RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *RSC Sustainability*, 2025, **3**, 1564

Technoeconomic analysis of an integrated camelina straw-based pellet and ethanol production system†

Cuong N. Dao, *[a] Lope G. Tabil, ‡[a] Edmund Mupondwa,‡[b] Tim Dumonceaux,‡[b] Xue Li‡[b] and Ajay K. Dalai ‡[a]

Received 4th December 2024
Accepted 4th February 2025

DOI: 10.1039/d4su00769g

rsc.li/rscsus

This study proposes an innovative biorefinery concept, integrating microbial pretreatment (MBP), wet storage (WS), and mushroom cultivation to transform herbaceous biomass into high-value products, including biofuel pellets, Turkey tail mushrooms, and ethanol. This environmentally friendly approach reduces pretreatment times, economically delignifies lignocellulosic structures, and improves the durability and enzymatic digestibility of densified pellets. The biorefinery model includes five pellet-mushroom production facilities (Pellet Plant A) and one ethanol plant (Ethanol Plant A), strategically located approximately 140 km south of Saskatoon (50°53′16.1″N, 106°42′15.5″W) in the province of Saskatchewan, Canada, to minimize pellet transport distances. Pellet Plant A, with a capacity of 250 000 t per year, incurs unit production costs (UPC) of US$201–242 per t, primarily driven by the cost of fungal liquid inoculum preparation. These costs exceed those of conventional steam-explosion pellet plants, such as natural gas-fired (US$181 per t) and biomass-fired systems (US$166 per t). Consequently, ethanol produced at Ethanol Plant A, using these pellets, costs US$1.32 per L, compared to US$0.89 per L for centralized MBP straw bales-to-ethanol plants and US$0.57 per L for conventional dilute acid pretreatment plants. The economic viability of this biorefinery concept requires a minimum ethanol selling price (MESP) of US$1.03 per L and at least 50% farmer participation to achieve a positive net present value (NPV) without mushroom credits. However, integrating revenue from Turkey tail mushroom production significantly enhances financial outcomes, increasing Pellet Plant A's NPV by up to US$10 billion. This enables a reduction in pellet selling prices, lowering the MESP to US$0.77 per L with a pellet purchasing cost of US$100 per t. These findings demonstrate the economic feasibility and sustainability of this innovative biorefinery model, emphasizing the potential of combining microbial pretreatment technologies with diversified revenue streams.

Sustainability spotlight

Our work contributes to the United Nations' Sustainable Development Goals (SDGs) by promoting sustainable agriculture, affordable clean energy, and responsible production. By developing an integrated system that converts camelina straw into biofuel pellets, medicinal mushrooms, and bioethanol, this research supports SDG 7 (Affordable and Clean Energy) by creating renewable energy sources. The inclusion of microbial pretreatment and strategic plant placement minimizes waste and chemical/energy inputs and reduces transportation emissions, aligning with SDG 13 (Climate Action). Additionally, the economic viability of this model encourages sustainable agricultural practices and local economic growth, contributing to SDG 8 (Decent Work and Economic Growth) and SDG 12 (Responsible Consumption and Production).

1 Introduction

Global decarbonization prioritizes increasing the renewable bioenergy share for improved life cycle performance, utilizing waste and residues instead of dedicated crops, and avoiding emissions from waste management.[1] Canada has significant potential to lead globally in clean technologies utilizing lignocellulose to cut greenhouse gas emissions and enhance economic growth.[2] It ranks 4th worldwide and 1st among OECD nations in forestry area per capita,[3] and is the largest cereal

[a]Department of Chemical and Biological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK, S7N 5A9, Canada. E-mail: cuong.dao@usask.ca

[b]Saskatoon Research and Development Centre, Science and Technology Branch, Agriculture and Agri-Food Canada, 107 Science Place, Saskatoon, SK, S7N 0X2, Canada

† Electronic supplementary information (ESI) available: Methods, Fig. S1–S12, Tables S1–S11, and R code session. See DOI: https://doi.org/10.1039/d4su00769g

‡ These authors contributed equally to this work.

producer with the 3rd largest cultivable land per capita.[4,5] Utilizing agro-wastes, forestry residues, and urban waste for energy could yield 1.5–2.2 EJ, surpassing coal energy by 2–3 times and representing 14–21% of Canada's primary energy supply.[6,7] Harnessing this bioenergy could cut GHG emissions by 125 million metric tonnes of CO_2 equivalents.[2] This bioenergy shift positions Canada to lead in climate action, create jobs, and expand market access for resources like natural gas and minerals.[2] Lignocellulosic biomass links bio- and clean technologies with traditional industries, demanding a skilled workforce across oil, gas, and chemical sectors as well as experts in bioenergy innovation.[2] With bioenergy generating 5.5 jobs per 1 MW-higher than PV solar and wind-Canada stands to capitalize on lignocellulosic biomass fully, advancing both environmental and economic goals.[8]

The Canadian prairie provinces of Alberta (AB), Saskatchewan (SK), and Manitoba (MB) possess vast grasslands, prairies, abundant farming areas, and natural resources.[9] A significant portion of agricultural residues is generated in SK and AB.[10] Saskatchewan has the largest share of Canadian farm area (39.2%) with 24.4 million hectares, followed by Alberta (32.0%) and Manitoba (11.1%).[11–13] Camelina (*Camelina sativa*), an energy crop, holds promise for biofuel production due to its resilience, quick maturation cycle, and compatibility with existing machinery.[14,15] Biodiesel from camelina boasts a net energy ratio of 1.47, reducing emissions compared to conventional diesel fuel.[16] The leftover camelina straw (CS) can also be used for bio-ethanol or biofuel pellet production. The brown soil zone was chosen by researchers from Agriculture and Agri-Food Canada for growing camelina as a bioenergy crop.[17] The most fertile area is in the dark brown soil zone, which has approximately 30 g kg^{-1} of organic matter.[17]

The sectors classified as "difficult-to-transition" including aviation, heavy-duty truck transportation, and maritime shipping, continue to pose challenges when it comes to adopting electric power, resulting in an ongoing reliance on combustion technologies of solid and liquid fuels.[18] To counter the impact of burning fossil fuels and reduce greenhouse gas accumulation, incorporating renewable sources into existing energy infrastructure like co-firing solid biofuel pellets with coal and blending bio-ethanol with gasoline are practical strategies.[19,20] Pelletization offers an effective strategy for utilizing agro-residues as bioenergy sources both domestically and internationally.[21] The uniformity in size, shape, density, and durability of pellets, coupled with their excellent flow characteristics, low moisture content, high hydrophobicity, and elevated energy density, renders them well-suited for various applications.[22] These include residential cookstoves, grills, home heating systems, and thermal power plants with fully automated control systems.[23] The potential applications of ethanol extend to other "drop-in fuels" including renewable fuel oil for ships and hydrogen production.[24] While ethanol cannot serve directly as aviation fuel due to the need for more complex hydrocarbons, it can serve as an intermediary for catalytic conversion to renewable aviation fuels.[25] The alcohol-to-jet process using the ethanol pathway comprises four consecutive reactions: dehydration of ethanol, oligomerization, hydrogenation, and fractionation, resulting in the production of sustainable aviation fuel and renewable diesel.[26,27]

Given the recent surge in North American oil prices[28] and projections of the global pellet market potentially doubling from US$11 billion in 2023 to US$20 billion in 2033,[29] there is increasing interest in shifting from gasoline to bioethanol in vehicles and substituting solid biofuel pellets for coal/natural gas. Nevertheless, producing these biofuels necessitates thermo-physico-chemical pretreatments aimed at surmounting the resistance posed by lignocellulosic structures. These pretreatment steps augment solid biomass particle cohesion in pellet production[30] and improve enzymatic accessibility during biochemical conversion.[31] The increasing energy costs and the necessary pretreatment agents play a substantial role in driving up the overall pretreatment expenses.[32] Consequently, this leads to an escalation in the total production costs of second-generation biofuels, especially when the expenses associated with input streams are on the rise.[33]

Recent studies highlight a growing interest in microbial biomass pretreatment (MBP) as an effective, economically viable approach for lignocellulosic biomass delignification.[34] Biodegradation with white-rot fungi offers an environmentally sustainable strategy, facilitating the partial breakdown of complex lignocellulosic matrices.[35] MBP has demonstrated improvements in both the physical robustness and enzymatic digestibility of densified biomass such as camelina straw and switchgrass pellets, achieving these enhancements with low energy and chemical requirements.[36] Additionally, white-rot fungi pretreatment has been shown to improve the pellet properties of wheat straw[37] and enhance pellet quality and enzymatic digestibility in switchgrass.[38]

To address the significant drawback of extended processing times associated with MBP, the concept of integrating indoor wet storage with fungal pretreatment is introduced as a viable approach. Rather than allowing straw bales to deteriorate in open fields or storing them in open warehouses, they can be placed in controlled environments with regulated humidity and temperature. This controlled storage enables the application and cultivation of microorganisms on the surfaces of the straw bales, optimizing conditions for fungal growth and biomass degradation.

To enhance the economic value of the biorefinery concept, we incorporated a specific white-rot fungal strain capable of developing into the edible mushroom, *Trametes versicolor*. *T. versicolor* m4D (TVm4D), a genetically modified strain that selectively degrades lignin while conserving cellulose in lignocellulosic substrates, facilitating efficient downstream sugar production.[1,36,39,40] Notably, the tensile strength of camelina straw pellets increased from 2.0 MPa in untreated samples to 6.3 MPa following a 31-day treatment with TVm4D.[36] The delignification capability of TVm4D facilitates the release of lignin from CS, which subsequently acts as a natural binder, enhancing the tensile strength of CS pellets and thereby reducing transportation and handling costs. Additionally, the improved enzymatic digestibility of microbially pretreated CS pellets reduces the severity of acid hydrolysis needed in upstream biorefinery processes, effectively lowering both associated costs and environmental impacts. Furthermore, the fruiting body of this strain, known as the Turkey tail mushroom, is a source of high-value medicinal compounds. *T. versicolor* produces nutritionally and medicinally valuable bioactive substances,[41,42] including antioxidants.[43,44] It also exhibits antimicrobial,[45,46] anticancer,[47] antidiabetic,[48] and anti-obesity properties,[47] alongside benefits for cardiovascular health,[49] immunomodulatory effects,[50] and acetylcholinesterase inhibition activity.[43] Consequently, revenue generated from the sale of Turkey tail mushrooms is anticipated to lower the minimum selling price (MSP) of microbially pretreated CS pellets for local thermal power plants or biorefineries, thereby improving the overall economic viability of the proposed production concept.

To the best of the authors' knowledge, no studies have examined the pilot-to-large-scale implementation of microbial pretreatment combined with mushroom cultivation for producing solid biofuel pellets, bioethanol, and supplements. In one study, Slavens[51] assessed the delignification and holocellulose degradation of 27 switchgrass bales treated with *Pleurotus ostreatus* (Oyster mushroom) over 81 days in a controlled moisture and temperature environment. Similarly, Li[52] investigated the delignification and holocellulose degradation of rectangular and cylindrical switchgrass bales treated with *P. ostreatus* over nine months in a natural storage environment. Both studies focused solely on compositional analyses of treated biomass bales without evaluating the economic feasibility of food and biofuel production from these processes. Research on the technoeconomic analysis of microbial pretreatment of lignocellulosic materials for producing bioenergy and food remains scarce. Vasco-Correa and Shah[53] conducted simulations to identify key technoeconomic barriers associated with fungal pretreatment of biomass sources, including perennial grasses, corn stover, agricultural residues, and hardwood. However, the study focused solely on producing fermentable sugars.

This study proposes and simulates the production of solid biofuel pellets and Turkey tail mushrooms through the pretreatment of camelina straw bales using *Trametes versicolor* m4D. The integrated mushroom-and-pellet production concept was applied across five locations in Saskatchewan, Canada, to supply Turkey tail mushrooms and biofuel pellets to local markets. Pellets were designated for delivery to a local cellulosic bioethanol plant for ethanol production, while the mushrooms were assumed to be marketed for supplemental and medicinal purposes. Two alternative pellet production designs-utilizing steam explosion pretreatment with camelina straw-fired and gas-fired steam boilers, respectively served as benchmark comparisons for pellet production efficiency. For ethanol production benchmarks, a centralized MBP pretreatment ethanol plant and a conventional acid pretreatment straw-to-ethanol plant were included. This study provides new insights into converting agricultural residues into biofuels and bioproducts, emphasizing reduced energy input and limited use of harmful chemicals. The scope of this analysis focuses on the domestic market within Saskatchewan, Canada.

2 Materials and methods

2.1 Study region and feedstock supply

2.1.1 The pellet-mushroom plants. The main pellet production facility is in Weyburn, SK, chosen for its fertile soil and proximity to the primary camelina cultivation area in Midale, SK. Additional pellet plants strategically placed in Moose Jaw, Swift Current, Kindersley, and a fifth facility 21 km south of Saskatoon and 87 km east of Kindersley cover the majority of the Dark Brown and Brown soil zone in Saskatchewan (see Fig. 1).

The plant capacity was plotted against the collection radius (refer to Fig. S1 in the ESI†) considering an average camelina yield of 1.967 t per ha per year as calculated from Table S1.† Assuming that a 100% farmer participation rate is impractical; a more realistic 10% participation rate was considered. The plant's feedstock collection was capped at a 100 km radius, leading to a chosen baseline capacity of 1270 t per day. Straw capacity, determined using a 1.00 to 1.66 straw-to-grain ratio,[54] considers the lowest value for harvesting losses. The base-case assumes an operating time of 8400 h per year (350 days per annum), resulting in an annual feedstock requirement of approximately 444 500 t per year. The relationship between feedstock supply capacity and collection area is described by using eqn (1).[55]

$$D = A \cdot Y \cdot F_1 \cdot F_2 \tag{1}$$

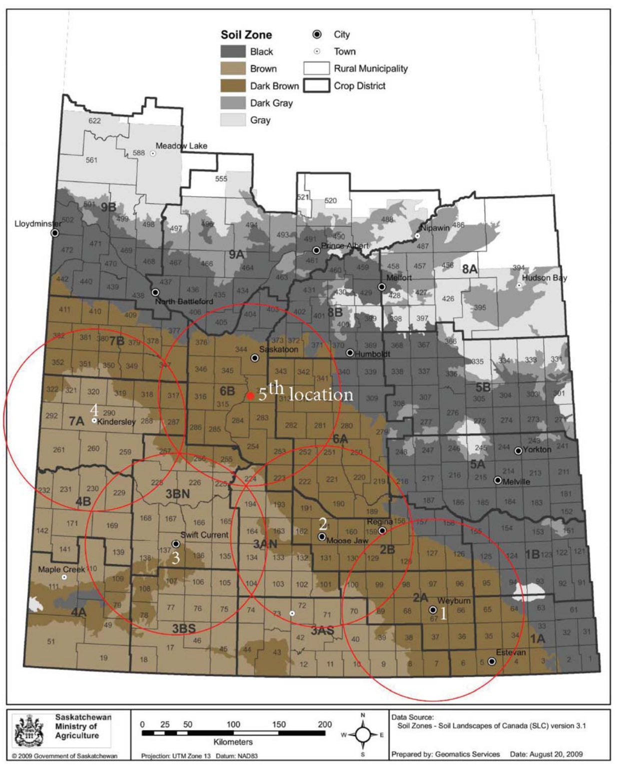

Fig. 1 Soil zones in southern Saskatchewan (source: Government of Saskatchewan) and the five proposed locations of the pellet plants within a 100 km radius (red circles).

where D = the feedstock supply capacity to the biofuel plant, [t per year]; A = the circular area of collection around the plant, $A = \pi \cdot r^2$, [m^2]; Y = the amount of collected feedstock per specific area per year, [t per m^2 per year]; F_1 = the percentage of total farmland from which the feedstock can be collected, [decimal]. It was assumed that 25% of the land was used for infrastructure such as buildings and roads, and therefore $F_1 = 75\% = 0.75$; F_2 = the proportion of neighboring farmland suitable for crop cultivation, [decimal]. The farmer participation rate, F_2, in the sensitivity analysis represents the willingness of surrounding farms to engage in camelina seed and straw cultivation and sale. Due to limited statistical data on camelina production in Saskatchewan, this assumption is based solely on theoretical considerations of land availability.

The cost of CS for each pellet plant includes harvesting, baling, loading/unloading, transport, storage and fertilizers for soil preparation (refer to Table S2 in the ESI†). The transport cost was calculated based on the specific transport cost (Table S3 in the ESI†) and the total feedstock cost, as derived from previous studies (Table S4 in the ESI†). Radial and areal methods are commonly used to estimate the average transport distance.[56–60] In practical applications, however, truck transportation distances deviate from straight-line measurements due to the tortuosity (τ) of the road network, which reflects its curvature and complexity.[56,61] Consequently, the average transport distance can be mathematically described by using eqn (2).[17] In this study, the location under consideration is Saskatchewan, home to Canada's largest croplands, facilitating efficient feedstock collection from points nearest to the processing center. Since the calculated average transportation distance inherently incorporates truck routing considerations, the influence of road tortuosity is disregarded in this analysis.

$$L = \tau \frac{2}{3} r \tag{2}$$

where L is the average transport distance, [km]; r is the collection radius, [km]; and τ is the tortuosity factor ($\tau = 1$ in this study).

2.1.2 The bioethanol plant. The (x, y) coordinates for each pellet plant were determined using ArcGIS Pro 3.0.1 (Esri™, Redlands, CA, USA). Subsequently, the optimal coordinates for the bioethanol plant were computed, minimizing the sum of distances to each pellet plant through the optim function in R version 4.3.1 (2023-06-16).[62] The ethanol plant's coordinates are $x = 50.8878$, $y = -106.7043$ in decimal degrees (or 50°53′16.1″N, 106°42′15.5″W in degrees, minutes, seconds). Positioned around 140 km south of Saskatoon, the bioethanol plant ensures the shortest transport distance (refer to Fig. S2 in the ESI†). The algorithm used is detailed in the Code section of the ESI.†

The pellet feedstock cost at the ethanol plant's gate was calculated by adding the pellet's MSP at the pellet plant's gate to the transportation cost. This calculation considers that the pellet-specific transport cost is three times smaller than the straw bale-specific transport cost due to the higher bulk density of pellets (approximately 600 kg m^{-3}) compared to straw bales (approximately 200 kg m^{-3}) (refer to Table S5 in the ESI†). The distances between pellet plant locations and the ethanol plant were determined using ArcGIS Pro 3.0.1.

2.2 Process design

2.2.1 Process design scenarios. Three types of pellet plants were considered: (1) Pellet Plant A: on-farm indoor wet storage combined with MBP, mushroom production, and a pellet plant; (2) Pellet Plant B: a conventional pellet plant employing steam-explosion pretreatment, with heat/steam generated by a natural gas-fired steam boiler and electricity purchased from the grid (refer to Fig. S3 in the ESI†); and (3) Pellet Plant C: a conventional pellet plant employing steam-explosion pretreatment, where part of the biomass feedstock is used to operate a biomass-fired steam boiler to generate heat/steam for the process, while electricity is purchased from the grid (Fig. S4 in the ESI†). The steam explosion pretreatment conditions were drawn from a study by Lam,[63] wherein ground CS underwent treatment with high-pressure steam (200 °C, 16 bar) for a duration of 5 min. The cost of the CS feedstock for Pellet Plant B and Pellet Plant C was calculated as shown in Table S2 (ESI†) and the relevant technoeconomic factors of those plants were established in a manner consistent with that in Scenario 2 for cost factors detailed in Table S6 (ESI).†

Three types of bioethanol plants were considered: (1) Ethanol Plant A: the microbially pretreated pellets were transported from the five Pellet Plant A sites to the plant located at the optimal location as per Section 2.1.2 to be converted to bioethanol. (2) Ethanol Plant B (Fig. S5†): the "microbially pretreated straw bale-to-ethanol" process involved the direct transportation of unprocessed CS bales from the five designated study areas to the bioethanol plant located at the same optimal point. In this scenario, a centralized MBP facility was integrated with the bioethanol plant, where the straw was stored and subjected to MBP for 30 days before being further processed at the ethanol plant. Notably, there was no densification step in this setup. (3) Ethanol Plant C (Fig. S6†): the "untreated straw bale-to-ethanol" process entailed the direct transport of untreated straw bales to the ethanol plant located at the same optimal point, without undergoing any prior MBP. In this scenario, the conventional pretreatment conditions were adjusted to align with the methods detailed in Humbird *et al.*[64] For specific details regarding the determination of straw bale costs at the ethanol plant's entrance, please refer to Table S7 in the ESI.†

Pellet plants and bioethanol facilities were planned and simulated using SuperPro Designer software (Version 10.0, Build 7.0, Intelligen Inc., Scotch Plains, NJ, USA) with an assumed annual operational time of 8400 h (equivalent to 350 days per year) and full-capacity operation at 100%. Subsequent sections detail the design specifics for each process. Base-case and comparative scenarios for benchmarking pellet and ethanol production are illustrated in Fig. 2.

2.2.2 Feedstock characterization and the effect of MBP on the enzymatic saccharification of microbially pretreated pellets. CS was sourced from the AAFC Research Farm (Saskatoon Research and Development Centre, SK, Canada). Camelina,

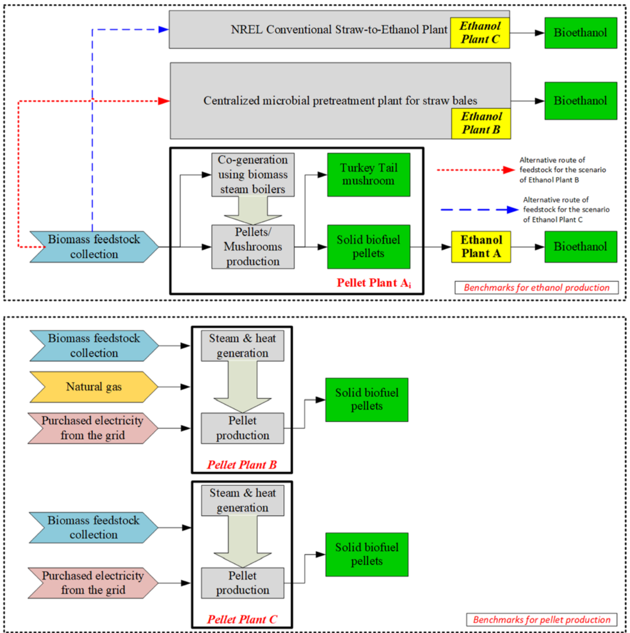

Fig. 2 Base-case and comparative scenarios for benchmarking pellet and ethanol production.

comprising 17 breeding lines and cultivars Midas, Cypress, Sonny, Dolly, Calena, and AAC 10CS0046, was planted in May and harvested in September 2023. The straw was air-dried in the field and manually collected in cloth bags. The characterization of microbially pretreated pelletized CS followed the procedure in Dao *et al.*[36]. Raw CS was chopped into 50 mm pieces, mixed with *T. versicolor* m4D (TVm4D) fungal inoculum to achieve 70% moisture content in a plastic bag, and incubated at 27 °C with 100% humidity for 30 days. After incubation, mycelium-bound substrates were manually separated and oven-dried at 45 ± 3 °C. Dried CS was ground with a 1.6 mm screen, stored with 8% moisture, and pelletized using an Instron Model 3366 testing machine (Instron Corp., Canton, MA, USA) as described in Dao *et al.*[36].

Cellulose, hemicellulose, and lignin contents of both untreated and treated samples were determined based on the two-step acid hydrolysis based on the NREL Laboratory Analytical Procedure (LAP).[65] At the same time, their enzymatic saccharification was conducted in accordance with the LAP outlined by the NREL[66] with details similar to those in the work from Dao *et al.*[36]. The higher heating value (HHV) of the untreated and treated CS was measured utilizing a 6400 Automatic Isoperibol calorimeter (Parr Instrument Company, Moline, IL, USA) in accordance with the guidelines outlined in ASTM D5865/D5865M-19.[67] The ash content of the samples was obtained following the ASTM D7582-15.[68] Feedstock characteristics of untreated CS and CS treated with TVm4D for 30 days are indicated in Table 1. As a result of MBP, the cellulose conversion of CS increased 4.7-fold, from 12.9% in untreated CS to 61.1% in CS treated with TVm4D, while the corresponding xylose yield improved 3.4-fold, from 14.6% to 50.1% (Table 2). Kinetics of reactions used for simulating solid-state fermentation MBP bioreactors are shown in Table S8 in the ESI.†

Table 1 Feedstock characteristics of untreated and microbially pretreated camelina straw[a]

Component	Unit	Untreated CS	CS treated with TVm4D
Cellulose	[wt%]	34.2	19.8
Glucan	[wt%]	34.2	19.8
Hemicellulose	[wt%]	24.4	12.5
Xylan	[wt%]	19.1	9.8
Arabinan	[wt%]	2.4	1.3
Galactan	[wt%]	1.5	0.8
Mannan	[wt%]	1.3	0.7
Lignin	[wt%]	37.3	23.6
Extractives	[wt%]	2.8	3.8
Fungal biomass	[wt%]	0.0	5.2
Ash content	[wt%]	1.33 ± 0.04	0.96 ± 0.04
HHV	[MJ kg^{-1}]	18.59 ± 0.50	17.54 ± 0.40

[a] CS = camelina straw, TVm4D = *T. versicolor* m4D, and HHV = higher heating value.

2.2.3 Microbial pretreatment pellet-mushroom production plant (Pellet Plant A).

The diagram of the MBP pellet plant is presented in Fig. 3, while the fully detailed design is provided in Fig. S7 in the ESI.† The green block represents on-site fungal inoculum preparation (FIP), the red block denotes the pellet production process (PP), and the orange block signifies the boiler-turbine-generator (BTG) plant. In the FIP block, a small amount of fungal liquid inoculum is prepared in the lab using flask shaking (P-8/SFR-101) following the procedure by Dao *et al.*[36] The cells grow in the broth for 5 days before transfer to seed fermentors 1 (P-10/SFR-102), 2 (P-9/SFR-103), and the production-scale fermentor (P-33/FR-102), each for 5 days. The fungal liquid inoculum stream (S-144) is used for MBP of lignocellulosic feedstock. In the PP block, rectangular CS bales (2.4 × 1.2 × 0.9 m) are trucked in (P-1) and placed on a conveyor (P-4). They are washed with water to remove debris (P-4), sterilized in an autoclave (P-2) using local straw-generated steam (P-5), and then treated with liquid fungal inoculum (10 mL liquid fungal inoculum per 20 dry g substrate[36]) and stored for 30 days (P-7). The biomass bales undergo microbial pretreatment in a humidity- and temperature-controlled warehouse, concurrently with mushroom production. Once pretreatment and mushroom growth are complete, the mushrooms are harvested from the surface of the straw bales. After mushroom removal, the straw bales exit the incubation warehouse and are further processed for pellet production. The microbially pretreated straw bales are shredded (P-36), dried (P-42), ground (P-37),

Table 2 Enzymatic digestibility of untreated and microbially pretreated camelina straw[a]

Sample	Cellulose conversion* [%]	Hemicellulose conversion* [%]
Untreated CS	12.88 ± 0.37	14.56 ± 0.84
CS treated by TVm4D	61.13 ± 0.65	50.12 ± 0.75

[a] CS = camelina straw, TVm4D = *T. versicolor* m4D, and *: data are mean ± standard error (n = 3).

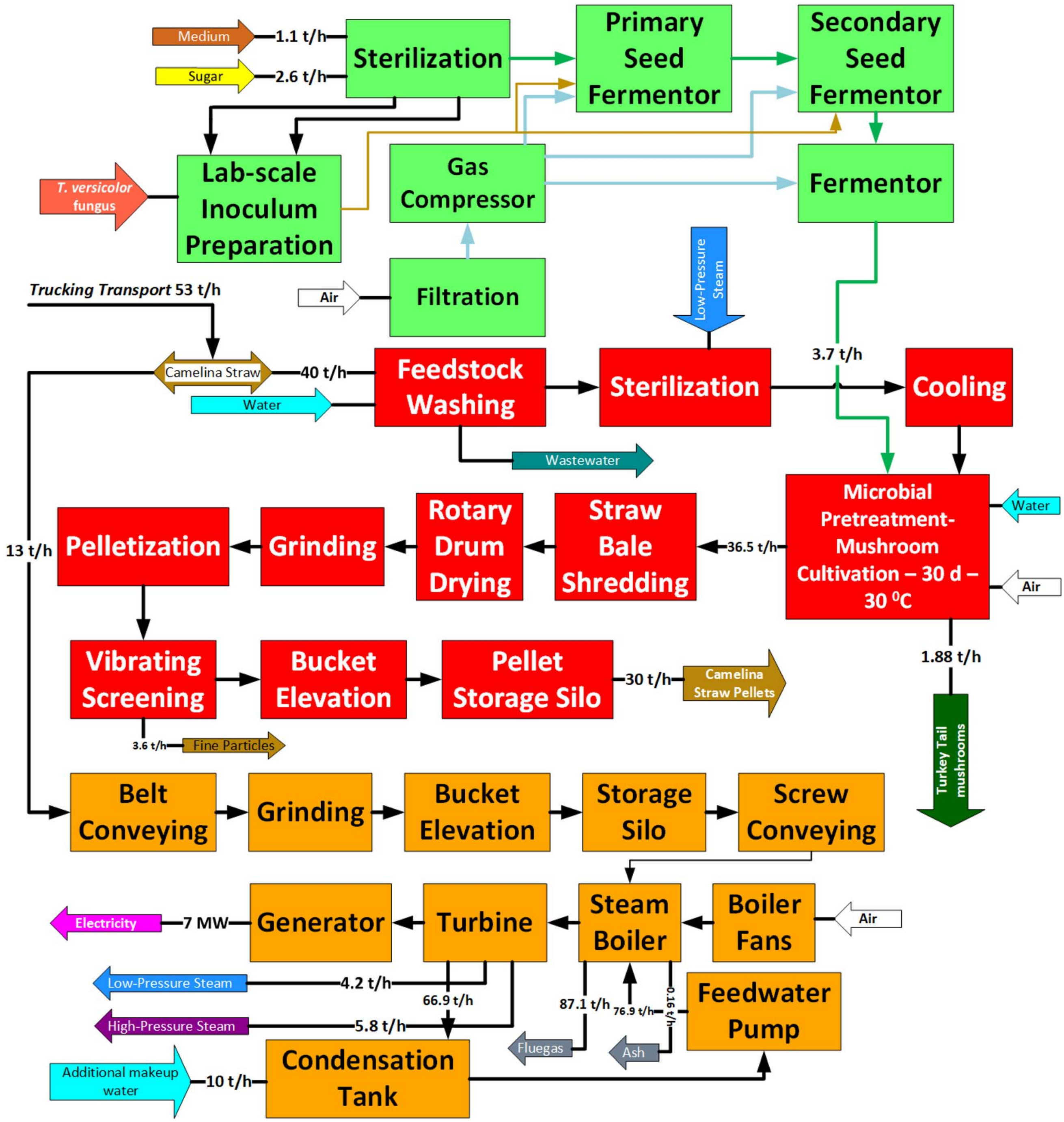

Fig. 3 Simplified block diagram of the modeled camelina straw pellet production process using microbial pretreatment (Pellet Plant A): participation rate = 10%, feedstock capacity = 1270 t per day = 52.81 t per h (note: green color: Fungal Inoculum Preparation (FIP) block, red color: Pellet Production (PP) block, and orange color: Boiler-Turbine-Generator (BTG) block).

pelletized (P-38), cooled (P-39), sifted (P-40), and stored (P-41). These pellets can be packaged for subsequent thermochemical/biochemical conversions. In the BTG block, a biomass steam boiler (P-5) efficiently burns feedstock to generate steam for the turbine-generator (P-49). High-pressure steam (H. P. steam out) and low-pressure steam (L. P. steam out) are extracted and used for plant operations. The co-generation system produces 7 MW, meeting the plant's 6.4 MW electricity demand. Condensed turbine water is mixed with fresh water for boiler efficiency (P-18).

2.2.4 The pellet-to-bioethanol plant (Ethanol Plant A). The design of the bioethanol plant (Ethanol plant A in Fig. 4 and S8†) is based on the proposals by Humbird *et al.*[64] and Petrides[69] and consists of 7 divisions, namely: (1) feedstock storage and handling (Z1 in brown color), (2) pretreatment (Z2 in red color), (3) enzymatic hydrolysis and fermentation (Z3 in blue color), (4)

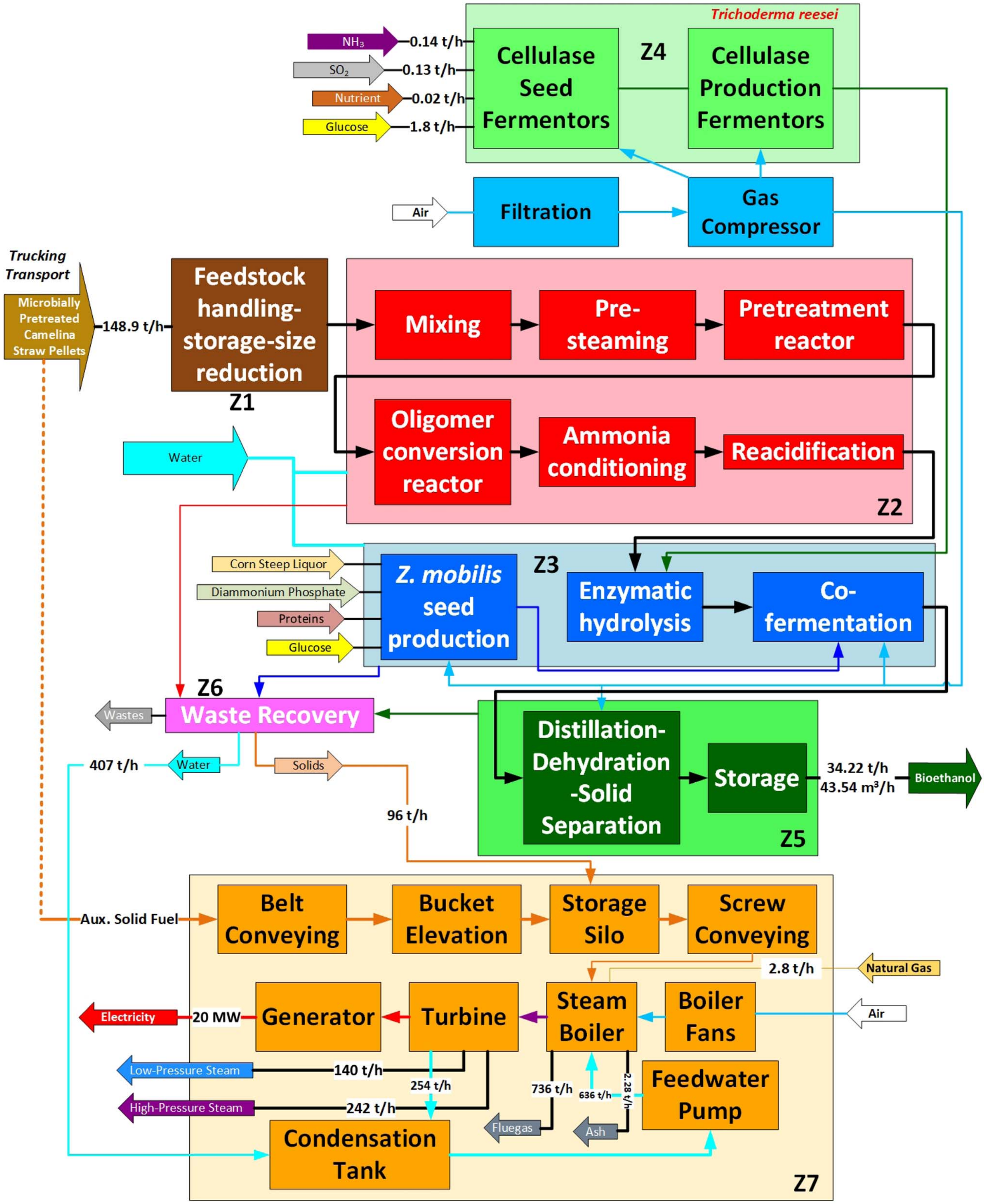

Fig. 4 Simplified block diagram of the modeled cellulosic ethanol production process using microbially pretreated camelina straw pellets as feedstock (Ethanol Plant A): farmer participation rate = 10%, pellet feedstock capacity = 148.90 t per h (note: green block: enzyme production, brown block: feedstock handling and storage, red block: pretreatment, blue block: enzymatic hydrolysis and fermentation, dark green block: product recovery, violet block: waste recovery, and orange block: co-generation plant).

enzyme production (Z4 in green color), (5) product recovery (Z5 in dark green color), (6) waste recovery (Z6 in pink color), and (7) co-generation plant (Z7 in orange color). The operational parameters for the enzymatic hydrolysis reactors and co-fermentation tanks remained consistent with the base-case operating conditions adopted from Humbird *et al.*[64] and detailed in Table S9 in the ESI.†

Z1 processes pellet feedstock supplied by 5 Pellet Plant A from the 5 previously mentioned locations, amounting to 148.90 t per h (equivalent to 1 250 760 t per year, base-case scenario). The pellets are ground to an appropriate size through mechanical comminution and mixed with water to achieve a biomass slurry with around 30% solids.

Z2 is responsible for converting the hemicellulose content of the feedstock into soluble sugars through hydrolysis reactions. It breaks down the cell wall structure, partially delignifies some lignin into soluble lignin, and reduces the cellulose crystallinity and carbohydrate lengths. The process includes a pre-steamer where the biomass slurry (30 wt%) undergoes pretreatment with low-pressure steam (100 °C and 1.02 bar).

It is anticipated that the partial delignification of microbially pretreated CS pellets would allow for a reduction in the operating conditions for subsequent dilute acid pretreatment within the bioethanol plant. This adjustment is reflected in the concentration of H_2SO_4 used in the acid mixer (P-1/MX-101) of Z2, with a reduced mixing ratio of 4.3 mg acid per dry g of substrate, compared to the 18 mg acid per dry g recommended by Humbird *et al.*[64] As a result, a corresponding reduction in ammonia concentration is applied to neutralize the substrate slurry pH in the ammonia conditioner (P-19/V-103). Sulfuric acid (4.3 mg acid per dry g of feedstock) is added to the biomass stream before it enters the pretreatment reactor operating at 158 °C and 5.5 atm for 5 min. The contents of the pretreatment reactor are discharged into a flash tank to maintain a temperature of 130 °C. A secondary oligomer conversion reactor (operating at 130 °C under 5.7 atm) injects an additional 4.1 mg acid per dry g of feedstock, bringing the total acid loading to 8.4 mg acid per dry g of feedstock.

Z3 comprises a seed train system (*Zymomonas mobilis*), enzymatic hydrolysis reactors, and fermentation tanks. Cellulase enzyme from Z4 is mixed with pretreated hydrolysate in a specific ratio to convert cellulose to glucose. The seed train system produces *Z. mobilis* inoculum, which is then mixed with the main saccharified slurry along with corn steep liquor (CSL) and diammonium phosphate (DAP) before entering the fermentation tanks. Z4 involves submerged aerobic cultivation of a *Trichoderma reesei*-like fungus on a medium of glucose and distilled water. The bioreactors received glucose solution, nutrients, ammonia (NH_3) and sulfur dioxide (SO_2). The bioreactors were supplied with compressed-cooled air, corn oil for antifoam, and chilled water for maintaining the temperature.

Z5 separated the fermentation broth from Z3 into anhydrous ethanol, combustible solids, and water. Distillation took place using two distillation columns-the beer column discharges dissolved CO_2 and most of the water, while the rectification column concentrated the ethanol to a near-azeotropic composition. The ethanol concentration was further increased to 99.9% using vapor-phase molecular sieve adsorption.

Z6 separated combustible substances and water for the co-generation plant (Z7) and process water system, respectively. The separated combustible substances were combined with other solid fuels (coal or biomass pellets) and natural gas and then burnt in a multi-fuel-fired furnace to supply heat for the steam boiler. The steam extracted from the steam turbine was used as high-pressure steam (H. P. steam) and low-pressure steam (L. P. steam) for the plant's operation, while the remaining steam drove the generators to produce electricity for the plant.

2.3 Process economics

2.3.1 Total capital investment (TCI). To predict the potential TCI range for Pellet Plant A, two scenarios (Scenario 1 and Scenario 2) were proposed, considering cost factors (A to L). In Scenario 1, known as the minimum cost factor scenario, all costs were set to their minimum values based on Mupondwa *et al.*[17] In Scenario 2, labelled as the maximum cost factor scenario, higher values were assigned to the factors, aligning with those of the fluid-solid process type[70] (refer to Table S6 in the ESI†).

For Pellet Plant A, equipment purchase costs were primarily determined using the SuperPro Designer Built-In Cost Model, except for major equipment. Costs for storage tanks, seed fermentors, and the final fermentor were based on units recommended by Humbird *et al.*[64] The indoor-wet-storage MBP combined with mushroom cultivation facility cost was estimated by calculating straw volume over a 30-day period, factoring in expenses for constructing a facility with insulation, ventilation, moisture, and lighting. Since the pellet mill was not standard in the software, the extrusion unit represented it, and its cost was sourced from vendors.

For the bioethanol plant, equipment costs were obtained from the SuperPro Designer Built-In Cost Model based on their capacities. Cost assumptions for both pellet and bioethanol plants are detailed in Table S6 (ESI).† Pellet Plant A considered minimum and maximum cost factors (A–L) for TCIs, while maximum factors were used for the ethanol plants, Pellet Plant B, and Pellet Plant C. Actual equipment costs were calculated using eqn (3).[70]

$$C_{\text{actual}} = C_{\text{base}}\left(\frac{S_{\text{actual}}}{S_{\text{base}}}\right)^n\left(\frac{\text{CEPCI}_{\text{current}}}{\text{CEPCI}_{\text{base}}}\right)f_{\text{installation}} \tag{3}$$

where S_{actual} = the actual equipment size as determined from the simulation; S_{base} = the base equipment size acquired from the literature; C_{actual} = the final equipment cost with the capacity S_{actual}; C_{base} = the base equipment cost with the capacity S_{base}; n = the exponential scaling factor which could be obtained from Humbird *et al.*[64] and Towler and Sinnott;[70] $\text{CEPCI}_{\text{current}}$ = the Chemical Engineering Plant Cost Index (CEPCI) of the year 2023 which could be acquired from CEPCI;[71] $\text{CEPCI}_{\text{base}}$ = the CEPCI of the base year which could be acquired from CEPCI;[71] and $f_{\text{installation}}$ = the installation factor.

2.3.2 Unit production cost (UPC). The UPC is calculated by dividing the annual total operating cost by the plant's capacity. The MSP for pellets ensures a zero NPV. Operating costs comprise materials, consumables, labor, utilities, waste treatment, facilities, laboratory/QC/QA, transportation, miscellaneous, advertising, running royalties, and failed product disposal. Variable operating costs, incurred during active operation, cover raw materials, utilities, consumables, waste disposal, and packaging. Fixed operating costs include labor, supervision, salary overhead, maintenance, property taxes, insurance, rent, plant overhead, license fees, capital charges, and sales/marketing costs.

2.3.3 Profitability analysis of the biofuel plants. The economic viability of each biofuel plant was assessed using capital investment analysis to maximize the net present value (NPV) within a predetermined initial capital investment, considering operating costs and yearly cash flows from biofuel sale revenue. Revenue computation employed production theory to define the profit function ($\Pi(p,w;F) \equiv \max_{qx}\{p\cdot q - w\cdot x(q,x{:}F) \in S\}$), dependent on biofuel plant technology.[17] Variables include p (biofuel prices), w (input prices), q (biofuel output), x (inputs for one unit of biofuel), F (fixed inputs), and S (feasible input/output combinations). The closed, bounded, smooth, and strictly convex set S implies an optimal production plan determinable by plant managers. Using this principle, the NPV is derived from the disparity between discounted yearly cash flows from biofuel sales and corresponding production costs, as defined by using eqn (4).[72]

$$\mathrm{NPV} = -I_0 + \sum_{t=1}^{N} \frac{\mathrm{CFA}_t}{(1+r)^t} + \frac{\mathrm{SV}_N}{(1+r)^N} \tag{4}$$

where I_0 = the TCI of the biofuel production plant; CFA_t = the annual cash flow, $\mathrm{CFA}_t = (\mathrm{TR}_t - \mathrm{TC}_t - \mathrm{DEP}_t)(1 - T) + \mathrm{DEP}_t$, where TR_t is the total revenue before tax, TC_t is the total cost, DEP_t is the depreciation over the depreciation period, and T is the corporate marginal tax rate; SV_N = the salvage value of the plant; r = the discount rate or cost of capital; $t = 1, 2, 3,\ldots,N$ denotes year with N terminal times. The salvage value, depreciation period, and discount rate can be acquired from Table S6 in the ESI.†

2.3.4 Sensitivity analysis

2.3.4.1. Pellet and mushroom production from Pellet Plant A

2.3.4.1.1. Effect of pellet selling price on profitability. In cost-factor scenarios 1 and 2 of Pellet Plant A, the initial sensitivity analysis assessed the impact of the pellet selling price (PSP) on key financial metrics, including NPV, internal rate of return (IRR), payback time (PBT), return on investment (ROI), and unit production cost (UPC). PSP varied from US$200 per t to US$400 per t, considering the pellet market outlook from 2009 to 2023.[73] The feedstock cost was fixed at US$48.84 per t.

2.3.4.1.2. Effect of feedstock cost on profitability. The second sensitivity analysis assessed the impact of plant site feedstock costs on the mentioned financial metrics in both scenarios. While the PSP remained at US$300 per t, the feedstock price varied from US$30 to US$70 per t.[17] Fixed parameters in both analyses included a feedstock supply capacity of 1270 t per day, a US$5 million MBP facility cost, project-financed equity at 40% of the direct fixed cost (DFC), and a 10% interest rate over 10 years.

2.3.4.1.3. Effect of farmer participation rate on profitability. The third analysis explored the economy-of-scale impact on pellet UPC in Scenario 2. Farmer participation rates ranged from 10% to 100%, affecting feedstock supply capacities from 1270.0 t per day to 12 699.8 t per day. These adjustments revealed changes in pellet production capacity, unit production cost, and MSP. Simultaneously, the impact of PSP on the project NPV across varied plant capacities was also studied. PSP ranged from US$100 per t to US$300 per t, with a fixed feedstock cost of US$48.84 per t. Five cases of farmer participation rates corresponding to different pellet production capacities were considered.

2.3.4.1.4. Effect of major important factors on pellet UPC. In the fourth analysis, key technoeconomic variables of Pellet Plant A were individually adjusted by ±30%, and the ensuing changes in pellet UPC were recorded. Scenario 2 was the reference point for this analysis, selected as the baseline for representing the "worst-case" scenario with the highest TCI.

2.3.4.1.5. Effect of mushroom selling price on profitability. The selling price of Turkey tail mushrooms was estimated based on the average market price of Turkey tail extract. This average price was calculated from nine products, initially listed in Canadian dollars, and converted to USD (see Table S10 in the ESI†). The final average selling price of Turkey tail extract was approximately 653.1 USD per kilogram. To estimate the selling price of Turkey tail mushrooms at the plant gate, this value was adjusted to represent between 10% and 50% of the extract's price, resulting in a range of 65 to 327 USD per kilogram. The corresponding project's NPV was then calculated based on this range of selling prices. Fungal biomass yield was adjusted from 10% to 100% of the maximum fungal biomass yield obtained from our previous study.[1] Scenario 2 of the maximum cost factor was used, and the pellet selling price was kept at US$100 per t.

2.3.4.1.6. Effect of MBP facility cost on profitability. The effect of MBP facility cost on the project's profitability was investigated by adjusting the MBP facility cost from US$5 million to US$50 million. Constant values used were US$100 per t for pellet selling price, US$196 per kg for mushroom selling price (30% of the Turkey tail extract price), and 0.02475 g of fungal biomass per gram of dry substrate (50% of the maximum fungal biomass yield).

2.3.4.2. Bioethanol production from Ethanol Plant A. In the initial analysis, pellet feedstock cost and ethanol plant capacity were chosen to assess ethanol UPC across varied farmer participation rates. Pellet feedstock cost ranged from US$50 per t (ref. 64) to US$300 per t,[73] with plant capacity adjusted from 356 582 328 L per year (93 949 835 gal per year) to 1 762 125 949 L per year (464 272 705 gal per year), corresponding to participation rates of 10% to 50%. Cases of 75% and 100% participation rates were excluded from ethanol plant design due to impracticality and high utility costs. In the second analysis, the NPV of the bioethanol production project was examined with varying minimum ethanol selling prices (MESP) and different farmer participation rates, specifically 10%, 25%, and

50%. MESP ranged from US\$0.79 per L (US\$3.00 per gal) to US\$1.45 per L (US\$5.50 per gal).

3 Results and discussion

3.1 Pellet and mushroom production

3.1.1 Mass and energy balance. The mass balance of Pellet Plant A was determined and is depicted in Fig. S9 (ESI).† Analysis of the graph reveals that 75.7% of the provided feedstock (the primary carbon stream) was utilized for pellet production, while 24.3% was used for generating heat and electricity. During the MBP and pelleting processes, approximately 25.6% of the input feedstock for pellet production was lost, primarily due to hydrocarbon consumption by the white-rot fungus. The majority of the feedstock allocated for heat and electricity generation was converted into combustion products, namely flue gas and bottom ash. In terms of the water balance, three main water input streams were identified, namely new makeup-water, moisturizing water for MBP, and water for medium preparation. These streams accounted for 70.8%, 21.3%, and 7.9%, respectively. Water loss accounted for 58.9% of the total input water, distributed respectively to L. P. steam for sterilization (50.5%), medium preparation (13.4%), and water for maintaining moisture content of straw bales (36.1%). The energy balance of the pellet production is also illustrated (Fig. S10 in the ESI†). The BTG block was responsible for providing heat and electricity for the whole plant including FIP, PP blocks and itself. The useful energy includes: (1) the turbine shaft power (11% of the energy from combustion (EFC)); (2) the H. P. steam extraction (7% of EFC); and (3) the L. P. steam extraction (4% of EFC), leading to an efficiency of 22%. The majority of energy loss was *via* (1) condensation to cooling water (58% of EFC), (2) flue-gas (15% of EFC), and (3) heat loss to the surrounding environment (6% of EFC).

3.1.2 Process economics

3.1.2.1. TCI of Pellet Plant A. All prices in the results are presented in 2023 US dollars unless specified otherwise. The TCI breakdown analysis of Pellet Plant A is depicted in Fig. 5(a) and (b). For Scenario 1, the TCI of Pellet Plant A amounted to US\$55 931 000, while for Scenario 2, it reached US\$117 449 000. The TCI plays a significant role in influencing the production cost per unit of pellets through the cost associated with the facility and its dependencies. Various cost factors have the potential to double the TCI of the plant, such as increased installation costs, process piping expenses, instrumentation expenditures, electrical costs, building expenses, auxiliary costs, and engineering fees. In Scenario 1, equipment purchase costs accounted for 40.2% of the TCI but decreased to only 19.1% in Scenario 2. Similarly, the installation cost decreased from 13.6% to 6.5% between the two scenarios. It is crucial to thoroughly examine and minimize these associated costs, in addition to equipment purchase and installation expenses, as doing so can significantly impact the TCI and subsequently reduce the production cost per unit.

When examining conventional wood pellet plants, a wood pellet plant with a capacity of 22.5 t per h (equivalent to 180 000 t per year) incurred costs ranging from US\$18 million to US\$20 million (in 2008 \$), which translated to approximately US\$100.8 per [t per year] to US\$133.3 per [t per year].[74] The specific capital investment for 250 000 t per year plants was estimated to be around US\$140 $[\text{t per year}]^{-1}$.[75] As extrapolated from the study by Pantaleo *et al.*,[76] the TCI of a 250 000 t per year wood pellet plant would be between US\$72.3 million to US\$90.7 million. Thus, considering a wood pellet plant with a capacity of 250 000 t per year (as envisioned in this study), the capital investment could amount to approximately US\$36 million to US\$90.7 million. Notably, these conventional plants utilized sawdust and woody biomass, which required minimal pretreatment and did not necessitate additional pretreatment facilities. On a different note, Pirraglia *et al.*[77] presented a cost estimation of US\$50 million (in 2013 \$) for a torrified-wood pellet production facility with an annual capacity of 100 000 t. Extrapolating from this, a pellet plant with a capacity of 250 000 t per year would entail an estimated cost of approximately US\$180 million. In summary, the TCI for a pellet plant with a capacity of 250 000 t per year, as proposed in this study, would fall within the range of US\$36 million to US\$180 million. The exact figure would be contingent on the pretreatment facility's cost and the prevailing market prices of equipment offered by vendors.

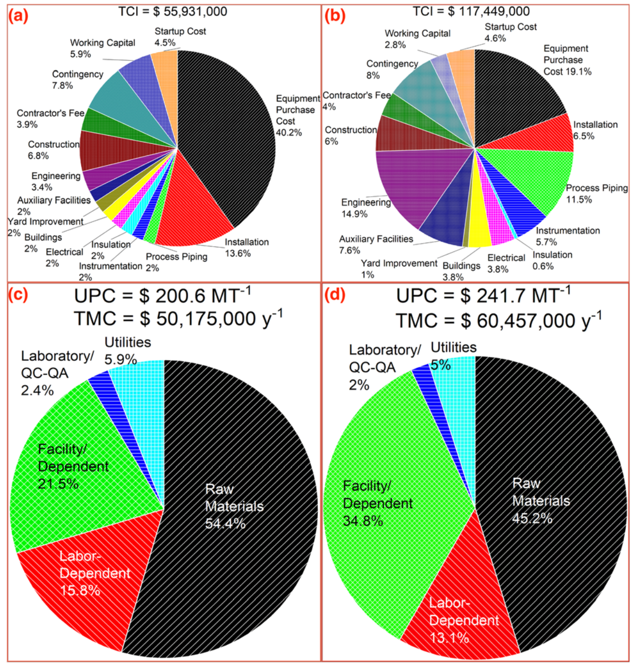

Fig. 5 Total capital investment (TCI), total manufacturing cost (TMC), and unit production cost (UPC) of Pellet Plant A. (a) and (c) Scenario 1: cost assumption factors (A to L) were set to the minimum; (b) and (d) Scenario 2: cost assumption factors (A to L) were set to the maximum (see Table S6 in the ESI† for more details on cost scenarios).

3.1.2.2. UPC of Pellet Plant A, B, and C. Fig. 5(c) and (d) present a visual representation of the UPC of Pellet Plant A. A twofold increase in TCI, from US\$55 931 000 in Scenario 1 to US\$117 449 000 in Scenario 2, resulted in a noteworthy 20% increase in the pellet UPC, equivalent to US\$41 per t of increment. Specifically, the UPC escalated from US\$200.6 per t to US\$241.7 per t between Scenarios 1 and 2. In the specific context of Scenario 1, the cost of raw materials accounted for the largest portion, contributing to 54.4% of the overall expenses. Following this, the facility-dependent cost constituted the second-largest share at 21.5%, while the labor-dependent cost represented 15.8%. Upon doubling the TCI from Scenario 1 to Scenario 2, the share of facility-dependent cost (34.8%) experienced a substantial increase, while the share of raw material cost reduced to 45.2%. Notably, the utility cost, which encompasses cooling and chilled water, remained limited to a range of 5.0% to 5.9% of the UPC, owing to the utilization of biomass fuel for in-house co-generation. Of the various components contributing to raw material expenses, the largest portion, constituting 79.3%, was attributed to the feedstock cost, with the subsequent expense being the cost of glucose (19.7%), which serves the purpose of sustaining microbial growth.

The HHV of CS pellets pretreated with TVm4D was 17.5 MJ kg^{-1} leading to a pellet UPC of US$11.5 per GJ and US$13.8 per GJ for Scenarios 1 and 2, respectively. The pellet UPC determined in this study was higher than that of torrefied-wood pellets. Specifically, the MSP of the torrefied-wood pellets at the plant gate was calculated to be US$207 per t (US$8.5 per GJ) for the 100 000 t per year plant, and this slightly decreased to US$186 per t (US$7.7 per GJ) for the 200 000 t per year plant.[78]

The increased pellet UPC obtained in this study is probably due to the fungal liquid inoculum, currently set at a ratio of 10 mL liquid fungal inoculum per 20 dry g substrate. By refining the flow rate and concentration of the fungal inoculum, there is potential for optimizing nutrient expenses and subsequently diminishing the pellet UPC. To reduce the pellet UPC, several strategic avenues can be explored. Firstly, incorporating agricultural activities into the MBP process, such as cultivating mushrooms on straw bales (see the preliminary result in Fig. S11 of the ESI†), can add significant value to the operation. Within the MBP phase, mushrooms can be cultivated and harvested within a brief timeframe of 35–42 days before the straw bales are transported to the pellet production facility. This integration can yield additional benefits and efficiency to the entire operation. Secondly, expanding feedstock capacity by

Table 3 Comparative technoeconomic analysis of pellet production between Pellet Plant A, Pellet Plant B, and Pellet Plant C[a]

Parameters	Unit	Pellet Plant A	Pellet Plant B	Pellet Plant C
Pellet unit production cost	[US$ per t]	241.71	180.72	166.34
Feedstock cost	[US$ per t]	48.84	48.84	48.84
Feedstock capacity	[t per year]	443 607	443 607	443 607
Pellet production capacity	[t per year]	250 118	344 925	239 792
Pellet yield	[t pellet per (t w.b. feedstock)]	0.56	0.78	0.54
	[t pellet per (t d.b. feedstock)]	0.60	0.82	0.57
Discount rate	[%]	10	10	10
Equity percent of total investment	[%]	40	40	40
Capital costs				
(1) Equipment purchase cost	[US$]	22 461 000 (19.12%)	15 418 000 (17.76%)	12 232 000 (18.32%)
(2) Installation	[US$]	7 599 000 (6.47%)	7 935 000 (9.14%)	5 495 000 (8.23%)
(3) Process piping	[US$]	13 476 000 (11.47%)	9 251 000 (10.65%)	7 339 000 (10.99%)
(4) Instrumentation	[US$]	6 738 000 (5.74%)	4 625 000 (5.33%)	3 670 000 (5.50%)
(5) Insulation	[US$]	674 000 (0.57%)	463 000 (0.53%)	367 000 (0.55%)
(6) Electrical	[US$]	4 492 000 (3.82%)	3 084 000 (3.55%)	2 446 000 (3.66%)
(7) Buildings	[US$]	4 492 000 (3.82%)	3 084 000 (3.55%)	2 446 000 (3.66%)
(8) Yard improvement	[US$]	1 123 000 (0.96%)	771 000 (0.89%)	612 000 (0.92%)
(9) Auxiliary facilities	[US$]	8 984 000 (7.65%)	6 167 000 (7.10%)	4 893 000 (7.33%)
(10) Engineering	[US$]	17 510 000 (14.91%)	12 699 000 (14.62%)	9 875 000 (14.79%)
(11) Construction	[US$]	7 004 000 (5.96%)	5 080 000 (5.85%)	3 950 000 (5.91%)
(12) Contractor's fee	[US$]	4 728 000 (4.03%)	3 429 000 (3.95%)	2 666 000 (3.99%)
(13) Contingency	[US$]	9 455 000 (8.05%)	6 858 000 (7.90%)	5 333 000 (7.99%)
(14) Working capital	[US$]	3 276 000 (2.79%)	4 028 000 (4.64%)	2 388 000 (3.58%)
(15) Startup cost	[US$]	5 437 000 (4.63%)	3 943 000 (4.54%)	3 066 000 (4.59%)
Total capital investment	[US$]	117 449 000 (100%)	86 835 000 (100%)	66 778 000 (100%)
Total capital investment/annual t	[US$]	469.57	251.75	278.48
Manufacturing cost				
Raw materials	[US$ per year]	27 317 000 (45.18%)	43 303 000 (69.47%)	24 474 000 (61.36%)
Labor-dependent	[US$ per year]	7 909 000 (13.08%)	1 016 000 (1.63%)	1 252 000 (3.14%)
Facility-dependent	[US$ per year]	21 050 000 (34.82%)	15 188 000 (24.37%)	11 833 000 (29.67%)
Laboratory/QC/QA	[US$ per year]	1 186 000 (1.96%)	152 000 (0.24%)	188 000 (0.47%)
Utilities	[US$ per year]	2 995 000 (4.95%)	2 675 000 (4.29%)	2 139 000 (5.36%)
Total manufacturing cost	[US$ per year]	60 457 000 (100%)	62 334 000 (100%)	39 886 000 (100%)

[a] Scenario 2 of maximum cost factors, assuming zero revenue from selling mushrooms, was used for Pellet Plant A, Scenario 2 of maximum cost factors was also used for Pellet Plant B and Pellet Plant C, and values in brackets represent the percentage contribution of each factor to the total capital investment or total manufacturing cost.

sourcing diverse agricultural residues from the province can contribute to cost efficiency. Thirdly, optimizing equipment choices, focusing on more cost-effective options that produce pellets of acceptable quality, can result in substantial savings in the initial capital investment. Lastly, considering the potential for carbon credits or government subsidies is essential, especially as the setup does not rely on fossil fuels. These multifaceted approaches hold promise for enhancing both the economic viability and sustainability of the pellet production process.

Table 3 presents the technoeconomic analysis of Pellet Plant A, B, and C. Additionally, the impact of varying CS bale costs on their pellet UPCs can be found in Fig. 6. With a feedstock price of US$48.84 per t, the results reveal that Pellet Plant C, which employs biomass-fired steam boiler and steam explosion pretreatment (with a pellet UPC of US$166 per t or US$8.9 per GJ), exhibits the most cost-efficient pellet production. Following this, Pellet Plant B achieves a pellet UPC of US$181 per t (US$9.7 per GJ), and Pellet Plant A registers the highest pellet UPC at US$242 per t (US$13.8 per GJ). The observed pellet UPC values for steam explosion pretreatment plants align with those in a previous study. For instance, steam-pretreated wheat straw pellets and steam-pretreated switchgrass pellets achieved UPCs of US$152.63 per t and US$156.31 per t, respectively.[79] The primary reason for the lower pellet UPCs in scenarios where heat and steam are produced from gas-fired steam boilers, and electricity is procured from the grid, is the favorable pricing of natural gas and electricity in Saskatchewan.

3.1.2.3. Sensitivity analysis of Pellet Plant A

3.1.2.3.1. Effect of the pellet selling price on profitability. The impacts of PSP on the NPV, IRR, PBT, and ROI for Scenario 1 and Scenario 2 of Pellet Plant A, assuming zero revenue from selling mushrooms, are depicted in Fig. 7(a) and (b) respectively. In Scenario 1, achieving a PBT of 5 years necessitated a PSP value of US$240 per t, resulting in a corresponding NPV of US$63 million, an IRR of 21.5%, and an ROI of 19.9%. As for Scenario 2, with an increase in TCI, maintaining a 5 year PBT required a higher PSP of at least US$320 per t. This led to a corresponding NPV of US$133 million, an IRR of 22.4%, and an ROI of 19.6%.

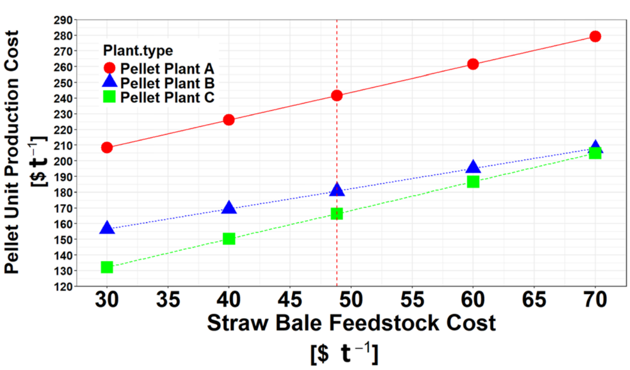

Fig. 6 Comparison of unit production cost between the microbial pretreatment pellet plant and steam-explosion pretreatment pellet plant: the vertical red line represents a straw bale feedstock cost of US$48.84 per t; Pellet Plant A: microbial pretreatment pellet plant, Pellet Plant B: steam explosion pellet plant using a natural gas-fired steam boiler, Pellet Plant C: steam explosion pellet plant using a biomass-fired steam boiler.

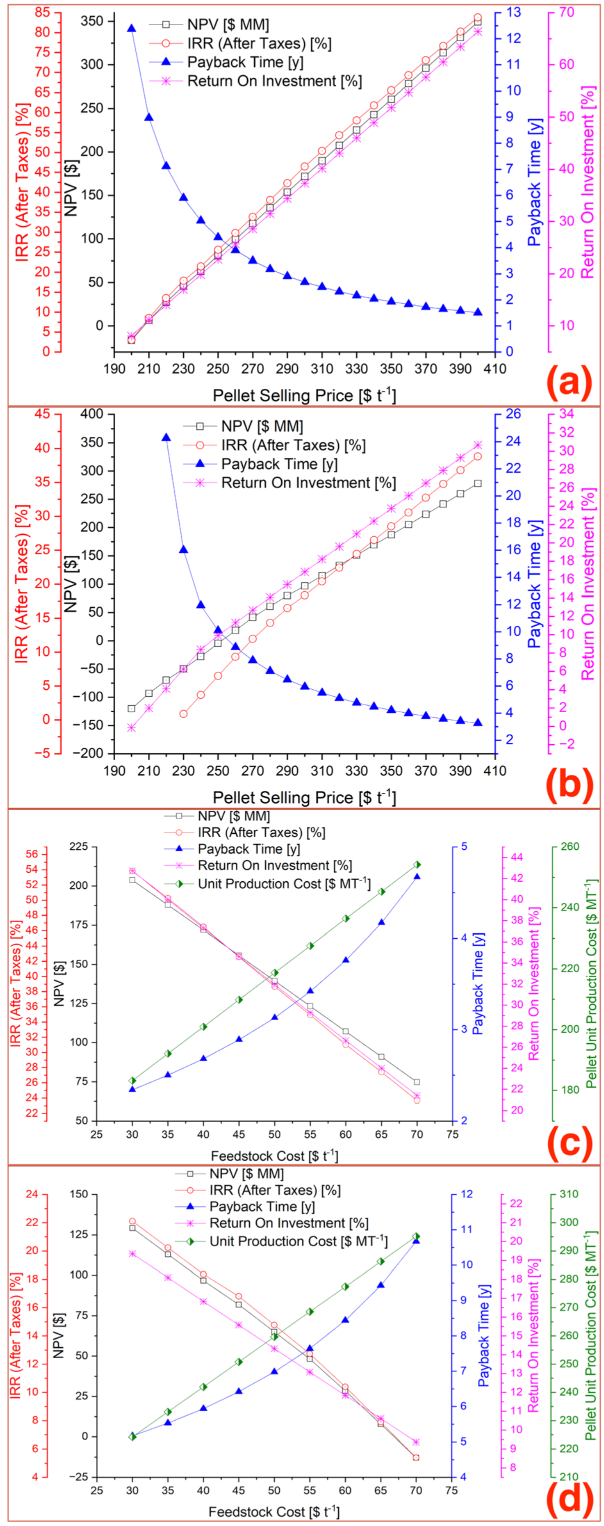

Fig. 7 Impact of pellet selling price and feedstock cost on the economic viability of Pellet Plant A without revenue from selling mushrooms: (a) and (c) data for Scenario 1, while (b) and (d) correspond to values for Scenario 2.

3.1.2.3.2. Effect of the feedstock cost on profitability. The figures presented in Fig. 7(c) and (d) illustrate the impact of feedstock cost on the NPV, IRR, PBT, ROI, and UPC of Pellet Plant A, assuming zero revenue from selling mushrooms and a PSP of US$300 per t. For both scenarios, an increase in feedstock cost was observed to correspondingly increase the UPC and PBT values, while decreasing the NPV, IRR, and ROI. In Scenario 1, regardless of the feedstock cost, the PBT remained below 5 years, and the UPC ranged from US$183.2 to US$254.2 per t. Interestingly, the NPV exhibited positive values within this feedstock cost range, indicating a predicted feedstock cost of US$93.2 per t that would yield an NPV of zero. This means the maximum feedstock cost the plant in Scenario 1 is willing to buy, assuming the pellet is sold at a market price of US$300 per t, is US$93.2 per t. Consequently, the corresponding IRR and ROI decreased from 53.8% to 23.7% and from 42.8% to 21.4%, respectively. In Scenario 2, as the feedstock cost increased from US$30 to US$70 per t, the UPC increased from US$224.2 to US$295.2 per t, while the PBT extended from 5.2 to 10.7 years. The feedstock cost at which the NPV reached zero was determined to be US$67.6 per t.

3.1.2.3.3. Effect of the participation rate on profitability. Table 4 illustrates the impact of farmer participation rate on various technoeconomic parameters of each Pellet Plant A. When the participation rate increased by a factor of 10, ranging from 10% to 100%, the feedstock supply capacity also underwent a tenfold increase. However, the TCI and TMC experienced only 5.1 and 6.1 times increments, respectively. Consequently, the UPC and MSP decreased by a factor of 1.8, reaching optimal values of US$135.3 per t and US$139.5 per t, respectrively. It is important to note that achieving a farmer participation rate exceeding 10% may appear challenging in practice. However, it is worth noting that MBP pelleting facilities have the flexibility to utilize residues from various crops – such as canola, wheat, flax, lentils, oats, barley straw, and others – thereby increasing the feedstock supply capacity.

The NPV of Pellet Plant A is plotted against the PSP for different production capacities (Fig. 8). The red line indicates the NPV's zero value. Evidently, the PSP demonstrates a tendency to decrease as the plant capacity increases.

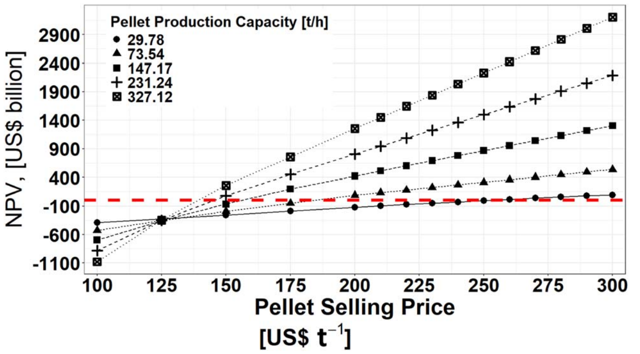

Fig. 8 Net present value for 30–330 t per h Pellet Plant A at the baseline (10%) discount rate, a camelina straw feedstock cost of US$48.84 per t, for a range of pellet prices, and 100% capacity utilization (assuming zero revenue from selling mushrooms).

According to Strauss[73] in their study on the pellet market, a commercial-grade biomass pellet could fetch a price of approximately US$300 per t. This price, as a result, has the potential to yield a positive NPV across all production capacity scenarios considered in this study.

3.1.2.3.4. Effect of major important factors on the pellet UPC. Fig. 9 illustrates the fluctuations of pellet UPC resulting from ±30% adjustments in various technoeconomic variables. It is evident that the most pronounced impact on pellet UPC is attributed to feedstock cost, closely followed by equipment purchase cost. This emphasizes the significance of reducing straw bale costs and minimizing plant investment expenses to effectively lower pellet UPC. The allowable depreciation period also exerts notable influence on pellet UPC, demonstrated by the decrease from US$241.7 per t to US$232.2 per t as the depreciation period extends from 10 to 13 years. This suggests that further extending the depreciation period could yield a greater reduction in pellet UPC since the plant's lifetime was proposed as 30 years. A 30% alteration in pretreatment time exhibits a 5% shift in pellet UPC. However, any decrease in pretreatment time should consider its implications on delignification efficacy, which in turn affects pellet quality.

Table 4 Effect of farmer participation rate on the technoeconomic indices of Pellet Plant A[a]

Farmer participation rate	[%]	10	25	50	75	100
Feedstock capacity	[t per d]	1270.0	3174.9	6349.9	9524.8	12 699.8
	[t per year]	444 500	1 111 215	2 222 465	3 333 680	4 444 930
Feedstock for pellet production	[t per h]	40.0	100.0	201.1	317.5	449.8
Feedstock for heat-power production	[t per h]	12.9	32.3	63.5	79.4	79.4
Pellet capacity	[t per h]	29.8	73.5	147.2	231.2	327.1
Power consumed	[MW]	6.44	9.10	13.43	18.13	23.36
Power generated	[MW]	7.03	10.97	14.34	19.83	26.94
Total capital investment	[US$]	117 454 000	195 305 000	312 507 000	445 801 000	594 508 000
Total manufacturing cost	[US$ per year]	60 518 000	109 485 000	186 311 000	273 656 000	371 713 000
Unit production cost	[US$ per t]	242.0	177.2	150.7	140.9	135.3
Minimum selling price	[US$ per t]	252.0	183.7	155.8	145.4	139.5

[a] Feedstock cost = US$48.84 per t for all cases of participation rate. Scenario 2 of maximum cost factors, assuming zero revenue from selling mushrooms was used.

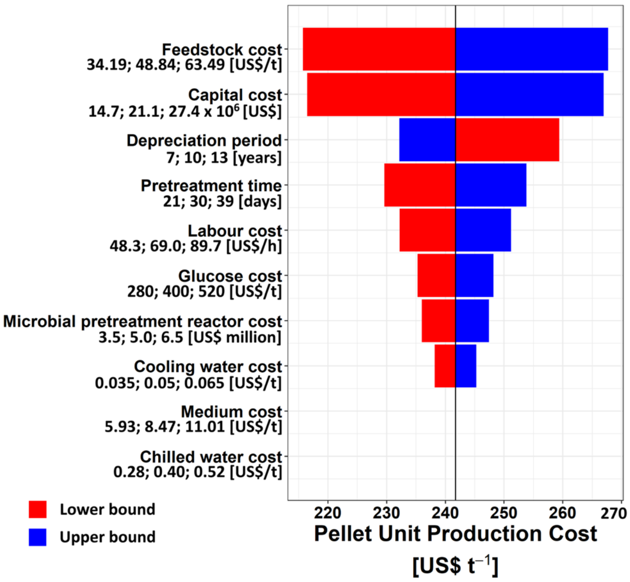

Fig. 9 Sensitivity analysis of pellet unit production cost from Pellet Plant A (Scenario 2): UPC = US$242 per t at the base case and each factor was adjusted ±30%.

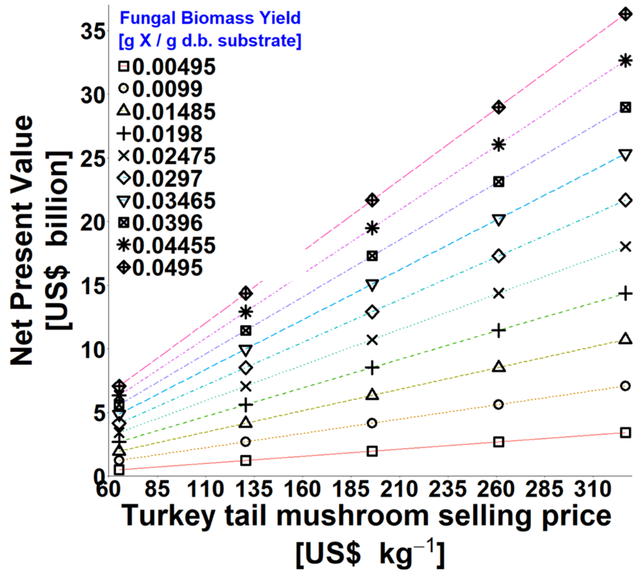

Fig. 10 Effect of mushroom selling price on Pellet Plant A's net present value (note: Pellet Plant A-Scenario 2, pellet selling price = US$100 per t).

Additional factors such as labor cost, glucose expenditure, and cooling water outlay significantly impact pellet UPC. Moreover, the costs associated with developing the "on-farm-indoor-wet-storage-MBP facility" are noteworthy and contribute to the overall capital investment costs.

3.1.2.3.5. Effect of mushroom selling price on profitability. Selling mushrooms for supplementary production could significantly boost the profitability of Pellet Plant A. Fig. 10 illustrates how the mushroom selling price and fungal biomass yield affected the NPV of the pellet plant. Even with only 10% of the maximum fungal biomass yield (0.00495 g of fungal biomass per g of dry substrate), the NPV shifted from US$478.6 million to US$3405 million over a 30 year plant life when the mushroom selling price increased from US$65 per kg to US$327 per kg. Revenue from selling mushrooms could reduce the pellet MSP, making the pellet price more competitive in the market. A lower MESP of ethanol produced from microbially pretreated pellets could also be expected due to the reduced pellet purchasing price.

3.1.2.3.6. Effect of MBP facility cost on profitability. Several factors can influence the development cost of a large-scale mushroom incubation plant, making it reasonable to consider a potential increase in MBP facility cost by up to 10 times (US$50 million). Despite this significant cost increase, the project consistently generated a highly positive NPV of around US$10 billion. As the TCI increased from US$118 million to US$348 million, the gross margin decreased from 96% to 93%, ROI fell from 846% to 283%, payback time extended from 0.12 to 0.35 years, and IRR dropped from 670% to 301% (Fig. 11). This indicates that even with a substantial increase in MBP facility cost, Pellet Plant A's profitability from both pellet and mushroom sales remained largely unaffected.

3.2 Bioethanol production

3.2.1 Mass and energy balance. The mass balance of Ethanol Plant A was determined and is plotted in Fig. S10 (ESI).† The total mass flow rate was 20.3 t per h for the enzyme production block, 482.3 t per h for the feedstock handling & pretreatment block, 487.5 t per h for the enzymatic hydrolysis & fermentation block, 132.4 t per h for the product recovery block, 514.9 t per h for the waste recovery block, and 1562.8 t per h for the co-generation plant. Considering the carbon mass flow, with 148.9 t per h of pellets entering the plant, 34.2 t per h of ethanol was produced leading to an ethanol yield of 285 L per (t w.b. pellets) (equivalent to 75 gal per (t w.b. pellets)) or 304 L per (t d.b. pellets) (equivalent to 80 gal per (t d.b. pellets)). This finding aligns with the conclusions drawn in a prior research study conducted by Humbird *et al.*,[64] where they reported an ethanol yield of 79 gal per t of corn stover feedstock. In terms of water balance, the majority of water loss was *via* L. P. steam 1 utilized in the pre-steamer of the FHP block. This loss accounted for 32% of the new make-up water demand of the ethanol plant.

The energy balance of Ethanol Plant A is also provided (refer to Table S11 in the ESI†). The energy breakdown from biomass feedstock constituted 95% of the total energy input, with the remaining 5% attributed to natural gas. The principal energy output streams were represented by ethanol, which accounted for 33% of the energy input, followed by high-pressure steam for the overall process at 26%, low-pressure steam for the process at 13%, and the turbine's shaft work at 6%. Notable energy losses occurred *via* the boiler's flue gas, accounting for 11% of the energy input, as well as low-pressure steam utilized in the pre-steamer, which accounted to 9% of the energy input. Additional losses within the entire process contributed to 11% of the

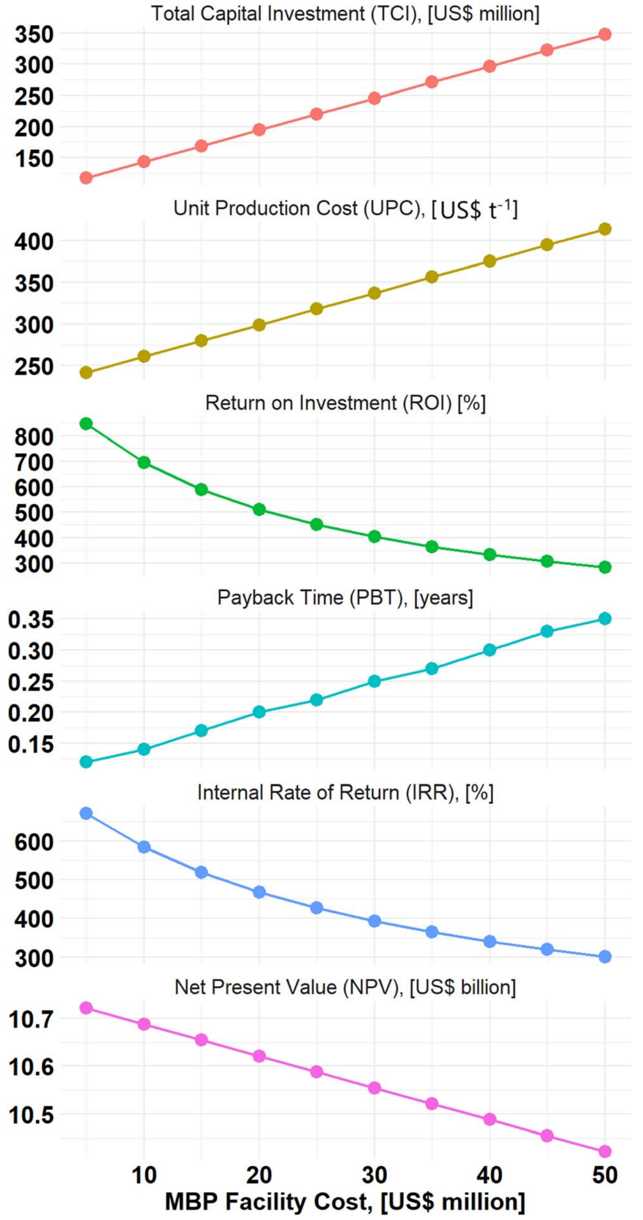

Fig. 11 Effect of MBP facility cost on Pellet Plant A's total capital investment, pellet unit production cost, return on investment, payback time, internal rate of return, and net present value (note: Pellet Plant A-Scenario 2, pellet selling price = US$100 per t, mushroom selling price = US$196 per kg, fungal biomass yield = 0.02475 g biomass per (g d.b. substrate)).

energy input. In total, the sum of useful energy stood at 77.8% of the initial process input energy.

3.2.2 Process economics

3.2.2.1. TCI of Ethanol Plant A, B, and C. Table 5 indicates the technoeconomic analysis of Ethanol Plant A in comparison with Ethanol Plant B and Ethanol Plant C. Among the three ethanol plants considered, Ethanol Plant A exhibited the lowest TCI at US$478 million, followed by Ethanol Plant C with US$684 million, and Ethanol Plant B with approximately US$1 billion. The notably high TCI for Ethanol Plant B stemmed from substantial investments directed toward establishing centralized MBP facilities designed large enough to handle feedstock sourced from five distinct zones. In terms of TCI per annual liter of ethanol, Ethanol Plant C boasted the lowest value at US$1.03 per annual liter (or US$3.92 per annual gallon), followed by Ethanol Plant A at US$1.34 per annual liter (or US$5.08 per annual gallon) and Ethanol Plant B at US$2.03 per annual liter (or US$7.72 per annual gallon). These results are consistent with a previous benchmark where the TCI per annual liter from corn stover was approximately US$1.82 (in 2011 US$) (or US$6.92 per annual gallon in 2011 US$).[64]

3.2.2.2. UPC of Ethanol Plant A, B, and C. Ethanol Plant A (A^1 in Table 3) showcased the highest ethanol UPC at US$1.32 per L (US$5.01 per gal), followed by Ethanol Plant B at US$0.89 per L (US$3.36 per gal), and Ethanol Plant C at US$0.57 per L (US$2.15 per gal). Ethanol Plant C's ethanol UPC aligned with the outcome presented by Humbird *et al.*[64]. Although MBP managed to curtail the expenses associated with upstream pretreatment at the ethanol plant, the elevated cost of microbially pretreated pellets themselves posed a challenge in justifying their use for ethanol production.

Revenue from selling Turkey tail mushrooms could lower the pellet production cost and selling price, thereby reducing the ethanol MESP. For instance, the MESP of Ethanol Plant A (A^2 in Table 3) decreased to US$0.77 per L (US$2.90 per gal) with a pellet feedstock cost of US$100 per t, making it highly competitive with the MESP of Ethanol Plant C. A strategy to integrate the ownership of five Pellet Plant A with one Ethanol Plant A, assuming revenue from mushroom sales and zero cost for purchasing pellets for the bioethanol plant, could further reduce the MESP to US$0.41 per L, making both the pellet plants and the ethanol plant economically viable.

The elevated ethanol UPC in Ethanol Plant A resulted primarily from the high UPC of pellets from Pellet Plant A. It is crucial to note that the modeled pellet plant aimed for premium pellet production for overseas shipping. In practical applications, cost-effective equipment producing "adequate" pellets could be used to reduce capital investment and, consequently, pellet production costs. This approach is viable when pellets are destined for local power plants or biorefinery facilities within the same province.

Given that ethanol production from microbially pretreated pellets may not be economically feasible, exploring the possibility of upgrading this ethanol to aviation fuel presents an opportunity to enhance the selling price of the final biofuels. Additionally, co-firing microbially pretreated pellets alongside coal and natural gas in local power plants emerges as an alternative strategy to expedite the incorporation of renewable energy into the province's power production sector. These approaches signify potential avenues for optimizing the economic and environmental benefits of the biofuel production process.

In the correlation between pellet feedstock cost and ethanol UPC across various ethanol production capacities (Fig. 12), a minor decrease in ethanol UPC was noted with a participation rate increase from 10% to 25%. Intriguingly, a noteworthy increase in ethanol UPC was witnessed with a further increase

Table 5 Comparative technoeconomic analysis of bioethanol production between Ethanol Plant A, Ethanol Plant B and Ethanol Plant C[a]

Parameters	Unit	A[1]	A[2]	B	C
Ethanol unit	[US$ per gal]	5.01	2.90	3.36	2.15
production cost	[US$ per L]	1.32	0.77	0.89	0.57
Feedstock cost	[US$ per t]	258.88	100	69.48	69.48
Feedstock capacity	[t per year]	1 250 761	1 250 761	2 217 600	2 217 600
Ethanol production	[gal per year]	93 949 835	93 949 835	129 709 932	174 404 032
capacity	[L per year]	356 582 328	356 582 328	492 308 151	661 942 576
Ethanol yield	[gal per (t w.b. feedstock)]	75	75	58	79
	[L per (t w.b. feedstock)]	285	285	220	300
	[gal per (t d.b. feedstock)]	80	80	62	83
	[L per (t d.b. feedstock)]	304	304	235	315
Discount rate	[%]	10	10	10	10
Equity percent of total investment	[%]	40	40	40	40
Capital costs					
(1) Equipment purchase cost	[US$]	82 937 000 (17.37%)	82 937 000 (18.01%)	188 666 000 (18.83%)	123 712 000 (18.09%)
(2) Installation	[US$]	41 985 000 (8.79%)	41 985 000 (9.12%)	76 783 000 (7.66%)	62 341 000 (9.12%)
(3) Process piping	[US$]	49 762 000 (10.42%)	49 762 000 (10.80%)	113 200 000 (11.30%)	74 227 000 (10.85%)
(4) Instrumentation	[US$]	24 881 000 (5.21%)	24 881 000 (5.40%)	56 600 000 (5.65%)	37 114 000 (5.43%)
(5) Insulation	[US$]	2 488 000 (0.52%)	2 488 000 (0.54%)	5 660 000 (0.56%)	3 711 000 (0.54%)
(6) Electrical	[US$]	16 587 000 (3.47%)	16 587 000 (3.60%)	37 733 000 (3.77%)	24 742 000 (3.62%)
(7) Buildings	[US$]	16 587 000 (3.47%)	16 587 000 (3.60%)	37 733 000 (3.77%)	24 742 000 (3.62%)
(8) Yard improvement	[US$]	4 147 000 (0.87%)	4 147 000 (0.90%)	9 433 000 (0.94%)	6 186 000 (0.90%)
(9) Auxiliary facilities	[US$]	33 175 000 (6.95%)	33 175 000 (7.20%)	75 466 000 (7.53%)	49 485 000 (7.24%)
(10) Engineering	[US$]	68 137 000 (14.27%)	68 137 000 (14.79%)	150 319 000 (15.00%)	101 565 000 (14.85%)
(11) Construction	[US$]	27 255 000 (5.71%)	27 255 000 (5.92%)	60 127 000 (6.00%)	40 626 000 (5.94%)
(12) Contractor's fee	[US$]	18 397 000 (3.85%)	18 397 000 (3.99%)	40 586 000 (4.05%)	27 423 000 (4.01%)
(13) Contingency	[US$]	36 794 000 (7.70%)	36 794 000 (7.99%)	81 172 000 (8.10%)	54 845 000 (8.02%)
(14) Working capital	[US$]	33 295 000 (6.97%)	16 261 000 (3.53%)	21 791 000 (2.18%)	21 630 000 (3.16%)
(15) Startup cost	[US$]	21 157 000 (4.43%)	21 157 000 (4.59%)	46 674 000 (4.66%)	31 536 000 (4.61%)
Total capital investment	[US$]	477 584 000 (100%)	460 550 000 (100%)	1 001 943 000 (100%)	683 885 000 (100%)
Total capital investment/annual gallon	[US$]	5.08	4.90	7.72	3.92
Total capital investment/annual liter	[US$]	1.34	1.29	2.03	1.03
Manufacturing costs					
Raw materials	[US$ per year]	366 976 000 (77.94%)	168 255 000 (61.82%)	221 822 000 (50.82%)	213 699 000 (57.03%)
Labor-dependent	[US$ per year]	5 643 000 (1.20%)	5 643 000 (2.07%)	10 588 000 (2.43%)	5 424 000 (1.45%)
Facility-dependent	[US$ per year]	81 585 000 (17.33%)	81 585 000 (29.98%)	180 339 000 (41.31%)	121 510 000 (32.43%)
Laboratory/QC/QA	[US$ per year]	847 000 (0.18%)	847 000 (0.31%)	1 588 000 (0.36%)	814 000 (0.22%)
Consumables	[US$ per year]	5000 (0.00%)	5000 (0.00%)	45 000 (0.01%)	30 000 (0.01%)
Utilities	[US$ per year]	15 818 000 (3.36%)	15 818 000 (5.81%)	21 818 000 (5.07%)	33 232 000 (8.87%)
Total manufacturing cost	[US$ per year]	470 874 000 (100%)	272 152 000 (100%)	436 200 000 (100%)	374 709 000 (100%)

[a] A[1]: Ethanol Plant A – microbially pretreated pellets to bioethanol plant; feedstock cost = pellet selling price without mushroom selling revenue = US$258.88 per t, A[2]: Ethanol Plant A – microbially pretreated pellets to bioethanol plant; feedstock cost = pellet selling price with mushroom selling revenue = US$100 per t, B: Ethanol Plant B – centralized microbially pretreated straw bales-to-bioethanol plant, C: Ethanol Plant C – untreated straw bales-to-bioethanol plant, and values in brackets represent the percentage contribution of each factor to the total capital investment or total manufacturing cost.

in the participation rate to 50%. This surge was attributed to the substantial escalation in utility expenses, including costs associated with fuel (natural gas), cooling, chilling, and well water. Furthermore, to establish a competitive ethanol UPC in the market, aligning with the benchmark UPC of US$0.57 per L (US$2.15 per gal) as indicated by Ethanol Plant C and Humbird *et al.*,[64] the cost of microbially pretreated pellets as feedstock must fall below US$50 per t. This scenario seems impossible to achieve without considering the mushroom revenue, as it only covers the cost of straw bales without accounting for the

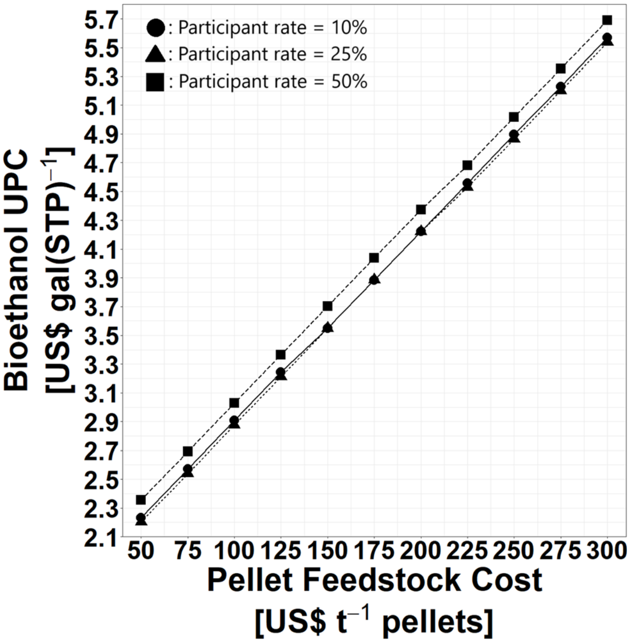

Fig. 12 The effect of pellet feedstock cost on Ethanol Plant A's ethanol unit production cost with different farmer participation rates (☐: participation rate = 10%, feedstock supply = 1.25 Mt per year, ethanol production = 93.95 Mgal(STP) per year = 356 ML per year; ▲: participation rate = 25%, feedstock supply = 3.09 Mt per year, ethanol production = 232 Mgal(STP) per year = 878 ML per year; ☐: participation rate = 50%, feedstock supply = 6.18 Mt per year, ethanol production = 464.3 Mgal(STP) per year = 1757.6 ML per year).

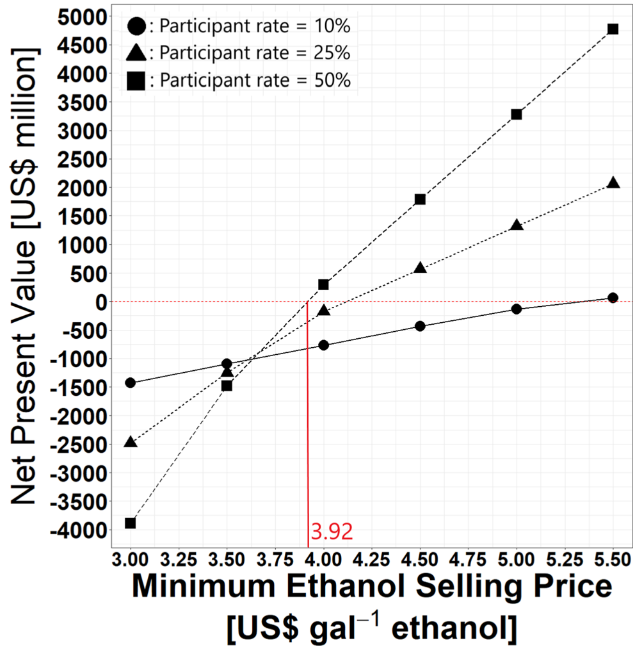

Fig. 13 The relationship of the net present value and minimum ethanol selling price of Ethanol Plant A at different farmer participation rates (☐: participation rate = 10%, pellet minimum selling price = US$252.0 per t, ethanol production = 93.95 Mgal(STP) per year = 356 ML per year; ▲: participation rate = 25%, pellet minimum selling price = US$183.7 per t, ethanol production = 232 Mgal(STP) per year = 878 ML per year; ☐: participation rate = 50%, pellet minimum selling price = US$155.8 per t, ethanol production = 464.3 Mgal(STP) per year = 1757.6 ML per year).

additional pretreatment and densification costs. This aligns with the current state of the cellulosic ethanol industry, where technological immaturity, declining oil prices, overly optimistic investor expectations, and regulatory uncertainties have been cited as factors contributing to the underperformance of what was once a promising biofuel technology.[24] Additionally, challenges in competitiveness in comparison to conventional starch-based ethanol are apparent, as numerous commercial-scale cellulosic ethanol plants currently seem to be either idle or placed on hold.[80]

In the examination of the relationship between the NPV of Ethanol Plant A and the MESP across different farmer participation rates, assuming no revenue from mushroom sales (Fig. 13), the NPV remained positive when the MESP exceeded US$1.03 per L (US$3.92 per gal) and the participation rate exceeded 50%, to bring down the pellet MSP to US$155.8 per t. This figure clearly underscores the economic viability of combining the two base-case scenarios explored in this study: five instances of Pellet Plant A and one instance of Ethanol Plant A within the province of Saskatchewan. To ensure positive cash flow in this setup, assuming zero revenue from the sale of Turkey tail mushrooms, it is necessary to utilize 50% of the designated agricultural land for the production of agricultural residues for the plants. Additionally, ethanol must be sold at a minimum price of US$1.03 per L (equivalent to US$3.92 per gal). This agrees with previous studies on the importance of managing the feedstock supply, and ethanol selling price plays a key role in the viability of the biorefinery.[81] In the realm of biofuel production, ensuring a reliable supply chain is imperative for success.[82] A crucial component of this entails establishing a well-defined, dependable source of cellulosic material, accompanied by a clear understanding of procurement costs.[81] In the context of North America, the presence of advanced biofuel technology was evident; however, a critical shortfall lay in the absence of an organized supply chain infrastructure.[24] This deficiency hindered the efficient transportation and delivery of substantial quantities of biomass to biorefineries, thereby posing a significant challenge to the growth and stability of the industry.

4 Conclusions

This study proposes an innovative biorefinery concept for Saskatchewan, integrating five pellet-mushroom production facilities (Pellet Plant A) and one bioethanol plant (Ethanol Plant A) utilizing microbially pretreated pellets. Ethanol Plant A, strategically located approximately 140 km south of Saskatoon (50° 53′16.1″N 106°42′15.5″W), minimizes pellet transport distances, optimizing logistics for the entire system.

The pellet UPC for each 250 000 t per year Pellet Plant A ranges from US$201 per t to US$242 per t, driven primarily by the cost of fungal liquid inoculum preparation. These costs are higher than those of conventional steam-explosion pellet plants, such as natural gas-fired (US$181 per t) or biomass-fired systems (US$166 per t). Consequently, the ethanol produced using these pellets incurs a higher cost of US$1.32 per L, compared to US$0.89 per L for centralized microbially pretreated straw bales-to-ethanol and US$0.57 per L for conventional dilute acid pretreatment methods.

For the proposed biorefinery to achieve a positive NPV, a MESP of US$1.03 per L and at least 50% farmer participation are required. However, integrating mushroom cultivation and carbon credit revenue streams significantly enhances the economic viability of this concept. Revenue from Turkey tail mushrooms could increase the NPV of each Pellet Plant A by up to US$10 billion, enabling a reduction in pellet selling prices. This, in turn, could lower the MESP to US$0.77 per L with a pellet purchasing cost of US$100 per t, making both ethanol and pellet production economically viable.

These findings underscore the potential of combining microbial pretreatment technologies with diversified revenue streams to create sustainable and profitable bioeconomy solutions. Future research should focus on further cost reductions, co-product credits, scalability, and logistics, to facilitate the widespread adoption of this innovative biorefinery model.

Data availability

The data supporting this article have been included as part of the ESI.†

Author contributions

Cuong N. Dao: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, visualization. Lope G. Tabil: writing – review & editing, supervision, project administration, funding acquisition. Edmund Mupondwa: writing – review & editing, supervision, project administration, funding acquisition. Tim Dumonceaux: conceptualization, methodology, writing – review & editing, supervision, project administration, funding acquisition. Xue Li: methodology, writing – review & editing. Ajay K. Dalai: writing – review & editing, funding acquisition.

Conflicts of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cuong Ngoc Dao reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Cuong Ngoc Dao reports financial support was provided by Biofuelnet Canada.

Abbreviations

MBP	Microbial pretreatment
CS	Camelina straw
TCI	Total capital investment
TMC	Total manufacturing cost
UPC	Unit production cost
NPV	Net present value
IRR	Internal rate of return
PBT	Payback time
ROI	Return on investment
MESP	Minimum ethanol selling price
PSP	Pellet selling price
MSP	Minimum selling price

Acknowledgements

This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) (RGPIN-2017-05287 and RGPIN-2023-03940) and the BioFuelNet Canada (BFN) (ASC-16).

Notes and references

1 C. N. Dao, L. G. Tabil, E. Mupondwa and T. Dumonceaux, *Front. Microbiol.*, 2023, **14**, DOI: 10.3389/fmicb.2023.1130196.
2 J. Stephen and S. Wood-Bohm, *Biomass innovation-Canada's Leading Cleantech Opportunity for Greenhouse Gas Reduction and Economic Prosperity*, 2016.
3 W. Bank, Forest Area (% of Land Area), World Bank Database, Data retrieved from World Development Indicators, 2018, https://data.worldbank.org/indicator/AG.LND.FRST.ZS.
4 W. Bank, Cereal Production, World Bank Database, Data retrieved from World Development Indicators, 2018, https://data.worldbank.org/indicator/AG.PRD.CREL.MT.
5 W. Bank, Agricultural Land (% of Land Area), World Bank Database, Data retrieved from World Development Indicators, 2018, https://data.worldbank.org/indicator/AG.LND.AGRI.ZS.
6 S. M. Wood and D. B. Layzell, *A Canadian Biomass Inventory: Feedstocks for a Bio-Based Economy-Final Report*, 2003.
7 IEA, Key Energy Statistics, 2018, https://www.iea.org/countries/canada, accessed on Sep 01, 2023.
8 R. Ferroukhi, A. Khalid, A. Lopez-Pena and M. Renner, *Renewable energy and jobs: annual review 2015*, International Renewable Energy Agency (IRENA), 2017.
9 Y. Zheng and F. Qiu, *Biomass Bioenergy*, 2020, **140**, 105669.
10 M. Ebadian, S. Sokhansanj, D. Lee, A. Klein and L. Townley-Smith, *Energies*, 2021, **14**, 2263.
11 M. Pierre and S. Mhlanga, Canadian Agriculture at a Glance–Saskatchewan continues to live up to the title of breadbasket of Canada, 2022, https://www150.statcan.gc.ca/n1/pub/96-325-x/2021001/article/00008-eng.htm#shr-pg0.
12 M. Pierre and M. McComb, Canadian Agriculture at a Glance–Alberta has the highest farm operating revenues in Canada, 2022, https://www150.statcan.gc.ca/n1/pub/96-325-x/2021001/article/00009-eng.htm.
13 M. Pierre and M. McComb, Canadian Agriculture at a Glance–Manitoba has the highest proportion of young farm operators in Canada, 2022, https://

www150.statcan.gc.ca/n1/pub/96-325-x/2021001/article/00007-eng.htm.
14 B. J. Krohn and M. Fripp, *Appl. Energy*, 2012, **92**, 92–98.
15 F. M. Ibrahim and S. El Habbasha, *Int. J. PharmTech Res.*, 2015, **8**, 114–122.
16 J. Bacenetti, A. Restuccia, G. Schillaci and S. Failla, *Renew. Energy*, 2017, **112**, 444–456.
17 E. Mupondwa, X. Li and L. Tabil, *Biofuels, Bioprod. Biorefin.*, 2017, **11**, 955–970.
18 K. Nault, Clean hydrogen: A long-awaited solution for hard-to-abate sectors, 2022, https://seas.harvard.edu/news/2022/10/clean-hydrogen-long-awaited-solution-hard-abate-sectors.
19 P. Picciano, F. X. Aguilar, D. Burtraw and A. Mirzaee, *Resour. Energy Econ.*, 2022, **68**, 101296.
20 R. Kunwer, S. R. Pasupuleti, S. S. Bhurat, S. K. Gugulothu and N. Rathore, *Mater. Today: Proc.*, 2022, **15**, 8644.
21 S. E. Ibitoye, T.-C. Jen, R. M. Mahamood and E. T. Akinlabi, *Bioresour. Bioprocess.*, 2021, **8**, 75.
22 J. S. Tumuluru, C. T. Wright, J. R. Hess and K. L. Kenney, *Biofuels, Bioprod. Biorefin.*, 2011, **5**, 683–707.
23 I. Obernberger and G. Thek, *The Pellet Handbook: the Production and Thermal Utilisation of Pellets*, Routledge, 2010.
24 D. Kramer, *Phys. Today*, 2022, **75**, 22–24.
25 B. H. H. Goh, C. T. Chong, H. C. Ong, T. Seljak, T. Katrašnik, V. Józsa, J.-H. Ng, B. Tian, S. Karmarkar and V. Ashokkumar, *Energy Convers. Manage.*, 2022, **251**, 114974.
26 First Ethanol Alcohol-to-Jet Sustainable Aviation Fuel Production Facility Unveiled, 2024, https://www.energy.gov/eere/bioenergy/articles/first-ethanol-alcohol-jet-sustainable-aviation-fuel-production-facility, accessed 2024-08-26.
27 Our Alcohol-to-Jet (ATJ) technology is the first proven global technology solution for SAF from ethanol, 2024, https://www.lanzajet.com/technology, accessed 2024-08-26.
28 L. Kilian and X. Zhou, *Energy Econ.*, 2022, **113**, 106228.
29 FMI, Biomass Pellets Market Outlook (2023 to 2033), 2022, https://www.futuremarketinsights.com/reports/biomass-pellets-market.
30 M. Shaw, C. Karunakaran and L. Tabil, *Biosyst. Eng.*, 2009, **103**, 198–207.
31 K. Robak and M. Balcerek, *Microbiol. Res.*, 2020, **240**, 126534.
32 C. N. Dao, E. Mupondwa, L. Tabil, X. Li and E. C. Castellanos, *Technical Library of the Canadian Society for Bioengineering/La Société Canadienne de Génie Agroalimentaire et de Bioingénierie*, 2018.
33 B. Beig, M. Riaz, S. R. Naqvi, M. Hassan, Z. Zheng, K. Karimi, A. Pugazhendhi, A. Atabani and N. T. L. Chi, *Fuel*, 2021, **287**, 119670.
34 J. Vasco-Correa, A. Zuleta-Correa, J. Gómez-León and J. A. Pérez-Taborda, *Appl. Microbiol. Biotechnol.*, 2023, 1–20.
35 C. del Cerro, E. Erickson, T. Dong, A. R. Wong, E. K. Eder, S. O. Purvine, H. D. Mitchell, K. K. Weitz, L. M. Markillie, M. C. Burnet, D. W. Hoyt, R. K. Chu, J.-F. Cheng, K. J. Ramirez, R. Katahira, W. Xiong, M. E. Himmel, V. Subramanian, J. G. Linger and D. Salvachúa, *Proc. Natl. Acad. Sci. U. S. A.*, 2021, **118**, e2017381118.
36 C. N. Dao, L. Tabil, E. Mupondwa and T. Dumonceaux, *Renew. Energy*, 2023, **217**, 119147.
37 W. Gao, L. G. Tabil, T. Dumonceaux, S. E. Ríos and R. Zhao, *Biomass Bioenergy*, 2017, **97**, 77–89.
38 O. Onu Olughu, L. G. Tabil, T. Dumonceaux, E. Mupondwa and D. Cree, *Energies*, 2021, **14**, 7670.
39 J. Ramirez-Bribiesca, Y. Wang, L. Jin, T. Canam, J. Town, A. Tsang, T. Dumonceaux and T. McAllister, *Can. J. Anim. Sci.*, 2011, **91**, 695–702.
40 T. Canam, J. R. Town, A. Tsang, T. A. McAllister and T. J. Dumonceaux, *Bioresour. Technol.*, 2011, **102**, 10020–10027.
41 R. Davis, A. Taylor, R. Nally, K. F. Benson, P. Stamets and G. S. Jensen, *J. Inflamm. Res.*, 2020, 117–131.
42 M. Rašeta, M. Popović, P. Knežević, F. Šibul, S. Kaišarević and M. Karaman, *Chem. Biodiversity*, 2020, **17**, e2000683.
43 L. Janjušević, M. Karaman, F. Šibul, G. Tommonaro, C. Iodice, D. Jakovljević and B. Pejin, *J. Enzym. Inhib. Med. Chem.*, 2017, **32**, 355–362.
44 I. Kıvrak, S. Kivrak and E. Karababa, *Int. J. Med. Mushrooms*, 2020, **22**, year.
45 A. Bains and P. Chawla, *3 Biotech*, 2020, **10**, 404.
46 L. Orzali, M. T. Valente, V. Scala, S. Loreti and N. Pucci, *Antibiotics*, 2020, **9**, 628.
47 A. Bains, P. Chawla, S. Kaur, A. Najda, M. Fogarasi and S. Fogarasi, *Materials*, 2021, **14**, 7640.
48 E. Deveci, F. Çayan, G. Tel-Çayan and M. E. Duru, *J. S. Afr. Bot.*, 2021, **137**, 19–23.
49 Z. Huang, M. Zhang, Y. Wang, S. Zhang and X. Jiang, *Curr. Microbiol.*, 2020, **77**, 3526–3537.
50 M. H. Saleh, I. Rashedi and A. Keating, *Front. Immunol.*, 2017, **8**, 1087.
51 S. G. Slavens, MSc thesis, Oklahoma State University, 2016.
52 M. Li, MSc thesis, Oklahoma State University, 2015.
53 J. Vasco-Correa and A. Shah, *Fermentation*, 2019, **5**, 30.
54 AKC, Harvesting Surplus Cereal Straw, 2023, https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/field-crops/cereals-barley-wheat-oats-triticale/harvesting-surplus-cereal-straw.
55 D. Kumar and G. S. Murthy, *Biotechnol. Biofuels*, 2011, **4**, 1–19.
56 Z. Barta, E. Kreuger and L. Björnsson, *Biotechnol. Biofuels*, 2013, **6**, 1–16.
57 A. Uslu, A. P. Faaij and P. C. Bergman, *Energy*, 2008, **33**, 1206–1223.
58 D. R. Petrolia, *Biomass Bioenergy*, 2008, **32**, 603–612.
59 R. Overend, *Biomass*, 1982, **2**, 75–79.
60 M. K. Delivand, M. Barz and S. H. Gheewala, *Energy*, 2011, **36**, 1435–1441.
61 J. D. Stephen, PhD thesis, University of British Columbia, 2008.
62 R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, 2022.
63 P. S. Lam, PhD thesis, University of British Columbia, 2011.

64 D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, *et al.*, *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover, National Renewable Energy Lab.(nrel), Golden, Co (united states) Technical Report*, 2011.
65 A. Sluiter, B. Hames, R. Ruiz, C. Scarlata, J. Sluiter, D. Templeton and D. Crocker, *Laboratory Analytical Procedure*, 2010, vol. 1617, pp. 1–16.
66 M. G. Resch, J. Baker and S. Decker, *Low Solids Enzymatic Saccharification of Lignocellulosic Biomass*, National Renewable Energy Laboratory Golden, CO, 2015.
67 *Standard Test Method for Gross Calorific Value of Coal and Coke*, American society for testing and materials standard, 2019.
68 *Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis*, American society for testing and materials standard, 2016.
69 D. Petrides, *Corn Stover to Ethanol Conversion (Cellulosic Bio-Ethanol)-Process Modeling and Techno-Economic Assessment (TEA) Using SuperPro Designer*, Intelligen, USA, 2020.
70 G. Towler and R. Sinnott, *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*, Butterworth-Heinemann, 2021.
71 CEPCI, *Chemical Engineering*, 2023.
72 E. Mupondwa, X. Li, L. Tabil, A. Phani, S. Sokhansanj, M. Stumborg, M. Gruber and S. Laberge, *Bioresour. Technol.*, 2012, **110**, 355–363.
73 W. Strauss, 2023 wood pellet markets outlook, 2023, https://www.canadianbiomassmagazine.ca/2023-wood-pellet-markets-outlook/.
74 J. Peng, H. Bi, S. Sokhansanj, J. Lim and S. Melin, *Int. J. Green Energy*, 2010, **7**, 128–142.
75 A. Sultana, A. Kumar and D. Harfield, *Bioresour. Technol.*, 2010, **101**, 5609–5621.
76 A. Pantaleo, M. Villarini, A. Colantoni, M. Carlini, F. Santoro and S. Rajabi Hamedani, *Energies*, 2020, **13**, 1636.
77 A. Pirraglia, R. Gonzalez, D. Saloni and J. Denig, *Energy Convers. Manage.*, 2013, **66**, 153–164.
78 M. Manouchehrinejad, E. T. Bilek and S. Mani, *Renew. Energy*, 2021, **178**, 483–493.
79 H. Shahrukh, A. O. Oyedun, A. Kumar, B. Ghiasi, L. Kumar and S. Sokhansanj, *Biomass Bioenergy*, 2016, **87**, 131–143.
80 M. Padella, A. O'Connell and M. Prussi, *Appl. Sci.*, 2019, **9**, 4523.
81 S. Akhtari and T. Sowlati, *Appl. Energy*, 2020, **259**, 114124.
82 M. Aboytes-Ojeda, K. K. Castillo-Villar and S. D. Eksioglu, *Ann. Oper. Res.*, 2022, **314**, 319–346.