydrolysis (kg)			
Process	CO_2	N_2O (10^{-5})	CH_4 (10^{-4})	GWP	CO_2	N_2O (10^{-5})	CH_4 (10^{-4})	GWP
Collection	5.0	3.9	2.0	5.0	61.4	48.7	251.6	62.2
Grinding	40.8	32.0	16.4	41.0	28.6	22.4	117.2	29.0
Drying	51.4	40.3	20.6	51.6	–	–	–	–
Conversion	106.0	82.9	42.5	106.0	985.3	772.0	403.9	998.6
Oil transportation	48.2	37.8	19.4	48.4	–	–	–	–
Char transportation	14.0	1.1	5.6	14.1	–	–	–	–
Separation	0.7	0.5	0.3	0.7	5.2	4.1	21.5	5.31
Total	266	210	107	267	1080	847	794	1095

to improve yield.

4.1. Environmental assessment results

Pyrolysis and hydrolysis pathways result in 267 and 1095 kg of CO_2 eq., respectively, for producing a ton furfural. Additionally, hydrolysis process requires approximately 21,000 kg of water, whereas pyrolysis does not require extra water. This study does not consider the agricultural requirements for sugar beet production. Table 3 presents and compares the results of both pyrolysis and hydrolysis pathways, using the data from OpenLCA 1.8 and prior published studies, as well as defined assumptions from the proposed Idaho case study.

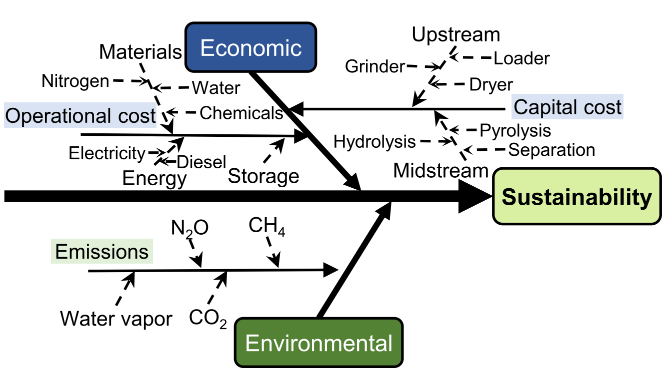

Fig. 7. Pareto analysis of the impacts of each SBP-based furfural production process on the environment.

Pareto analysis is utilized for analyzing the overall GHG emission (kg CO_2 eq.) of each process within pyrolysis and hydrolysis pathways, and comparing the environmental impacts across SBP-to-furfural life cycle system (Fig. 7). Pareto analysis follows the 80/20 principle in which 20% of causes (processes) are responsible for 80% of problems (emissions). Even in cases where the data does not strictly follow the rule, the analysis can be informative.

4.2. Techno-economic and multi-objective assessment results

To solve the developed mixed integer programming models, LINGO 9 software package is used, which is a well-developed software for solving linear and non-linear goal programming models (Paydar and Saidi-Mehrabad, 2015). The optimal solutions for the multi-objective model are obtained after solving eight cost and emission sub-problems for pyrolysis and hydrolysis pathways. In the main case study over a one-year time horizon, the pyrolysis pathway can convert 32,800 tons of SBP to 9,840, 18,040, and 4592 tons of biochar, bio-oil, and furfural, respectively. The total annual cost and unit furfural cost, using two portable refinery units are estimated at \$3,885,554 per year and \$846 per metric ton, respectively. Table 4 presents the estimated capital and operational costs of each point and process, using a method developed in the earlier study (Brinker et al., 2002) and adjusted for inflation to 2020, using the Producer Price Index (BLS, 2020). Capital cost includes purchase price, depreciation price, interest, insurance, and taxes. Operational cost includes repair and maintenance, fuel and lubricant, and overhead costs, as well as labor costs (wages and benefits). Operational costs cover approximately 60% of the total cost. Particularly, the major

Table 4
Capital and operational costs, and annual utilization rate for each conversion pathway.

Point to Point [0]	Process	Pyrolysis			Hydrolysis		
		Capital Cost ($/yr)	Variable Cost ($/yr)	Utilization rate (metric ton/yr)	Capital Cost ($/yr)	Variable Cost ($/yr)	Utilization rate (metric ton/yr)
i to j	Collection/ transportation[1]	72,828	39,618	60,000	72,828	442,529	60,000
i to j	Grinding[2]	184,363	590,231	37,500	184,363	590,231	37,500
i to j	Drying[3]	84,698	797,160	40,000	–	–	–
i to j	Conversion process[4,5]	204,606	44,638	16,400	34,826	2,391,750	16,400
j to z	Bio-oil transportation[1,6]	77,582	415,986	18,040	–	–	–
j to z	Separation[7]	574,484	142,011	18,040	100,933	272,661	164,000
j to k	Char storage[1]	80,798	167,034	9840	–	–	–
j to k	Biochar transportation[1]	77,582	232,851	10,419	–	–	–
j to z	Furfural storage[1]	92,357	77,949	4592	129,293	77,949	6560

[0] Points as shown in Fig. 4; Refs: [1] (Amin Mirkouei et al., 2016b); [2] (Zamora-Cristales et al., 2015); [3] (Kudra and Mujumdar, 2009); [4] (Hersh and Mirkouei, 2019); [5] (Struhs et al., 2020); [6] (Cieciura-Włoch et al., 2019); [7] (Ghosh et al., 2007).

operational cost drivers are drying ($797,160/yr) and grinding ($590, 231/yr), as well as bio-oil/biochar transportation. Additionally, the major capital cost drivers are production (conversion and separation) processes. It is possible to reduce the drying cost if SBP is allowed to dry naturally in the field before mechanical drying or if pyrolysis products (e.g., gas and biochar) are used to produce drying heat (Struhs et al., 2020). On the other hand, the hydrolysis pathway over a one-year time horizon can convert 32,800 tons of SBP to 16,400 and 6560 tons of pentose and furfural, respectively. The total annual cost and unit furfural cost for the main case with one hydrolysis refinery unit are estimated at $6,426,828 per year and $980 per metric ton, respectively. The results show that approximately 90% of the total cost is due to operational cost, particularly, hydrolysis conversion process (Table 4).

The appropriate values for the weights (w_i, a_i) are usually determined by decision makers (e.g., managers and researchers). In order to obtain $g_{i.max}$and $g_{i.min}$, the following sub-problems with specific objectives have been solved herein:

- ➢ $g_{1.min}$ can be obtained by solving Min TC ($)
- ➢ $g_{1.max}$ can be obtained by solving Max TC ($)
- ➢ $g_{2.min}$ can be obtained by solving Min TGHG (kg CO_2 eq.)
- ➢ $g_{2.max}$ can be obtained by solving Max TGHG (kg CO_2 eq.)

The results of the multi-objective model for both pyrolysis and hydrolysis pathways when ($w_i, a_i = 1$) show that TC and TGHG are fully satisfied because the total deviation values are zero and the results of pyrolysis pathway are lower than hydrolysis pathway. In other words, TC and TGHG of pyrolysis and hydrolysis pathways have reached 100% aspiration levels, which is the percentage of goal achievement (Table 5). The results for both pathways when ($w_i = 1, a_i = 2$) show that TC and TGHG are not fully satisfied because the total deviation values are not zero. TC and TGHG for pyrolysis pathway have reached 99.9% and 94.6% aspiration levels, respectively; however, TC and TGHG for hydrolysis pathway reached 99.4% and 100% aspiration levels, respectively.

Table 5
Multi-objective optimization model results for each pathway when ($\boldsymbol{w_i}, \boldsymbol{a_i} = 1$) or ($\boldsymbol{w_i} = 1, \boldsymbol{a_i} = 2$)

Objective	Pyrolysis	Goal achievement (%)	Hydrolysis	Goal achievement (%)
($\boldsymbol{w_i}, \boldsymbol{a_i} = 1$)				
TC ($)	3,885,554	100	6,426,828	100
TGHG (kg CO_2 eq.)	1,294,288	100	10,433,680	100
Total deviation	0		0	
($\boldsymbol{w_i} = 1, \boldsymbol{a_i} = 2$)				
TC ($)	3,881,968	99.9	6,393,228	99.4
TGHG (kg CO_2 eq.)	1,225,152	94.6	10,433,680	100
Total deviation	72,722		33,600	

4.3. Sensitivity analysis and discussion

Several parameters and variables can affect TEA and LCA results of furfural production. Sensitivity analysis is conducted herein to explore the effect of major parameters on economic and environmental performance. The results show that conversion, drying (only in the pyrolysis pathway), and transportation are three major parameters. Key parameters assessed in the sensitivity analysis include the conversion rates and the number of refinery units. Three scenarios are analyzed and compared with the main case study that provides further insights for enhancing sustainability benefits. Fig. 8 presents a fishbone diagram to better understand the cause and effect of techno-economic and environmental variables throughout the SBP-to-furfural life cycle.

Effect of conversion rates. Since the conversion rates through pyrolysis and hydrolysis pathways can vary depending on various factors (e.g., biomass type/size and process configuration), we investigated the effect of this variable on the commercial feasibility and environmental impacts of furfural production. Two case studies are considered (Table 6): (i) Case 1, the conversion rate is 5% less than in the main case study and (ii) Case 2, the conversion rate is 5% more than in the main case study. Furfural production costs and GWP (kg CO_2 eq.) per metric ton have changed monotonically with the conversion rates (Fig. 9). In Case 1 for pyrolysis pathway, compared to the main case study, GWP could increase by 101 kg CO_2 eq. per metric ton of furfural (~36%), while Case 2 could decrease GWP by 57 kg CO_2 eq. per metric ton of furfural (~20%). The change in conversion rates for pyrolysis pathway would also mirror this trend and reduce furfural production cost due to the change in the amount of produced biochar, bio-oil, and pyrolysis gas, and used for various purposes (e.g., SBP drying). Case 1 for pyrolysis pathway, compared to the main case study, would increase the furfural production cost by around 33%, and Case 2 would decrease the cost by around 18%. On the other hand, Case 1 for hydrolysis pathway, compared to the main case study, could increase GWP by 27%, while Case 2 could decrease GWP by 19%. Besides, furfural production cost per metric ton in Case 1 and Case 2 compared to the main case study could increase by around 25% and decrease by about 18%, respectively.

Effect of number of refinery units. The total amount of processed SBP (around 100 tons per day or 32,800 metric tons per year) in the main case study is based on the amount available in three selected sugar facilities in the southern Idaho region (Table 2). The high SBP amount available requires the use of multiple refinery units for both pyrolysis

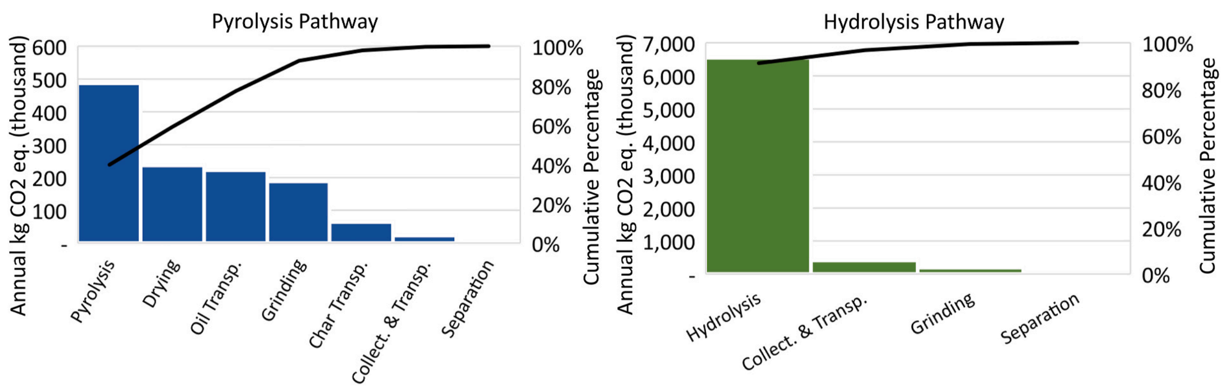

Fig. 8. Fishbone diagram for sustainability root cause analysis.

Table 6
Effect of conversion rates on economic and environmental aspects of furfural production.

Cases	Conversion rates (%)	Furfural production cost ($/metric ton)	GWP (kg CO_2 eq. per metric ton)
Pyrolysis			
Main Case	(α = 30%, β = 55%, γ = 25%)	846	282
Case 1 (−5%)	(α = 25%, β = 50%, γ = 20%)	1125	383
Case 2 (+5%)	(α = 35%, β = 60%, γ = 30%)	692	225
Hydrolysis			
Main Case	(δ = 50%, ρ = 40%)	980	1590
Case 1 (−5%)	(δ = 45%, ρ = 35%)	1228	2019
Case 2 (+5%)	(δ = 55%, ρ = 45%)	802	1285

and hydrolysis pathways. Therefore, we considered Case 3 in which the number of refineries is increased to four and two for pyrolysis and hydrolysis, respectively. In Case 3, compared to the main case study, furfural production cost per metric ton could decrease by around 6% and 1% for pyrolysis and hydrolysis, respectively (Table 7). Also, utilizing four and two refineries for pyrolysis and hydrolysis could decrease GWP by 11 and 5 kg CO_2 eq. per metric ton of furfural (around 4% and 0.3%) for pyrolysis and hydrolysis, respectively (Fig. 10). Optimally, Case 3 with higher refinery units can produce the largest amount of furfural and address sustainability challenges by reducing the unit price of furfural production and environmental impacts.

The results of this study indicate a reasonable comparison to recently published studies with similar feedstocks, operations, and process capacity, and discrepancies can be explained by differences in their applied methodology (Table 8).

The economic and environmental benefits of biochar consumption (Hersh et al., 2019; Amin Mirkouei et al., 2016a) for SBP drying and end use purposes (e.g., soil-plant health improvement in the agriculture sector and water treatment in the aquaculture sector) were not considered in this study. However, it can help to enhance sustainability benefits across pyrolysis pathway, and subsequently reduce the TC and TGHG of furfural production. According to Santos et al. (2018), furfural produced from sugar residues can be an intermediary chemical for jet fuel production. Recently, furfural market price experienced significant market fluctuation due to various reasons, such as its extensive application and high market demand (Zang et al., 2020). Future research should extend LCA system boundary to include the soil benefits of co-products, e.g., biochar. Additional research could also include further process and technology improvements (Mirkouei, 2020; Opare et al., 2021), including reaction temperature, pressure, and residence time, as

Table 7
Effect of number of refinery units on economic and environmental aspects of furfural production.

Cases	Refinery units	Furfural production cost ($/metric ton)	GWP (kg CO_2 eq. per metric ton)
Pyrolysis			
Main Case	2	846	282
Case 3	4	798	271
Hydrolysis			
Main Case	1	980	1590
Case 3	2	972	1585

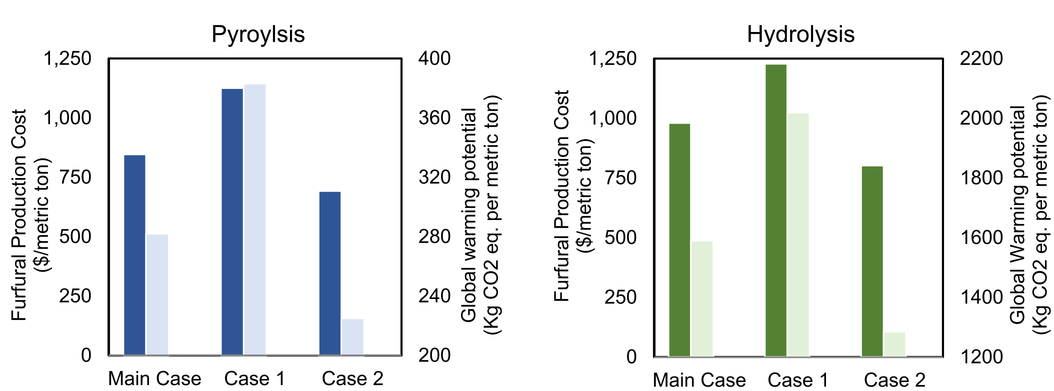

Fig. 9. Effect of conversion rates on sustainability performance of each pathway for furfural production.

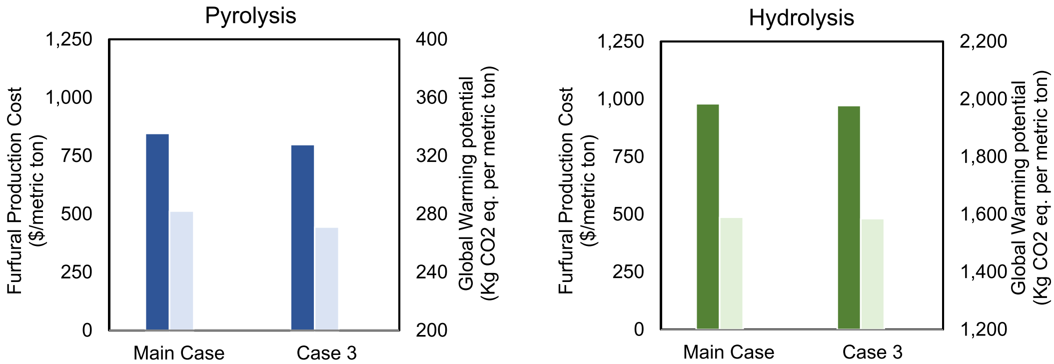

Fig. 10. Effect of portable refineries on sustainability performance of pyrolysis and hydrolysis pathways.

Table 8
Furfural production cost comparison with recently published studies.

Study	Technology	Capacity (ton/year)	Cost ($/ton)	GHG (kg CO_2 eq.)	Biomass type	Year
Pyrolysis						
Hossain et al. (2019)	Pyrolysis	7938	1700	–	Corn Stover	2019
This Study	Pyrolysis	4592	846	267	SBP	2020
Hydrolysis						
Wang et al. (2016)	Hydrolysis	360	–	1857	Corn Stalk	2016
Gómez Millán et al. (2020)	Hydrolysis	5000	1900	–	Birch	2020
Zang et al. (2020)	Hydrolysis	–	1000	–	Switchgrass	2020
This Study	Hydrolysis	6560	980	1095	SBP	2020

well as biomass type and size.

5. Conclusion

Furfural production from renewable resources (e.g., SBP) has shown great potential to address sustainability challenges and the growing global market demand, which is currently around $551 million. However, existing conversion technologies as the major cost and environmental contributors are at a nascent stage to meet the market needs. A multi-objective decision making framework is proposed in this study to assess techno-economic and environmental impacts of furfural production from SBP, using fixed hydrolysis and portable pyrolysis refineries. The proposed methodology herein can address three main deficiencies of prior studies, which are: (a) consideration of both techno-economic and environmental sustainability aspects, (b) comparison of hydrolysis and pyrolysis technologies, and (c) development of a multi-objective decision support system, computational solution, and evaluation procedure to facilitate identifying the sustainable pathway. This study couples the proposed multi-objective decision making framework with potential mixed-mode technologies (i.e., portable and fixed) for SBP-based furfural production. The motivation behind the proposed framework lies in overcoming the existing limitations and deficiencies for furfural production from renewable resources. As such, the resulting methodology integrates technological aspects with sustainability ideology to support broader commercial viability and overcome associated environmental hurdles. The results show that pyrolysis conversion pathway is simultaneously a cheaper process with lower environmental impacts than hydrolysis pathway for furfural production. The primary contributing factor of economic and environmental impacts for hydrolysis pathway is the energy consumption for heating a large volume of water. Hydrolysis process is associated with significantly higher variable (operational) cost in comparison to pyrolysis process. Potential paths for further research and development include (i) exploration of social and biodiversity benefits associated with land, water, and habitat enhancement, (ii) exploration of mixed-mode technology, mixed-pathway transportation, and multiple-year operation to assess the broader sustainability benefits, and (iii) exploration of upstream, midstream, and downstream segments to identify techno-economic and policy barriers.

CRediT authorship contribution statement

Matthew A. Thompson: performed environmental and techno-economic assessments, Formal analysis, Writing – original draft, and revised the manuscript. **Amir Mohajeri:** performed environmental and techno-economic assessments, Formal analysis, Writing – original draft, and revised the manuscript. **Amin Mirkouei:** performed environmental and techno-economic assessments, Formal analysis, Writing – original draft, and revised the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127695.

Nomenclature

Indices

a	Set of activities
i	Set of collection sites
j	Set of conversion sites
k	Set of biochar distribution sites
p	Set of system processes
z	Set of separation sites
h	Set of goal constraint
t	Set of time

Parameters

a_h	Weight for deviation variables of aspiration level for the *h*th goal
a_1	Weight for deviation variables of aspiration level for *TC*
a_2	Weight for deviation variables of aspiration level for *TGHG*
Cap_p	Capacity of process *p*
Cap_D_k	Annual capacity of a biochar distribution unit (metric ton/yr)
Cap_H_j	Annual capacity of hydrolysis process (metric ton/yr)
Cap_R_j	Annual capacity of pyrolysis refinery (metric ton/yr)
Cap_S_z	Annual capacity of separation process (metric ton/yr)
CCH	Unit cost of SBP transportation from collection site to hydrolysis facility ($/km)
CCR	Unit cost of SBP transportation from collection site to pyrolysis refinery ($/km)
CFH	Fixed cost for pretreatment and hydrolysis process ($)
CFR	Fixed cost for pretreatment and pyrolysis refinery ($)
CFS	Fixed cost for operating separation process ($)
CRD	Unit cost of biochar transportation from pyrolysis refinery to distribution center ($/km)
CRS	Unit cost of bio-oil transportation from pyrolysis refinery to separation facility ($/km)
CS_char	Unit cost of biochar storage ($/ton)
CS_fur	Unit cost of furfural storage ($/ton)
CVH	Variable cost of pretreatment and hydrolysis process ($/ton)
CVR	Variable cost of pretreatment and pyrolysis refinery ($/ton)
CVS	Variable cost of separation process ($/ton)
D	Distance (km)
dis_ch_{ij}	Distance between collection center *i* and hydrolysis facility *j* (km)
dis_cr_{ij}	Distance between collection center *i* and pyrolysis refinery *j* (km)
dis_rd_{jk}	Distance between pyrolysis refinery *j* and distribution center *k* (km)
dis_rs_{jz}	Distance between pyrolysis refinery *j* and separation facility *z* (km)
$g_{h.min}$	Minimum of the *h*th goal
$g_{h.max}$	Maximum of the *h*th goal
$g_{1.min}$	Minimum of total cost
$g_{1.max}$	Maximum of total cost
$g_{2.min}$	Minimum of total GHG emission
$g_{2.max}$	Maximum of total GHG emission
GWP_{sep}	Separation process GWP (kg CO_2 eq.)
GWP_{mid}	Midstream processes GWP (kg CO_2 eq.)
GWP_{up}	Upstream processes GWP (kg CO_2 eq.)
$GWP_{trans\text{-}char}$	Biochar transportation GWP (kg CO_2 eq.)
$GWP_{trans\text{-}oil}$	Bio-oil transportation GWP (kg CO_2 eq.)
M	A large number
M_{beet}	Mass of beet pulp (metric ton)
M_{char}	Mass of produced biochar (metric ton)
M_{oil}	Mass of produced bio-oil (metric ton)
$M_{pentose}$	Mass of produced pentose (metric ton)
R_{CH4}	Emissions rate of CH_4 (kg CO_2 eq./kg CH_4)
R_{CO2}	Emissions rate of CO_2 (kg CO_2 eq./kg CO_2)
R_{N2O}	Emissions rate of N_2O (kg CO_2 eq./kg N_2O)
W_h	Weight for deviation variables of the *h*th goal
W_1	Weight for deviation variables of *TC*
W_2	Weight for deviation variables of *TGHG*
η_p	Emissions factors of process *p*
η_{sep}	GHG emissions factor for separation processes (kg CO_2 eq. per ton)
$\eta_{sep,CH4}$	CH_4 emission factor of separation processes (kg CH_4 per ton)
$\eta_{sep,CO2}$	CO_2 emission factor of separation processes (kg CO_2 per ton)
$\eta_{sep,N2O}$	N_2O emission factor of separation processes (kg N_2O per ton)

η_{mid} GHG emissions factor for midstream processes (kg CO_2 eq. per ton)
$\eta_{mid,CH4}$ CH_4 emission factor of midstream processes (kg CH_4 per ton)
$\eta_{mid,CO2}$ CO_2 emission factor of midstream processes (kg CO_2 per ton)
$\eta_{mid,N2O}$ N_2O emission factor of midstream processes (kg N_2O per ton)
η_{up} GHG emissions factor for upstream processes (kg CO_2 eq. per ton)
$\eta_{up,CH4}$ CH_4 emission factor of upstream processes (kg CH_4 per ton)
$\eta_{up,CO2}$ CO_2 emission factor of upstream processes (kg CO_2 per ton)
$\eta_{up,N2O}$ N_2O emission factor of upstream processes (kg N_2O per ton)
$\eta_{trans\text{-}char}$ GHG emissions factor for biochar transportation (kg CO_2 eq. per ton)
$\eta_{trans\text{-}char,CH4}$ CH_4 emission factor of biochar transportation (kg CH_4 per ton)
$\eta_{trans\text{-}char,CO2}$ CO_2 emission factor of biochar transportation (kg CO_2 per ton)
$\eta_{trans\text{-}char,N2O}$ N_2O emission factor of biochar transportation (kg N_2O per ton)
$\eta_{trans\text{-}oil}$ GHG emissions factor for bio-oil transportation (kg CO_2 eq. per ton-mile)
$\eta_{trans\text{-}oil,CH4}$ CH_4 emission factor of bio-oil transportation (kg CH_4 per ton-mile)
$\eta_{trans\text{-}oil,CO2}$ CO_2 emission factor of bio-oil transportation (kg CO_2 per ton-mile)
$\eta_{trans\text{-}oil,N2O}$ N_2O emission factor of bio-oil transportation (kg N_2O per ton-mile)
α Conversion rate of SBP-to-biochar (%)
β Conversion rate of SBP-to-bio-oil (%)
γ Conversion rate of bio-oil-to-furfural (%)
δ Conversion rate of SBP-to-pentose (%)
ρ Conversion rate of pentose-to-furfural (%)
θ_p Demand of process p
θ_t Annual available SBP (metric ton/yr)

Decision Variables

d_h^+ Positive deviation variable of the hth goal
d_h^- Negative deviation variable of the hth goal
d_1^+ Positive deviation variable of *TC*
d_1^- Negative deviation variable of *TC*
d_2^+ Positive deviation variable of *TGHG*
d_2^- Negative deviation variable of *TGHG*
e_h^+ Positive deviation variable of aspiration level for the hth goal
e_h^- Negative deviation variable of aspiration level for the hth goal
e_1^+ Positive deviation variable of aspiration level for *TC*
e_1^- Negative deviation variable of aspiration level for *TC*
e_2^+ Positive deviation variable of aspiration level for *TGHG*
e_2^- Negative deviation variable of aspiration level for *TGHG*
x_a Binary variable for activity a
x_h_z Binary variable when hydrolysis facility z is operating
x_r_j Binary variable when pyrolysis refinery j is operating
x_s_z Binary variable when separation facility $z$is operating
A_h Aspiration level variable of the hth goal
A_1 Aspiration level variable of *TC*
A_2 Aspiration level variable of *TGHG*
y_a Continuous variable for activity a
Y_p Total net output of process p
y_beet_{ijt} Continuous variable for SBP mass transported from collection site i to pyrolysis refinery j during time period t (metric ton)
y_char_{jkt} Integer variable for biochar mass transported from pyrolysis refinery j to distribution center k during time period t (metric ton)
y_fur_{zt} Integer variable for furfural produced in separation center z during time period t (metric ton)
y_oil_{jzt} Integer variable for bio-oil transported from pyrolysis refinery j to separation center z during time period t (metric ton)
$y\_pentose_{jt}$ Integer variable for pentose produced in separation center j during time period t (metric ton)

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