Green Chemistry

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Journal:	*Green Chemistry*
Manuscript ID	GC-ART-08-2024-004270.R1
Article Type:	Paper
Date Submitted by the Author:	27-Sep-2024

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Economic and environmental sustainability of bio-based HMF production and recovery from lignocellulosic biomass

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Abstract

5-hydroxymethyl furfurals (HMF) is one of the versatile platform chemicals. However, green routes to produce it directly from lignocellulosic biomass are lacking. A significant amount of HMF produced during the hydrothermal valorization of lignocellulosic biomass is considered undesired and ends up in a waste stream. The study transformed the undesired byproduct into a valuable coproduct by advancing the existing biofuel production process. A detailed economic and environmental sustainability analysis of the integrated biorefinery design was performed. The evaluation showed that the biorefinery could afford a maximum feedstock purchasing price of \$115.17 MT^{-1} and produce HMF with a minimum selling price of \$4.54 kg^{-1} which is ~75% lower than the commercial price of HMF. The median global warming potential of HMF was estimated to be 3.92 kg CO_2-eq kg HMF^{-1} which was ~32% less than its counterpart bio-based p-xylene. Diverse coproducts produced in the biorefinery using transgenic feedstock positively impacted sustainability.

Keywords

Bio-based HMF, Techno-economic analysis (TEA), Life cycle assessment (LCA)

1. Introduction

Hydroxymethylfurfural (HMF) is a versatile biochemical. It serves as the precursor for many polymerization reactions, primarily due to its functional group. HMF is a suitable precursor for the production of various furan monomers and furanic derivatives that have great potential to produce a wide range of commercially important products such as polymers, surfactants, solvents, and pharmaceuticals.[1, 2] The most promising and practical feedstock for the synthesis of HMF is the abundant renewable carbon present in lignocellulosic biomasses. However, the recalcitrant structure of lignocellulosic biomasses makes direct conversion of

biomass to HMF economically and technically challenging.[3] The current bio-based HMF production processes primarily utilize fructose and glucose recovered from feedstocks. The conversion of recovered sugars to HMF involves multiple dehydration reactions using mineral acids, ionic liquids, and solid-acid catalysts (e.g., metal halides, zeolites, metal oxides, etc.) in aqueous, organic and deep eutectic solvents, followed by reactive extraction solvents.[4-7] Recent research advances have reported promising results at the lab scale; however, the selection of appropriate catalyst and solvent largely influenced the overall yield and energy requirements.[4, 8-10] Utilization of these catalytic solvent systems can pose a hazard to human health and environment and incur high production cost as well.[4] The catalytic technologies used for biomass conversion are technically and economically not at the commercial level like its petroleum analog. At present, commercial production of bio-based HMF cannot compete with its petroleum-derived analog p-xylene because of its high production cost.[11] Despite challenges, major pharmaceutical and chemical industries are developing new technologies for the production and recovery of HMF in a non-catalytical, and energy-efficient manner that can reduce the cost of production.[12]

To find a solution to the aforementioned problem, the authors have developed a green technology for the production and recovery of HMF along with three additional value-added bioproducts. The proposed technology advances the existing bioprocess design for drop-in fuel production. Note that in a biorefinery, the optimum recovery of fermentable cellulosic sugars from lignocellulosic biomasses requires chemical, physical, or biological treatment to solubilize the complex interlinking network of lignin, celluloses, and hemicelluloses of the biomass.[13] The pretreatment processes generate a significant amount of sugar degradation products that hinder the subsequent fermentation by inhibiting the growth of microorganisms.[14, 15] HMF and furfural

are among the major sugar degradation products produced during both chemical and hydrothermal pretreatment of lignocellulosic biomass that mandates detoxification before the fermentation process. These sugar degradation inhibitory products are also high-value platform chemicals that unfortunately end up in the waste product stream during detoxification steps. A quantitative study showed that in hydrothermal pretreatment, the concentrations of HMF and furfural can be increased exponentially by increasing the pretreatment temperature beyond 170 °C without affecting the total recovery of cellulosic sugars.[15] HMF produced in the pretreatment liquor as a byproduct of sugar degradation can be recovered as value-added coproduct.

The authors' previous research successfully optimized the hydrothermal pretreatment conditions to maximize the production of HMF and furfural and demonstrated the recovery of HMF and furfural from pretreatment liquor using two-step nanofiltration in series. Cellulosic sugars were also recovered from pretreated biomass residues post saccharification.[16, 17] The experimental results and technoeconomic analysis performed on the proposed bioprocess design at technology readiness level 1 (TRL 1) suggests that a biorefinery of intermediate size, processing ~2000 metric tons (MT) of transgenic sugarcane that produces vegetative lipids (oilcane) bagasse per day, can potentially produce approximately 900 − 1500, 65, 45 − 150, and 30 − 145 MT of cellulosic sugars, vegetative lipids, furfural, and HMF per day, respectively.[16, 17] The coproduction of diverse value-added coproducts has been shown to improve the revenue of the biorefinery and reduce the cost of production of the main product.[16, 18-20] This encouraged the authors to develop an advanced bioprocessing design that coproduces diverse value-added products in a biorefinery to improve the revenue stream and help lower the production cost of bio-based HMF.

The choice of feedstock plays a critical role in diversifying the coproducts in a biorefinery. The study utilizes metabolically engineered sugarcane developed by the Department of Energy-Center for Advanced Bioenergy and Bioproduct Innovations (DOE-CABBI), USA, referred to as 'sugarcane-oilcane'. The transgenic sugarcane-oilcane has been genetically modified to channel the carbon flux toward biosynthesis and hyperaccumulation of energy-rich lipid molecules in its vegetative tissues.[21, 22] The transgenic sugarcane-oilcane has shown the potential to produce 0.35 MT/ha of vegetative lipids, which accounts for 80% of soybean lipid yield.[23] The use of transgenic sugarcane-oilcane as feedstock will aid in the sustainable production of bio-based HMF by coproducing vegetative lipids which can be further converted into biodiesel/renewable diesel in the same or different biorefineries. The transgenic bioenergy crops are being developed to provide a dedicated supply of feedstock as they are targeted to grow on non-prime agricultural lands and do not compete with human food.

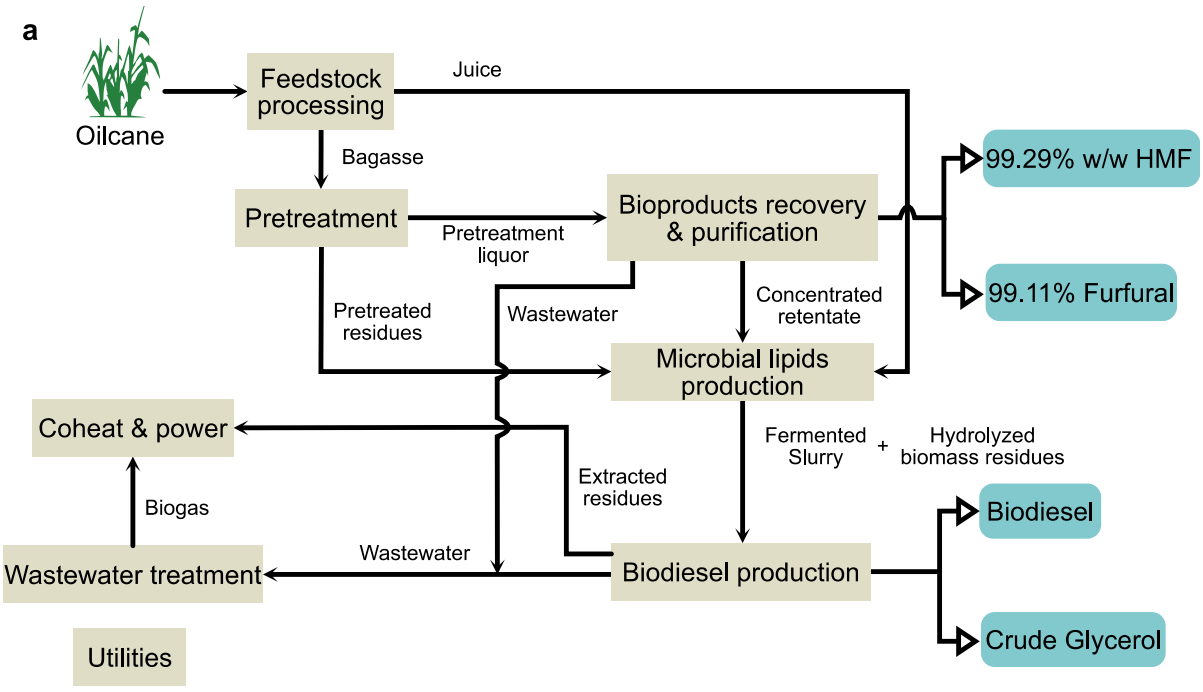
To this end, the study proposes a conceptual integrated bioprocessing model that coproduces four valuable products i.e., HMF, furfural, biodiesel, and crude glycerol from transgenic sugarcane-oilcane in a single run. A detailed technoeconomic analysis (TEA) and life cycle assessment (LCA) of the proposed bioprocessing model has been performed using BioSTEAM, an open-source python-based platform.[24] The study also systematically identifies the key parameters driving the economic and environmental performance of the bioprocessing model under uncertainties and quantifies their impact on overall performance of the biorefinery. Additionally, the study provides critical insights into the prioritization of research and potential technological advancements needed for the sustainable commercialization of bio-based HMF from transgenic bioenergy crops.

2. Methods

2.1. Biorefinery design

The proposed biorefinery that coproduces diverse bio-based products i.e., HMF, furfural, biodiesel, and crude glycerol from transgenic sugarcane-oilcane was designed, simulated and evaluated in BioSTEAM.[24, 25] The primary equipment of biorefinery design consists of five inside-battery-limit (ISBL) sections, including feedstock processing, hydrothermal pretreatment, bioproducts recovery and purification, microbial lipids production, and biodiesel production, along with three outside-battery-limit (OSBL) sections, including wastewater treatment (WWT), coheat and power (CHP), and other facilities (Figure 1a).

The biorefinery design assumes the processing of approximately 2000 MT transgenic sugarcane-oilcane stems per day, having 5% w w^{-1} lipid content.[26, 27] Lab-scale experimental data was used to determine critical model designs, including vegetative lipids losses throughout processing, conversion efficiencies of reactions during pretreatment, enzymatic hydrolysis, and fermentation.



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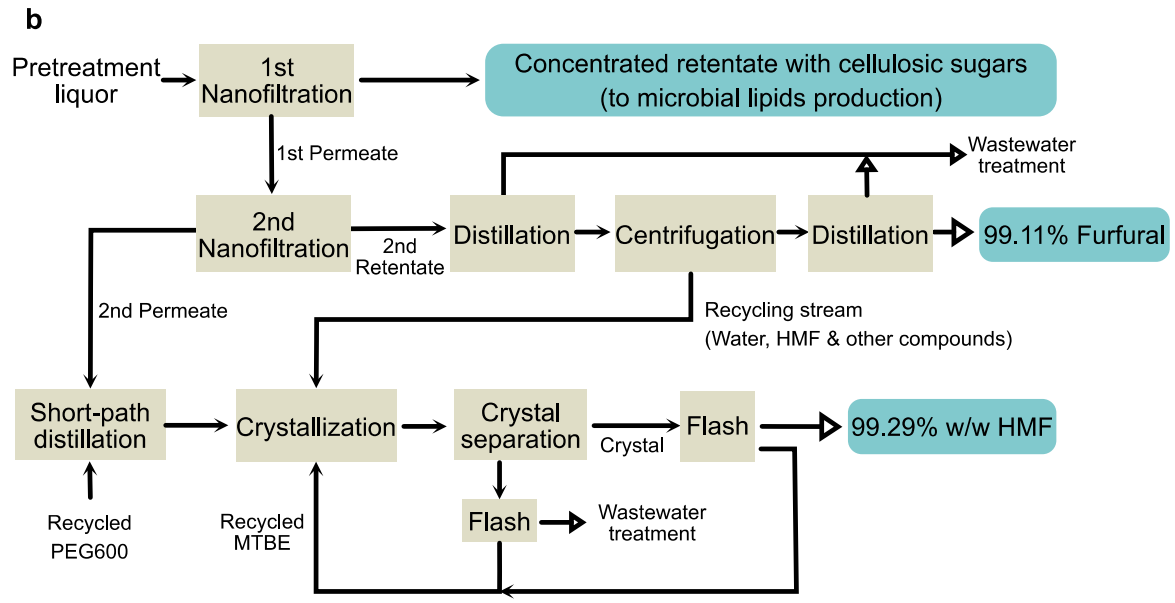

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130 **Figure 1:** Simplified flow diagram of the proposed biorefinery for (a) coproduction of HMF,
131 furfural, biodiesel, and crude glycerol from oilcane, and (b) bio-based products recovery and
132 purification section of the proposed biorefinery. Acronyms in the figure denote polyethylene
133 glycol 600 (PEG600), and methyl tert-butyl ether (MTBE).

2.1.1. Inside-Battery-Limit (ISBL) sections

In feedstock processing, transgenic sugarcane-oilcane stems were crushed to separate juice and bagasse. The extracted juice was clarified and stored for the production of microbial lipids. The bagasse with 50% w w^{-1} moisture was conveyed to hydrothermal pretreatment to be pretreated with liquid hot water at 210°C for 5 min. The pretreatment reactions and the conversion percentage of cellulose and hemicellulose to cellulosic sugars, HMF, and furfural were based on bench-scale experimental data.[17] Hydrothermal pretreatment converted 21.45% and 14.40% of glucan to glucose and HMF, and 31.23% and 51.10% of xylan to xylose and furfural, respectively.[17] The pretreated slurry was filtered to separate pretreated biomass residues and pretreatment liquor. The major fraction of vegetative lipids remained in the bagasse after crushing.[23]

Figure 1b displays the schematic design of bioproduct recovery and purification to separate cellulosic sugars (glucose, xylose, and arabinose) and acetic acid to recover and purify HMF and furfural from pretreatment liquor using two-step nanofiltration arranged in series. The percent retention of chemicals during nanofiltration was determined based on bench-scale experimental data.[17] The 1st nanofiltration system retained and concentrated 98.39%, 98.18%, 94.52%, and 84.28% of glucose, xylose, arabinose, and acetic acid from the liquor, respectively,[17] which was utilized for microbial lipids production. The permeate from 1st nanofiltration recovered 40.41% of furfural and 59.28% of HMF from the pretreatment liquor and was fed to 2nd nanofiltration system to separate HMF and furfural. 52.45% of HMF was recovered in the permeate of the 2nd nanofiltration system and 78.82% of furfural was concentrated in the retentate.[17] To produce purified HMF, 5% w w^{-1} polyethylene glycol 600 (PEG600) was mixed with permeate of 2nd nanofiltration system for short-path distillation.[28]

157 PEG600 was utilized as a non-volatile flowing agent to avoid forming undesired byproducts
158 (humins) and preventing their deposit in the distillation column.[28, 29] PEG600 in the bottom
159 stream was recycled. A 97% of HMF was recovered in the distillate, which was then dried and
160 mixed with methyl tert-butyl ether (MTBE) at a ratio of 3L MTBE per kg of crude HMF for
161 crystallization.[30] Crystallization recovered 90% HMF and yielded HMF solids with > 99%
162 purity.[30] Furfural with > 99% purity was generated from the retentate of 2nd nanofiltration system
163 through distillations, a conventional furfural purification process used in the industrial furfural
164 production process.[31, 32] Wastewater containing HMF and other impurities was generated from
165 furfural purification process and recycled to produce purified HMF. High-purity bio-based HMF
166 and furfural were stored and sold as the main products.

167 For microbial lipids production, pretreated biomass residues with negligible xylan were
168 enzymatically hydrolyzed with a glucan-to-glucose conversion of 93.47%.[17] The hydrolysate and
169 juice from feedstock processing, and concentrated retentate from 1st nanofiltration system were
170 combined and used as a fermentation medium to produce microbial lipids using an oleaginous
171 yeast *R. toruloides*. The yeast has approximately 55% of theoretical microbial lipid yield from
172 glucose, xylose, and arabinose.[33, 34] The designs for enzymatic saccharification and batch
173 fermentation followed previous studies.[25, 35] After completion of fermentation, the fermentation
174 broth was sent to biodiesel production. Approximately 70% of vegetative lipids in bagasse
175 remained in the biomass residues post-saccharification and were sent to biodiesel production.[23]

176 In biodiesel production, fermentation broth was centrifuged to separate yeast cells
177 containing microbial lipids. Microbial lipids and vegetative lipids were extracted from separated
178 yeast cells and hydrolyzed biomass residues, respectively, by solvent extraction.[36] Hexane was
179 recovered by evaporation for recycling. The extracted plant and microbial lipids were combined

and pretreated by glycerolysis to reduce free fatty acid contents and remove polar lipids.[37] The pretreated lipids were transesterified with methanol to produce biodiesel, which was separated by centrifugation, purified by washing and vacuum drying, and stored for sale as the main product.[18] After unreacted methanol was collected from the remaining liquid phase by evaporation for recycling, the liquid phase was distilled to produce crude glycerol with 80% purity as a coproduct.[18, 25] Additional specifications of the ISBL sections are listed in Table S1 – S4 (see supplementary material).

2.1.2. Outside-Battery-Limit (OSBL)

For CHP production, solid wastes, including hexane-extracted hydrolyzed biomass residues and hexane-extracted yeast cells, were burned to provide steam and electricity for the biorefinery by a cogeneration system including a combustor, a boiler, and a turbo-generator. Specifications of the system followed the previous study.[25] Additional electricity was purchased to satisfy system demands. A WWT system generated reusable water, biogas, and wastewater sludge from wastewater streams through anaerobic and aerobic digestion, membrane bioreactor and reverse osmosis.[26] Reusable water was recycled to the biorefinery while biogas and wastewater sludge were conveyed to CHP for cogeneration. Other facilities, for instance, the process water center, cooling tower, fire water tank, and so on, provided cooling water, chilled water, wastewater reuse, air distribution, and storage for the biorefinery.

2.2. Sustainability evaluation of economic and environmental parameters

TEA and LCA of the proposed biorefinery were performed in BioSTEAM. For capital and operating cost analysis, transgenic sugarcane-oilcane was assumed to have the same price as sugarcane,[38] and prices of other raw materials, products, and utilities estimated using data from public sources and published literature were listed in Table S6 (see supplementary material). The

costs associated with nanofiltration were modeled based on previous literature to estimate expenses incurred by membrane, instruments and controls, tanks and frames, membrane cleaning and regeneration, and miscellaneous supplies.[39-41] Other pieces of equipment and capital costs were estimated using correlations and data from previous studies and public sources.[18, 25, 26] The market price of HMF was scaled from its laboratory-scale prices to estimate operating costs due to the unestablished commercial market of HMF.[42-44] All costs are presented in 2023 USD and a detailed breakdown of estimated costs and revenues is listed in Table S6-S8 (see supplementary material).

The maximum feedstock purchasing price (MFPP) of transgenic sugarcane-oilcane, a feedstock-oriented indicator, was selected as the primary profitability indicator of the biorefinery. It represents the maximum price that a biorefinery can afford for the feedstock without incurring a financial loss. The minimum product selling price (MPSP) of HMF is another important indicator of the economic performance of the biorefinery. MFPP and MPSP of HMF were determined using discounted cash flow rate analysis to obtain a net present value (NPV) of zero. The analysis was performed for a project duration of 30 years with 330 annual operating days (35 days for maintenance) and a 10% internal rate of return, same as previous studies that evaluated the production of biofuels and bioproducts from transgenic sugarcane-oilcane.[16, 25]

A cradle-to-biorefinery-gate LCA (life cycle assessment) was performed for the proposed biorefinery to determine its environmental implications for climate change. Life cycle inventory data was obtained upon simulation and impact characterization factor of each input was estimated using various sources and published literature (Table S9, supplementary material).[45-47] The analysis methodology used was modified for the biorefinery from previous studies.[25, 48, 49]

One-hundred-year global warming potential (GWP_{100}) in the form of kg CO_2 eq. (carbon dioxide equivalent) were estimated using energy and economic allocation methods and employed as the primary indicator for the environmental performance of the biorefinery. Estimations based on data generated by economic allocation might be unreliable due to the unestablished and highly volatile market of HMF.[48] Thus, the study focuses on energy-allocated GWP results. Economic and energy allocation factors of the baseline biorefinery and distribution of economic-allocated GWP results are listed in Table S10 and Figure S1 (see supplementary material).

2.3. Estimation of economic and environmental sustainability under uncertainty

Using the baseline biorefinery, 2000 Monte Carlo simulations generated by varying 22 technological and cost-associated parameters were simulated in BioSTEAM. Besides common parameters, for instance, market prices of products, costs of utilities and raw materials, and so on, the uncertainty analysis was performed with an emphasis on three technological aspects, including nanofiltration, microbial lipids production, and vegetative lipids production. To investigate the implications of the nanofiltration system for recovery of bio-based HMF, membrane lifetime, membrane cost, HMF retention in 1st and 2nd nanofiltration, and furfural retention in 1st and 2nd nanofiltration were varied. Microbial lipid yields (from glucose and xylose), titer and productivity were included to investigate the impact of microbial lipid production. The lipid content of transgenic sugarcane-oilcane and its recovery after bioprocessing (pretreatment and enzymatic saccharification) were varied to investigate the impact of vegetative lipids production. A detailed list of all parameters with their range and distribution is presented in Table S11 (see supplementary material).

Main performance indicators, i.e., MPSP, MFPP, GWP_{100}, and other selected economic and environmental metrics of all simulations, such as total direct cost (TDC), total capital

investment (TCI), annual material cost, annual operating cost (AOC), annual usage of utilities, annual production of products, annual system GWP_{100}, internal rate of return and net present value, were analyzed to investigate their sensitivities to all uncertain parameters through Spearman's rank correlation coefficients (Spearman's ρ). The absolute value and sign of ρ show the degree and direction of correlation between parameter and metric, respectively. Input parameters with absolute values of $\rho \geq 0.1$ with selected metrics were identified as impactful parameters for the metrics. Based on results from uncertainty analysis, impact of two most significant technological parameters, i.e., HMF retention in the 1st and 2nd nanofiltration, along with lipid content of transgenic sugarcane-oilcane and microbial lipid yield (from glucose), on biorefinery sustainability were further investigated via separate analyses.

3. Results

3.1. The economic viability of the biorefinery producing bio-based HMF under uncertainty

3.1.1. Maximum feedstock purchasing price (MFPP)

The study uses a recently developed transgenic bioenergy crop that has not been commercialized yet.[22] Therefore, it is necessary to determine MFPP of the crop that can be sustained by the biorefinery, providing valuable insights into financial suitability of innovative transgenic sugarcane-oilcane as an alternative feedstock. The MFPP of transgenic sugarcane-oilcane was estimated to be \$115.17 MT^{-1} [80.16 – 154.19 MT^{-1}] (median, 5th and 95th percentiles in bracket) as generated by Monte-Carlo simulations (Figure 2a). 100% of simulations yielded MFPP higher than the average market price of sugarcane (\$34.5 MT^{-1}) in the USA.[38]

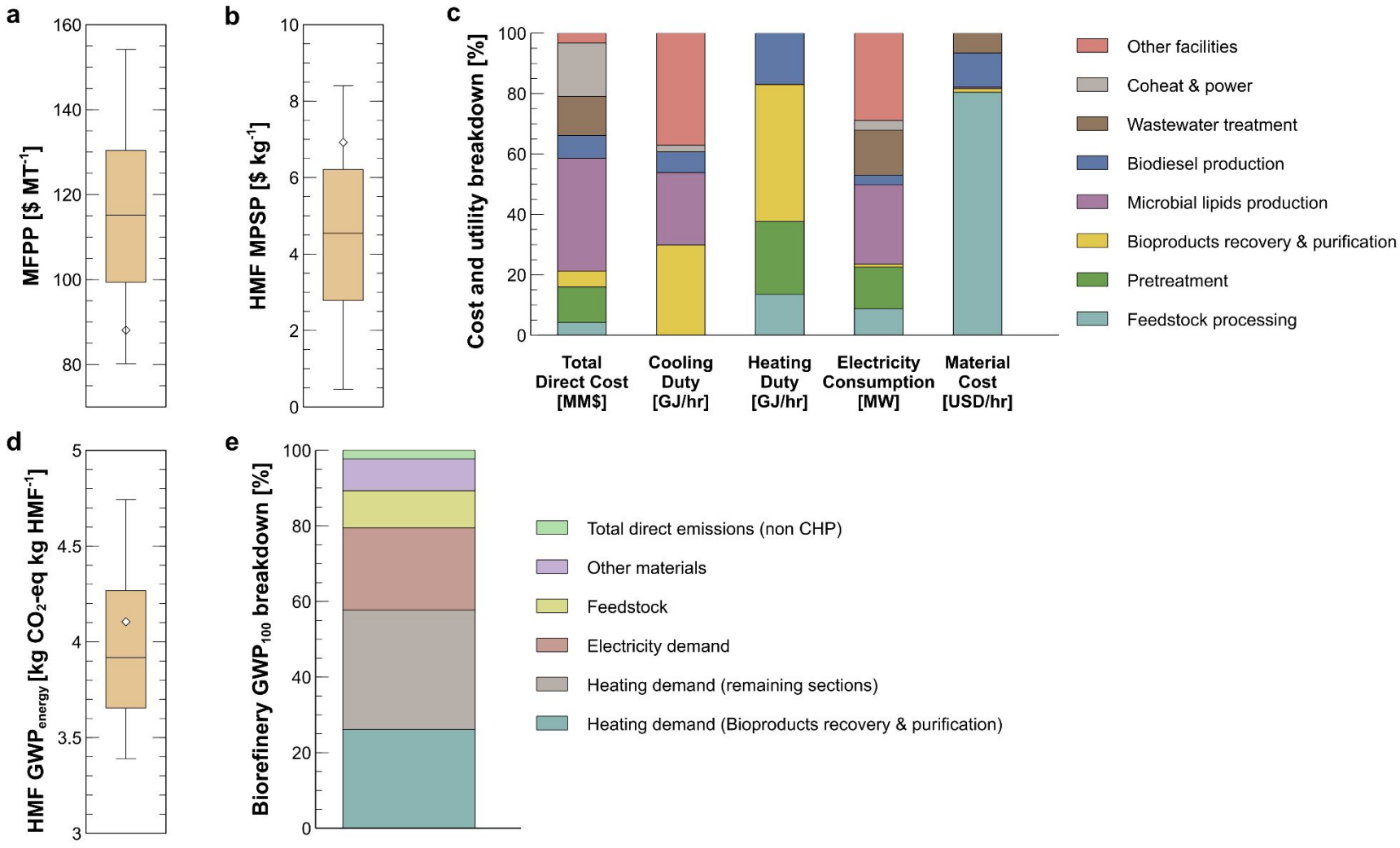


Figure 2: Cost estimation and environmental impacts of the biorefinery. Box and whisker plots of a) MFPP and b) HMF MPSP, c) breakdown of total direct cost and utility usage of baseline biorefinery, d) box whisker plot and e) breakdown of HMF GWP_{100}. Diamond markers in box and whisker plots represent values obtained from baseline biorefinery.

3.1.2. Minimum product selling price (MPSP)

At present, the market price of transgenic sugarcane-oilcane is uncertain. In the previous section, Monte Carlo simulations established the economic sustainability of biorefinery over a range of MFPP which was higher than the average market price of sugarcane. Therefore, in the study, the MPSP of HMF was simulated assuming transgenic sugarcane-oilcane was purchased at the same price as sugarcane. The MPSP of HMF was estimated to be \$4.54 kg^{-1} [0.47 – 8.40 kg^{-1}] (median, 5th and 95th percentiles in bracket) (Figure 2b). 100% of simulations generated under uncertainties yielded MPSP of HMF lower than the current market price of HMF (\$18.02 kg^{-1}),[42-44] which indicates economic feasibility, sustainability and market acceptability of bio-based HMF produced in the proposed biorefinery design.

3.1.3. Cost estimation and breakdown

The total capital investment of the pioneering biorefinery was estimated to be 985.87 [913.80 – 1087.18] million USD (MM\$) with an annual operating cost of 163.06 [138.95 – 188.21] MM\$ yr^{-1}. Across the system, microbial lipids production dominated capital costs, constituting 34.59% [30.36 – 40.03%] of total direct cost (TDC) (Figure 2c). The high capital cost of microbial lipids production was attributed to the use of aerated bioreactors for oleaginous yeasts to produce microbial lipids. Aeration in bioreactors have been widely recognized to have increased production costs as it requires high energy for uniform mixing of oxygen and cooling.[50-52] Feedstock processing was the largest contributor to operating costs, accounting for 79.22% [72.98 – 84.50%] of annual material costs (Figure 2c).

Heating duty, cooling duty, and electricity usage of 581.63 GJ hr^{-1} [505.62 – 666.79 GJ hr^{-1}], 946.50 GJ hr^{-1} [822.52 – 1040.16 GJ hr^{-1}], and 51.04 MW [45.80 – 56.01 MW], respectively, were required by the system. Bioproducts recovery and purification predominantly

298 consumed 44.23% [41.47 – 47.62%] and 32.39% [28.27 – 35.77%] of heating and cooling
299 duties, respectively, because of the multiple energy-intensive distillation columns used for HMF
300 and furfural purification. Other facilities and microbial lipids production dominated electricity
301 usage (30.31% [27.29 – 34.03%] and 23.19% [13.75 – 33.02%], respectively) and consumed a
302 critical part of cooling duty (36.49% [33.33 – 39.29%] and 23.50% [16.31 – 29.83%],
303 respectively) (Figure 2c).

304 **3.2. Environmental sustainability of bio-based HMF production under uncertainty**

305 The global warming potential of HMF (GWP_{100}) was estimated to be 3.92 [3.39 – 4.74]
306 kg CO_2-eq kg HMF^{-1} (Figure 2d). 100% of simulated results were lower than GWP_{100} of its
307 alternative, bio-based p-xylene (PX) (~5.8 kg CO_2-eq kg PX^{-1}),[53] indicating the produced HMF
308 is likely to be less environmentally impactful than bio-based PX. GWP_{100} was dominated by
309 system heating demand (Figure 2e). Heating demand from bioproducts recovery and purification
310 and the rest of the system constituted 28.00% [26.14 – 29.66%] and 35.52% [31.28 – 38.85%] of
311 biorefinery GWP_{100}, respectively. Electricity demand was also significant contributor to
312 environmental impacts of the biorefinery, comprising 17.50% [14.02 – 21.48%] of the
313 biorefinery GWP_{100} (Figure 2e).

314 **3.3. Drivers of economic and environmental sustainability**

315 Six out of 22 parameters i.e., HMF price, biodiesel price, feedstock lipid content, HMF
316 market price, HMF retention in 1st nanofiltration, microbial lipid yield from glucose, and
317 vegetative lipid recovery after pretreatment and saccharification were identified as impactful
318 parameters for MFPP (absolute value of $\rho \geq 0.1$) (Figure 3), affecting MFPP through annual
319 production of diverse coproducts, capital investment, and operating costs (Figure S2, see
320 supplementary material). Market prices of main coproducts, i.e., HMF and biodiesel, were the

most impactful parameters for MFPP (Figure 3). HMF retention in 1st nanofiltration significantly impacted MFPP through HMF recovery in bioproducts recovery and purification, which in turn affected the annual production of HMF. Among the examined parameters associated with lipid production, feedstock lipid content, vegetative lipid recovery after pretreatment and saccharification, and microbial lipid yield from glucose, significantly impacted MFPP. The sensitivity of HMF MPSP was similar to MFPP (Figure 3). Thus, reducing the percentage of HMF retention in 1st nanofiltration, and increasing the lipid content of transgenic sugarcane-oilcane, vegetative lipid recovery after pretreatment and saccharification and microbial lipid yield from glucose would simultaneously improve HMF MPSP and MPFF. Furthermore, enhancement in microbial lipid yield and vegetative lipid recovery from transgenic bioenergy crops would improve economic and environmental performance of the system at once due to their significant impact on HMF GWP_{100} (Figure 3).

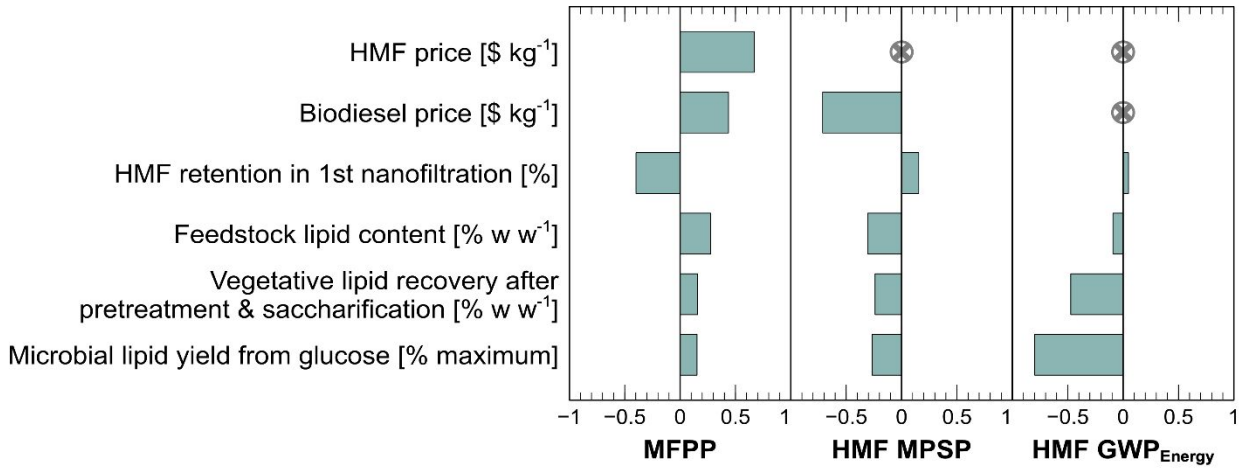


Figure 3. Spearman's ρ values between parameters and MFPP, HMF MPSP, and energy-allocated HMF GWP_{100}.

3.4. Implications of integrated microbial and vegetative lipid production

3.4.1. Microbial lipid production

At an industrial scale, both product yield and the titer of the product are critical. A lower yield and titer affect the economics of the company adversely. Therefore, biorefinery design was simulated at 400 different combinations of two fermentation parameters, i.e., microbial lipid yield from glucose (40 – 70%) and microbial lipid titer (8.8 – 28 g L^{-1}), keeping other parameters at baseline conditions. The analysis helped in quantifying the implications of technological advancements in these parameters on the sustainability of the biorefinery. Among 400 simulations, MFPP, HMF MPSP, and HMF GWP_{100} values spanned \$ 65.69 – 96.77 MT^{-1}, \$5.11 – 11.56 kg^{-1}, and 3.44 – 5.52 kg CO_2-eq kg HMF^{-1}, respectively (Figure 4a-c). The observation suggests that microbial lipids production is one of the major intermediary steps of the biorefinery.

An increase in microbial lipid yield from glucose benefitted MFPP and HMF MPSP in most situations (Figure 4a-b). The fermentation with higher microbial lipid yield produced more biodiesel and crude glycerol to provide additional revenue for the biorefinery. It also increased the fixed capital costs associated with the installation of larger pieces of equipment for microbial lipids fermentation and biodiesel production. However, the increased revenue was able to offset the associated higher costs in most situations, leading to improvements in MFPP and HMF MPSP. Moreover, higher microbial lipid production was able to counterbalance environmental impacts allocated to HMF without significantly increasing the environmental impacts of the system. Similarly, MFPP and HMF MPSP benefitted from higher microbial lipid titer in most cases (Figure 4a-b). Higher microbial lipid titer reduced capital and operating costs in microbial lipid production and downstream processing without affecting the annual production of microbial lipids. Uncertainty analysis indicates negligible or no impact of microbial lipid titer on HMF GWP_{100} (Figure 4c).

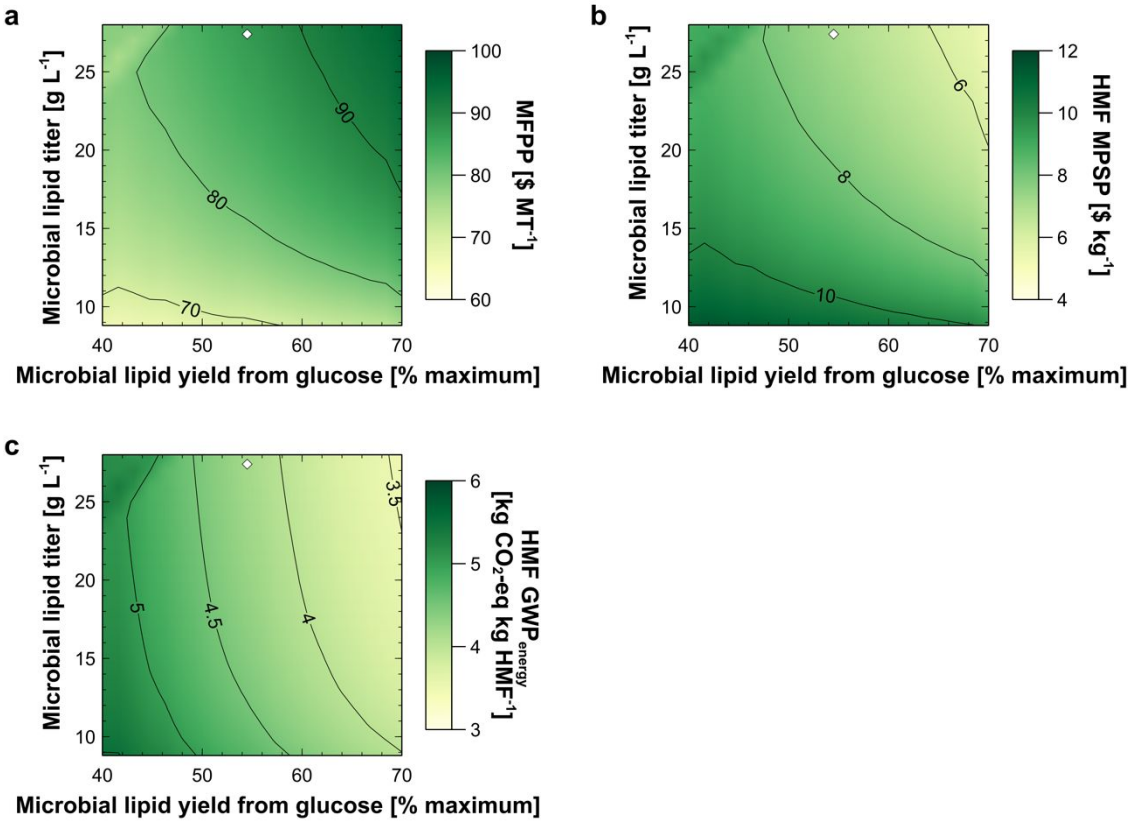


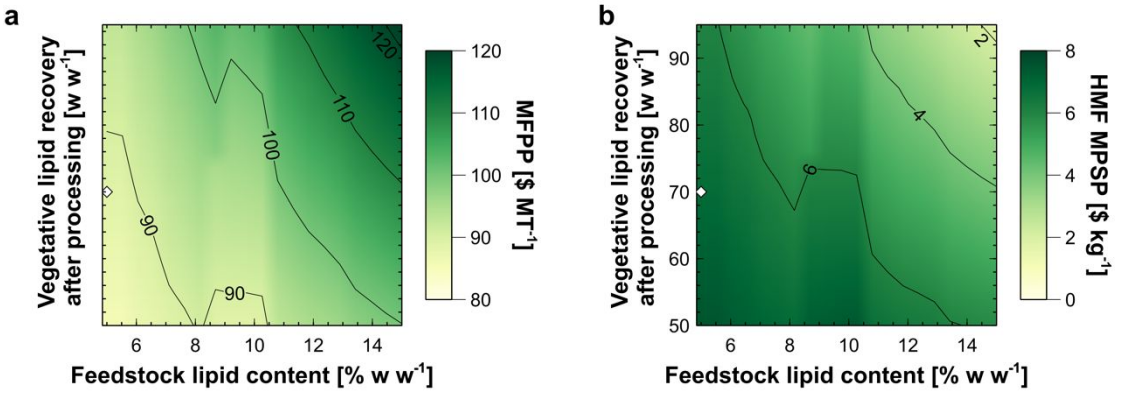
Figure 4. a) MFPP, b) HMF MPSP and c) HMF GWP_{100} using energy allocation at different combinations of microbial lipid yield from glucose and microbial lipid titer using baseline assumptions of other parameters. Diamond markers represent values obtained from the baseline biorefinery.

3.4.2. Vegetative lipid production from transgenic bioenergy crop

Transgenic sugarcane-oilcane provides an additional source of lipids that can be converted into biodiesel in a similar manner as microbial lipids. Therefore, the biorefinery design was simulated at 400 different combinations of two parameters related to the production and recovery of lipids from transgenic sugarcane-oilcane, i.e., feedstock lipid content (5 – 15%) and lipid recovery (50 – 95%) after processing (pretreatment and saccharification) to estimate their implications on the performance of the biorefinery. These simulations yielded MFPP, HMF MPSP, and HMF GWP_{100} values spanning \$ 85.01 – 121.85 MT^{-1} and \$1.75 – 7.55 kg^{-1}, and

375 3.37 – 4.76 kg CO_2-eq kg HMF^{-1} (Figure 5a-c). The observations indicate that higher lipid
376 content in the feedstock and improved recovery could significantly lower the cost of production
377 and selling price of bio-based HMF.

378 Similar to microbial lipids, an increase in feedstock lipid content and better recovery
379 improved the annual production of biodiesel and crude glycerol which resulted in higher revenue
380 for the biorefinery. The increased revenue neutralized the associated higher operating costs in
381 most cases, thereby improving MFPP and HMF MPSP. Higher feedstock lipid content had a
382 negligible impact on HMF GWP_{100} while an improvement in vegetative lipid recovery
383 significantly improved the global warming potential of the bio-based HMF (Figure 5c).
384 Increasing vegetative lipid recovery from 50 to 95% greatly reduced HMF GWP_{100} from a range
385 of 4.35 – 4.75 kg CO_2-eq kg HMF^{-1} to 3.37 – 3.84 kg CO_2-eq kg HMF^{-1} among simulations with
386 different feedstock lipid content. This is because improving the recovery of vegetative lipids
387 from feedstock provides more lipids for biodiesel production without significant utility
388 consumption or material usage.



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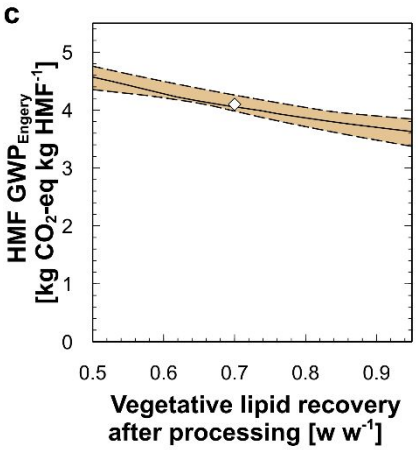

Figure 5. a) MFPP, b) HMF MPSP and c) HMF GWP_{100} using energy allocation at different combinations of feedstock lipid content and vegetative lipid recovery after processing (pretreatment and saccharification) using baseline assumptions of other parameters. Diamond markers represent values obtained from the baseline biorefinery. Dashed and middle lines in c represent minimum, maximum and median values from simulations with different feedstock lipid content at a constant vegetative lipid recovery after processing.

3.5. Setting target for HMF recovery using nanofiltration

An analysis of varying HMF retention in the 1st nanofiltration system (1 - 50%) was performed to quantify the impact of its advancement on MFPP and HMF MPSP. MFPP and HMF MPSP values spanned \$75.01 – 146.75 MT^{-1} and \$4.22 – 8.07 kg^{-1}, respectively. This suggests that reducing HMF retention in the 1st nanofiltration system directly and significantly improved MFPP and HMF MPSP (Figure 6) by increasing the annual production of HMF. A 1% reduction in HMF retention in 1st nanofiltration system increased MFPP by \$1.43 MT^{-1} and decreased HMF MPSP by \$0.077 kg^{-1}. The simulations yielded HMF GWP_{100} of 4.03 [3.94 – 4.13] kg CO_2-eq kg HMF^{-1} with negligible variance indicating no significant effect of the nanofiltration system on the environmental impacts of the system.

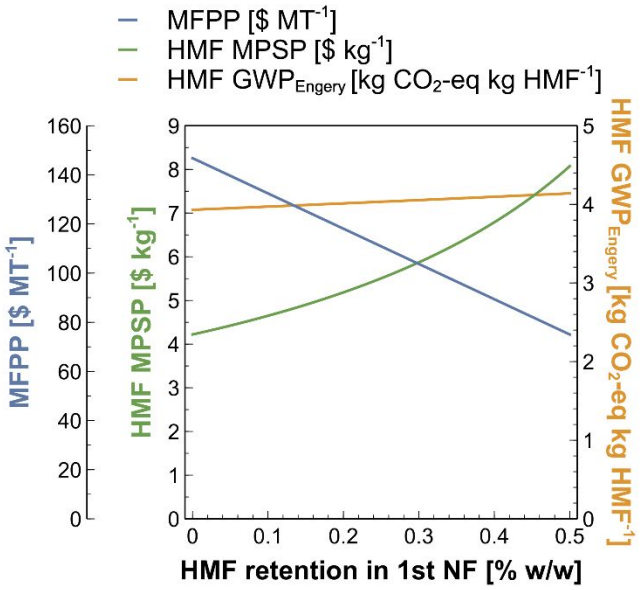

Figure 6. MFPP, HMF MPSP and HMF GWP_{100} using energy allocation at different HMF retention in 1st NF (nanofiltration) using baseline assumptions of other parameters.

4. Discussion

4.1. Transgenic sugarcane-oilcane as an alternative feedstock

For the production of bio-based products, feedstock plays a central role in the sustainability of the biorefinery. The use of transgenic sugarcane-oilcane improved the economic and environmental sustainability of bio-based HMF production by providing an additional revenue stream for the biorefinery. The estimated MFPP of transgenic sugarcane-oilcane was 2.3 to 4.5 times the average market price of sugarcane, suggesting that biorefinery is likely to be economically sustainable and can afford transgenic sugarcane-oilcane even if the commercial price is set to be higher than sugarcane. Note that MFPP estimation is largely dependent on the feedstock capacity and coproducts of the biorefinery,[25] therefore, the size of the biorefinery, amounts, and variety of coproduct products will have a significant impact. The use of transgenic sugarcane-oilcane increased the annual production of biodiesel by integrating vegetative lipids from the feedstock and microbial lipids produced from the fermentation of cellulosic sugars.

Biodiesel is the major co-product of the proposed biorefinery that provides an additional revenue stream to the biorefinery.

The estimated MPSP of HMF from the study is 53.39 to 97.41% lower than the current average market price of HMF.[42-44] The MPSP of HMF produced from starch or fructose using chemical catalysts in published literature ($0.35–2.16 kg^{-1}) is, however, more economical compared to most results in this study primarily due to higher sugar-to-HMF conversion rates and higher feedstock processing capacity of the biorefinery.[16, 54] The price difference is also associated with the amount of product produced annually by the biorefinery, the use of feedstock, green technology to produce and recover HMF, and conservative modeling based on experimental data in this study. Noteworthy, the study presents a detailed technological and environmental viability study with an alternative feedstock that averts the competition for human and animal food and limited agricultural land.

4.2. Carbon intensity of HMF and biodiesel production using transgenic sugarcane-oilcane

The carbon footprint of a biorefinery comprehensively measures all the emissions associated with the biorefinery while carbon intensity communicates the efficiency of each sector of biorefinery in terms of greenhouse gas emissions. To the best of the authors' knowledge, there are no published reports on the environmental impact of HMF production directly from lignocellulosic biomass using green technology. Only one study by Lam et al reported the environmental impact of HMF production from waste food.[55] The study normalized the results to understand the overall environmental impact. According to Lam et al, the environmental impacts on resources contributed 74% to the overall impacts which were attributed to resource depletion, mainly the metal catalysts. Health impacts contributed 25% due to the production and use of

organic solvents and metal catalysts, for instance, THF and aluminum chloride, respectively. Lam et al showed that the use of water as a solvent contributed only 0.003% of the overall impact. To this end, the present study uses water as a reaction medium during the pretreatment of lignocellulosic biomass. The environmental impact of HMF production was also compared with HMF-derived final products. The simulations generated for cradle-to-biorefinery gate GHG emissions of HMF production using transgenic sugarcane-oilcane in the proposed biorefinery design estimated a median HMF GWP_{100} of 3.92 kg CO_2-eq kg HMF^{-1}. The estimated value is approximately 1.2 − 30 times lower than reported values of CO_2 emissions per kg of hydroxymethyldiamine (HMDA), 2,5-furandicarboxylic acid (FDCA), and bio-based p-xylene (PX) produced from fructose (obtained from corn starch, high corn fructose syrup and oak) and glucose (obtained from wood chips).[54] However, the environmental impact of HMF production in the present study is competitive with the FDCA production from cellulose (derived from wood chips) i.e., 2.4 − 2.5 kg CO_2-eq kg $FDCA^{-1}$.[56]

Furthermore, biodiesel production from microbial lipids by fermentation of cellulosic sugars of transgenic oilcane results in half the carbon intensity as of soybean oil-derived biodiesel and 2-6 times higher biodiesel yield per unit land when juice sugars are used.[35] Assuming the carbon intensity of transgenic sugarcane-oilcane production (from cultivation and transportation) is similar to sugarcane, the overall carbon intensity of biodiesel production is expected to be lower than conventional biodiesel production using vegetable oil by improving the biodiesel yield by combining microbial and plant lipids.[35] Therefore, the use of transgenic bioenergy crops further improves environmental sustainability.

5. Conclusion

Systematic studies on the technoeconomic and environmental sustainability of bio-based HMF production directly from lignocellulosic biomass, especially alternative feedstocks, are limited. The study demonstrated the economic feasibility and environmental sustainability of the integrated biorefinery that produces multiple value-added bioproducts with the prioritization of research-set targets and potential technological advancements needed for further improvements. The study offers a unique perspective for the economic and environmental advantages of coproducing bio-based HMF from an alternative feedstock using green and non-catalytical technology. The study also introduces the benefits of using newly developed transgenic bioenergy crops to improve the economic and environmental sustainability of the process.

Author contributions

Yuyao Jia: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Shraddha Maitra**: Conceptualization, Methodology, Writing – reviewing & editing. **Lavanya Kudli**: Methodology, Writing – reviewing & editing. **Jeremy S. Guest**: Methodology, Resources, Supervision. **Vijay Singh**: Writing – reviewing & editing, Resources, Supervision, Project administration, Funding acquisition.

Conflict of interest

The authors declare no competing interests.

Data Availability

E-supplementary data of this work can be found in online version of the paper. The code used for the analysis generated using Python will be available at: https://github.com/BioSTEAMDevelopmentGroup/Bioindustrial-Park.

Acknowledgements

This work was funded by the DOE Center for Advanced Bioenergy and Bioproducts Innovation (U.S. Department of Energy, Office of Science, Biological and Environmental Research Program under Award Number DE-SC0018420). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the U.S. Department of Energy.

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Data availability statements

E-supplementary data of this work can be found in online version of the paper. The code used for the analysis generated using Python will be available at: https://github.com/BioSTEAMDevelopmentGroup/Bioindustrial-Park.