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Techno-economic and environmental impact analysis of integrated biodiesel production and tocopherol separation from rapeseed oil deodorizer distillate

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ABSTRACT

As the demand for sustainable energy and the importance of tocopherol increase, this study investigates the large-scale process model, economic analysis, optimum profitability scenario, and life cycle assessment of an integrated biodiesel production and tocopherol separation process using rapeseed oil deodorizer distillate. The primary objective is to evaluate the economic and environmental sustainability of this integrated approach. A large-scale process model was developed based on experimental data from the literature, and comprehensive assessments of technical and economic performance, minimum selling price, sensitivity analysis, and life cycle impact were conducted. This study demonstrates significant positive economic impacts, including an 18.04 % return on investment, a 5.54-year payback period, a 19.92 % internal rate of return, and a net present value of 21,876,000 USD at a 10 % discount rate. The minimum selling price of biodiesel and tocopherol is 0.67 and 20.07 US$/kg, respectively. Sensitivity analysis was performed considering variations in the prices of rapeseed oil deodorizer distillate, catalyst, biodiesel, and tocopherol. The environmental impact assessment revealed a global warming potential of 0.308 kg CO_2 eq per kg of biodiesel (well-to-wheel). The integrated process shows a lower minimum selling price and global warming potential.

1. Introduction

Fossil fuels are consumed in uncurbed amounts worldwide and play a pivotal role in the world energy market. According to the International Energy Agency, fossil fuel resources provided 81 % of the total energy in 2017 (Johnsson et al., 2019). The consumption of fossil fuels also creates an environmental imbalance. It spans a continuously growing wide range of hazards, pollutants, and ecosystem degradation. There are concerns not only with greenhouse gases but also with acid precipitation, ozone depletion, forest destruction, and radioactive substance emissions (Johnsson et al., 2019; Omidkar et al., 2023). The main sources of ground-level ozone and airborne particulate matter are the burning of fossil fuels including coal, gasoline, and diesel (Vohra et al., 2021). The combustion of fossil fuels accounts for 70 % of the total greenhouse gas emissions in the form of CO_2 (Johnsson et al., 2019).

Alternative fuels may vary by production and origin but possess the same production attribute without additional CO_2 emission through a feasible and clean procedure (Stančin et al., 2020). Biodiesel based on methyl ester fatty acids has proven to be a potential alternative fuel that meets all standards while reducing harmful gas emissions from internal combustion engines (Mofijur et al., 2019; Usman et al., 2023). It is sustainable, renewable, and nontoxic, with improved viscosity, biodegradability, clean energy with a high flashpoint, and calorific value comparable to fossil fuels; it has a promising commercial reputation (Chozhavendhan et al., 2020). Biodiesel can be produced from various sources, such as non-edible and edible oil, animal fats, waste oils, and microbial feedstocks (Naveenkumar and Baskar, 2020a, 2020b, 2021a, 2021b). However, biodiesel faces challenges in achieving full global

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commercialization due to its relatively high production costs compared to conventional fossil fuels (Gutiérrez-López et al., 2022). The market values of palm oil, sunflower oil, and others are comparatively high due to demand in the food industry, whereas some are crucial in the medical field, however using the deodorizer distillate of these oils can be economically feasible and eco-friendly. In biodiesel production, the feedstock constitutes a significant portion of the total production cost, accounting for 65–70 % ((Yaashikaa et al., 2022). One effective technique for reducing feed costs is the use of deodorizer distillate. The cost of deodorizer distillate varies, typically from $0.2 to $0.75 per kg, depending on the tocopherol content (Bouriakova et al., 2020).

An edible oil processing byproduct from a deodorization process is a deodorizer distillate comprising highly value-added compounds, such as squalene, glyceride, tocopherols, phytosterols, and fatty acids (Jafarian Asl and Niazmand, 2020). Annually, the global output of oil is prodigious, and millions of tons of deodorizer distillate, also known as "deodorizer scum" are produced. Rapeseed oil is the third most widely consumed vegetable oil; any rapeseed variety that produces an oil with an erucic content of more than 45 % (high erucic rapeseed oil) is known as "industrial rapeseed." Rapeseed oil deodorizer distillate (RODD), a byproduct of the oil industry, has excellent potential as a source of bioactive compounds. Utilizing RODD aligns with the principles of waste valorization and the circular economy; it shows a promising effect on biodiesel production in terms of economic and environmental values. Tocopherol, also known as Vitamin E, has four isomers, collectively known as "tocols" alpha (α), beta (β), gamma (γ), and delta (Ƃ); it is used as healthy products, additives in the food industry, and a strong antioxidant in cosmetic industries (Lv et al., 2021). During storage, it increases the shelf life of edible oils by preventing the rancidity of oils using its antioxidant properties. Based on the Straits Research report, in 2021–2025, tocopherol is expected to gain market growth with a compound annual growth rate of 8.75 %, and by 2030, it will reach $2288.73 (Straits Research, 2024). Many studies focused on the extraction of tocopherol using molecular distillation (Jiang et al., 2006; Martins et al., 2006; Posada et al., 2007; Shao et al., 2007).

Techno-economic analysis of biodiesel production has been studied under various circumstances and conditions. Biodiesel costs vary depending on the raw material, production technique, and separation process. Rajendran et al. produced biodiesel as byproducts from food waste in the production of polylactic acid and the minimum selling price of biodiesel ranges between 1.51 and 2.13 $/kg based on the composition of food waste (Rajendran and Han, 2021). Ortiz and de Santa-Ana investigated the techno-economic analysis of energy self-sufficient processes to produce biodiesel under supercritical conditions and concluded the minimum selling price of biodiesel from waste cooking oil using an alkaline catalytic process was 0.48 €/kg (Gutiérrez Ortiz and de Santa-Ana, 2017). The integrated process and utilization of waste feedstock are reducing the minimum selling price of the product and increasing economic sustainability (Longati et al., 2022; Rajendran and Han, 2022). RODD shows economic and commercial advantages for biodiesel production and bioactive compound extraction. The novelty of this study is to determine the economic feasibility and environmental impact of the integrated process. According to the literature, the economic and environmental studies for integrated biodiesel production and tocopherol separation are inadequate. This study will pave a path for commercial growth.

This study focuses mainly on the techno-economic analysis and lifecycle assessment of integrated biodiesel production and tocopherol separation from RODD. This study builds upon published research by (Lv et al., 2021; Zhu et al., 2013) and provides clear mass balance data which is essential for developing a large-scale process model. This study aims to develop a comprehensive large-scale process model, conduct a techno-economic analysis to evaluate the financial feasibility and economic benefits of the integrated process, identify key economic factors, perform a sensitivity analysis to understand their impact on the overall process, and conduct a lifecycle assessment to determine environmental impacts, focusing particularly on global warming potential. Through addressing these objectives, this study aims to provide a robust analysis of the potential benefits and challenges associated with utilizing RODD for integrated biodiesel and tocopherol production.

2. Material and methods

2.1. Process description

The techno-economic analysis was performed based on two published works on biodiesel production (Zhu et al., 2013) and tocopherol separation (Lv et al., 2021). SuperPro software was employed to perform the process simulation and economic analysis. The process model is shown in Fig. S1. The input and output of streams were classified. The study followed a continuous process. The geographical location of the project is in India. The plant production capacity is 50 metric tonnes (MT) per day of RODD. The duration of plant construction is 1 year, the startup is 4 months, and the lifetime is 20 years. The annual operating period of the plant is 330 days (7920 h) and the income tax is 25 %.

2.2. Technical performance

RODD contains free fatty acid (FFA) 43.50 ± 1.45 %, glycerides 34.92 ± 1.24 %, and tocopherols 5.06 ± 0.03 % (Zhu et al., 2013). An acid/base catalyst may affect the tocopherol due to high-temperature maintenance. Based on the literature data (Zhu et al., 2013), *B. cepacia* G63 lipase could be immobilized on a macroporous resin and used as a catalyst. RODD, methanol, and enzyme catalyst could be injected into the reaction tank, and based on literature data, 96 % of conversion was assumed with optimum conditions of a 1:1 compound lipase ratio, 2 % compound lipase dosage (based on oil weight), 1:0.25 oil/methanol ratio (g/mL), 35ºC reaction temperature, and 8 h reaction duration. In a transesterification reaction, triglycerides are converted into methyl ester and glycerol. To reduce the catalyst cost, 99 % of the immobilized lipase catalyst could be recovered using microfiltration and reused in subsequent reactions. The unreacted excess methanol could be instantly vaporized using a flash evaporator and condensed, 99 % of unreacted methanol could be recovered. In the decanting process, low-density biodiesel settled in the upper surface and high-density crude glycerol settled in the lower bottom. The crude glycerol could be eluted out and biodiesel and tocopherol mixture were washed with distilled water to remove the excess contamination to obtain pure biodiesel and tocopherol. About 96 % of biodiesel with a 98 % tocopherol retention rate could be produced. The recovery and separation of fatty acid methyl ester (FAME) and tocopherol could be performed in the molecular distillation unit. Molecular distillation is not available in SuperPro software, so the distillation equipment operated as molecular distillation with the same parameters. Afterwards, the biodiesel mixture could be transferred to a vessel and the temperature was maintained at 60ºC. The molecular distillation could be run by optimal conditions of the flow rate of 100 mL/h, wiper rolling speed of 380 rpm, evaporating pressure of 0.1 Pa, and 100ºC evaporating temperature, recovery of 99.12 ± 0.10 % of biodiesel and bioactive compound of 132 93.37 ± 4.08 % was achieved (Lv et al., 2021).

2.3. Economic performance

The material cost, wages, profit and loss, and other costs were given in US Dollars. The input unit costs for the materials were 0.50 $/kg for RODD, 54.03 $/kg for catalyst, 0.24 $/kg for methanol, and 0.01 $/kg for water. The price data were assumed based on previous literature studies, commercial websites and local vendors (Naveenkumar and Baskar, 2021a, 2021b). The selling prices of biodiesel and tocopherol are assumed to be 0.84 $/kg and 23.14 $/kg, based on previous literature studies and commercial websites. (Naveenkumar and Baskar, 2021a, 2021b). The capital investment calculations are shown in Table S1. The capital investment calculation relies on equipment purchase cost (Rajendran et al., 2022; Zheng et al., 2022). The capital investment is the sum of direct cost, indirect cost, other cost, working capital, and startup and validation cost. The equipment cost was determined based on the SuperPro cost built-in mode (Table S2). The utility and labor costs were collected from the literature, companies, and consultancy. The overall result includes plant capital investment, operating cost, production rate, unit production cost, net present value (NPV), internal rate of return (IRR), return on investment (ROI), gross margin (GM), and payback period.

Gross margin in simple terms is the profit made from total sales; it may vary from one company to another; however based on the rule of thumb, the low, medium, and high gross margins are 5 %, 10 %, and 20 %, respectively. It is calculated by net revenue minus raw material cost divided by net revenue.

$$Gross\ margin = \frac{Net\ revenue \quad Cost\ of\ raw\ materials}{Net\ revenue}$$

Return on investment is a profitability measure used to evaluate an investment's performance or efficiency or to compare different numbers of investment efficiencies. A return on investment of 100 % represents the doubling of initial investment. The return on investment calculation is a ratio between net profit and total investment used.

$$Return\ on\ investment = \frac{Net\ profit}{Total\ investment} \times 100$$

The payback period disregards the payback of money, i.e., the amount of time it takes to recover funds invested. The viability and feasibility of a plant can be found by the payback period. It is calculated by dividing the capital investment by annual cash flows.

$$Payback\ period = \frac{Capital\ investment}{Annual\ cash\ flows}$$

Internal rate of return is a core component of corporate finance and capital budgeting. This metric is used to estimate the profitability of potential investments in financial analysis; a discount rate that makes the net present value of a project zero. A project seems more profitable if the internal rate of return is higher. Net present value is the difference between the current value of cash in and outflows which helps to predict the project's profitability.

$$Net\ present\ value\ ^{1} = \sum_{t=1}^{T} \frac{Ct}{(1+r)t} \quad C0$$

where C0 is the initial investment, Ct is the return during the period t, r is the discount rate, and t is the number of cash flow periods (Naveenkumar and Baskar, 2020a, 2020b).

2.4. Minimum selling price

The Minimum Selling Price (MSP) represents the point where total revenue equals total cost, essentially the break-even price a concept explained as 'the lowest price at which a product can be sold'. MSP calculations were conducted for biodiesel and tocopherol to assess profitability. This analysis helps determine if the project can achieve a non-negative profit margin (Zheng et al., 2023a). The MSP calculations consider RODD and catalyst prices to estimate whether the project can recover initial investments and achieve a net present value of zero by the project's end.

2.5. Sensitivity analysis

Sensitivity analysis helps elucidate how the input variables/other variables affect the target variables in a process plant. Sensitivity analysis helps to find the economic feasibility of the process. This plays a crucial role in assessing the economic feasibility of the process and identifying opportunities to reduce major production costs, thereby enhancing the economic viability of the plant (Zheng et al., 2023b). The key variables are RODD (0.125–0.625 $/kg) and catalyst price (20–60 $/kg), biodiesel selling price (0.64–1.14 $/kg) and tocopherol selling price (10–35 $/kg); input values are incremented and decremented, which is assumed based on the base value; variations in the market due to supply/demand or other factors may cause some variables to fluctuate, which may affect the plant outcome.

2.6. Life cycle assessment

The life cycle assessment of biodiesel production and tocopherol separation from RODD has four steps (i) goal and scope, (ii) life cycle inventory analysis, (iii) life cycle impact analysis, and (iv) interpretation of results. The goal and scope of this study were to investigate the environmental impact of the process (biodiesel production and tocopherol separation from RODD). The life cycle inventory was performed based on input and output materials and an energy balance of 1 kg of biodiesel production. Rapeseed cultivation and biorefinery processes were neglected in this study because the biodiesel was produced from rapeseed biorefinery waste. The catalyst was neglected due to its small volume and recyclability. The life cycle assessment was performed according to the ISO 14040/14044 standard to observe the environmental impacts. The Simapro software 9.5 and GREET model were used to analyze the environmental impact of the overall biodiesel production process (well to wheel). The ReCiPe 2016 Midpoint (H) V1.04 method was employed in the life cycle impact assessment.

3. Results and discussion

3.1. Technical performance

The biodiesel produced at the optimal conditions of a 1:1 compound lipase ratio, 2 % compound lipase dosage (based on oil weight), 1:0.25 oil/methanol ratio (g/mL), 35°C reaction temperature, and 8 h reaction duration and separation at molecular distillation with conditions of 100 mL/h flow rate, 380 rpm wiper rolling speed, 0.1 Pa evaporating pressure, and 100°C evaporating temperature. The 50 MT/day of RODD, 9.87 MT/day of methanol, and 1 MT/day of immobilized lipase catalyst were fed into the reactor. After the transesterification process, 99 % of the catalyst and unreacted methanol were recovered, and 4.5 MT/day of crude glycerol was separated. The pure biodiesel mixture was transferred into the molecular distillation unit and separated as 2.48 and 45.78 MT/day of tocopherol and biodiesel, respectively. The process flow is shown in Fig. 1.

3.2. Economic performance

Economic analysis evaluates various factors including total capital cost, operating cost, revenue, unit production cost, gross margin, return on investment, internal rate of return, net present value, and payback period to predict plant profitability and sustainability. Methanol and catalyst recoveries reduce the production cost and increase profitability. Biodiesel and tocopherol were the main revenue streams; whereas methanol recovery, catalyst recovery, and crude glycerol were the other revenue streams. Tocopherol separation along with biodiesel production increased the economic value of the process. The total capital investment of the plant was estimated to be $ 31,065,000, annual operating cost was $ 37,185,000; the main revenue from the plant was $ 31,618,000, and the other revenue stream was $ 9631,000 with a 9.85 % gross margin, 18.04 % return on investment, 5.54 year payback period, 19.92 % internal rate of return, and $ 21,876,000 net present value. In main revenue, biodiesel accounts for 40.14 % and tocopherol accounts for 59.86 %. The capital investment, annual operating, and revenue costs are shown in Fig. 2. The annual operating cost of biodiesel production from canola oil was $ 53,710,000 for a capacity of 50 MT/

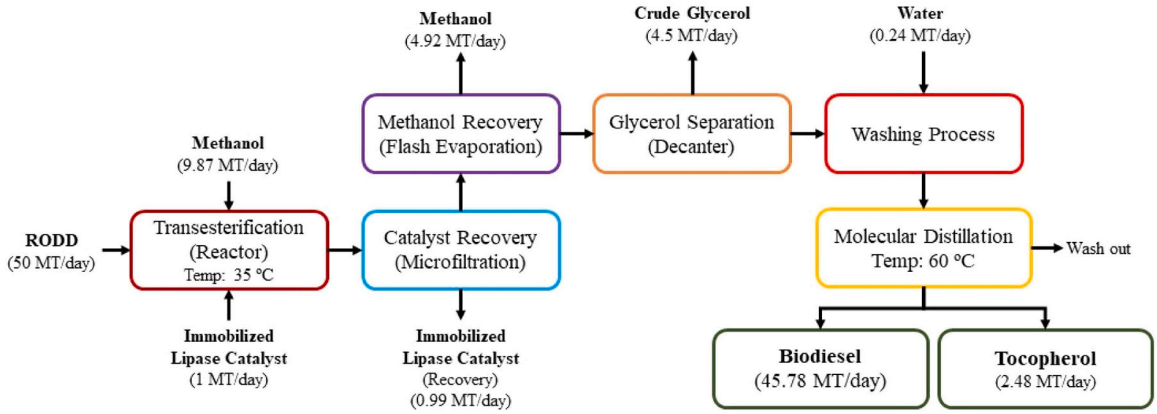

Fig. 1. Process flow of biodiesel and tocopherol from RODD.

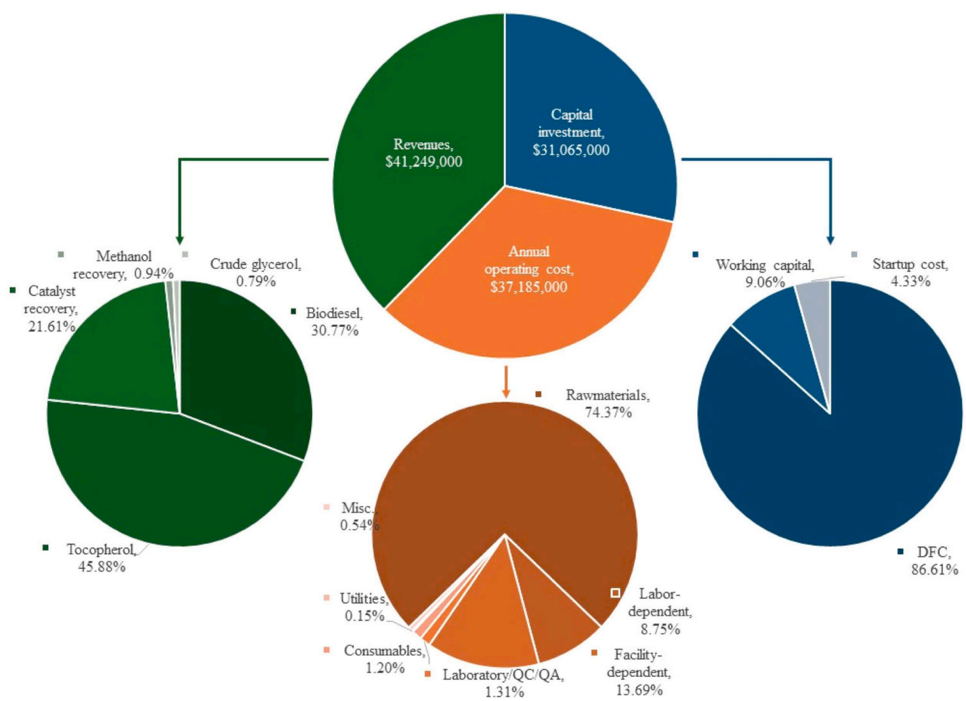

Fig. 2. Economic factors–capital investment, annual operating cost, and revenues.

year (Gholami et al., 2021), while for *Jatropha curcas,* it was $ 46,430, 000 for a capacity of 40 MT/year (Yusuf and Kamarudin, 2013). In this study, the operating cost was lower due to the use of low-cost feedstock. The unit operations, such as stirred reactor, microfilter, flash drum evaporator, decanter, and molecular distillation, were used in the process. The cash flow analysis is shown in Table S3. Positive values of net present value and internal rate of return show the project is profitable. The integrated biodiesel and tocopherol production from RODD was found to be economically profitable and liable.

The MSP of biodiesel and tocopherol were 0.67 and 20.07 $/kg, respectively. In the calculation of MSP, while calculating the MSP of biodiesel, biodiesel was considered as the main revenue and tocopherol as other revenue, while calculating the MSP of tocopherol, tocopherol was considered as the main revenue and biodiesel as other revenue. Dougher et al. reported the techno-economic analysis of biodiesel produced from soybean oil and the MSP of biodiesel was 0.78 $/kg (Dougher et al., 2023). Kedia et al. the MSP of biodiesel was reported to be 1.48 $/kg, produced from non-edible oil (Kedia et al., 2023). Gholami et al. calculated the cost of biodiesel produced from canola oil using ultrasonic cavitation, identifying a $1.02/kg and highlighting the significant role of feedstock costs (Gholami et al., 2021). Yusuf and Kamarudin conducted a techno-economic analysis of biodiesel production from Jatropha curcas utilizing a supercritical methanol process, the findings indicated that the production cost of biodiesel was $0.78 per kg (Yusuf and Kamarudin, 2013). Based on data from commercial e-commerce sites, the price of tocopherol varies depending on volume and quality. For instance, Jedwards International, Inc. sells 20 kg of D-alpha tocopherol for $1520, which equates to 76 $/kg (www.bulknaturaloils.com, 2024). In techno-economic analysis, the values are based on different factors, such as region, feedstock, process plant life, production method, capacity, reaction conditions, yield conversion and byproducts. In India, as of January 2024, the diesel dealer price (without excise duty, dealer commission, and sales tax) was 0.85 $/kg or 0.70 $/Liter (1 $=82.85 INR) (www.ppac.gov.in, 2024). The Government of India provides financial support and incentives for biodiesel production (www.mopng.gov.in, 2022). The MSP of biodiesel and tocopherol in this study is very competitive with previous biodiesel studies and the current dealer price of petrodiesel.

3.3. Sensitive analysis

The sensitivity analysis was performed to test uncertain variables and factors that affect the plant's economic feasibility. The MSP of biodiesel and tocopherol depends on various factors. Based on RODD prices vary from 0.125 to 0.75 $/kg, the biodiesel and tocopherol prices vary from 0.26 to 0.95 $/kg and 12.47–25.14 $/kg, respectively; based on catalyst prices from 20 to 70 $/kg, the biodiesel and tocopherol prices vary from 0.30 to 0.85 $/kg and 13.14–23.32 $/kg, respectively. The price of biodiesel was varied (1.39–0.03 $/kg) based on the tocopherol price (10–35 $/kg). The price of tocopherol price was varied (23.76–14.53 $/kg) based on biodiesel price (0.64–1.14 $/kg) (Fig. 3). Hence, lower cost of RODD and catalyst reduces production cost, which also reduces the MSP of biodiesel and tocopherol; an increase in the selling price of tocopherol reduces the MSP of biodiesel, similarly an increase in the selling price of biodiesel also reduces the MSP of tocopherol. Therefore, reducing the feedstock and catalyst costs would make the process more economically sustainable.

In sensitive analysis, parameters such as return on investment, payback period, net present value, and internal rate of return were investigated. The range of input variables is the assumption based on the base value; the input variable is shown in Fig. 4. Considering the RODD price from 0.125 to 0.625 $/kg, the net present value varies from 54.07 to 3.30 M$; after 0.625 $/kg, it became a negative value, whereas, at 0.125 $/kg, it shows the highest return on investment of 33.59 %, low payback period of 2.98 years and 41.48 % internal rate of return. Considering catalyst price from 20 to 60 $/kg, the net present value varies from 50.95 to 9.98 M$; after 60 $/kg, it attains a negative value, whereas, at 20 $/kg, it shows a low payback period of 3.06 years, the highest return on investment of 32.67 %, and IRR of 40.23 %. When the biodiesel selling price is 1.14 $/kg, there is a high return on investment of 28.98 %, a low payback period of 3.45 years, a net present value of 43.64 M$, and a 34.77 % internal rate of return. When the tocopherol selling price is 35 $/kg, there is a high return on investment of 41.46 %, a low payback period of 2.41 years, a net present value of 74.89 M$, and 53.83 % internal rate of return. Input variables will change based on region, time, demand, and some unforeseen crises, so sensitivity analysis helps to understand how uncertain variables affect the economics of biodiesel and tocopherol production plan.

3.4. Life cycle assessment

The life cycle assessment of biodiesel production and tocopherol separation from RODD investigated the global warming potential. The life cycle inventory input and output data are shown in Table S4. In the life cycle assessment, three output products were considered biodiesel, tocopherol and glycerol and mass allocation was followed. Recovered catalyst and methanol were not considered in the mass allocation. The global warming potential of 1 kg biodiesel, 0.05 kg tocopherol, and 0.10 kg glycerol production is 0.159 kg CO_2 eq (well to pump). Biodiesel accounts for 86.96 % of the total global warming potential in terms of mass allocation (0.139 kg CO_2 eq), of which methanol accounts for 47.84 %, steam accounts for 31.75 %, electricity accounts for 19.48 %, and water accounts for 0.93 %. Tocopherol and glycerol account for 8.70 % (0.014 kg CO_2 eq) and 4.34 % (0.007 kg CO_2 eq) of the total global warming potential, respectively. The global warming potential of consumption of 1 kg of biodiesel is 0.169 kg CO_2 eq (pump to wheel), so the global warming potential of well to wheel is 0.308 kg CO_2 eq/kg of biodiesel, which is lower than the conventional diesel well to wheel (4.473 kg CO_2 eq/kg of diesel) (GREET, 2022). In the life cycle assessment, agriculture activities were not included as it was considered a waste byproduct of oil refineries. Gupta et al. reported the global warming potential of producing 1 kg of biodiesel from rapeseed oil was 2.63 kg CO_2 eq and found the rapeseed agriculture stage accounted for more than 65 % of the total CO_2 emissions (Gupta et al., 2022). Al-Mawali et al. conducted a life cycle assessment of biodiesel production from waste date seed oil, finding the global warming potential for producing 1 kg of biodiesel was 1.11 kg CO_2 eq and highlighted the catalyst preparation and reuse stages exhibited the highest global warming potential (Al-Mawali et al., 2021). Perez-Lopez et al. conducted an LCA of producing bioactive compounds from *Tetraselmis suecica* at a pilot scale, the α-tocopherol production accounted for 0.67 kg CO_2 eq per 69.7 mg, which is significantly higher than the 0.014 kg CO_2 eq per 0.05 kg reported in this study and highlighted using large volumes of fertilizer and electricity considerably increases the environmental impact (Pérez-López et al., 2014). Using waste feedstocks

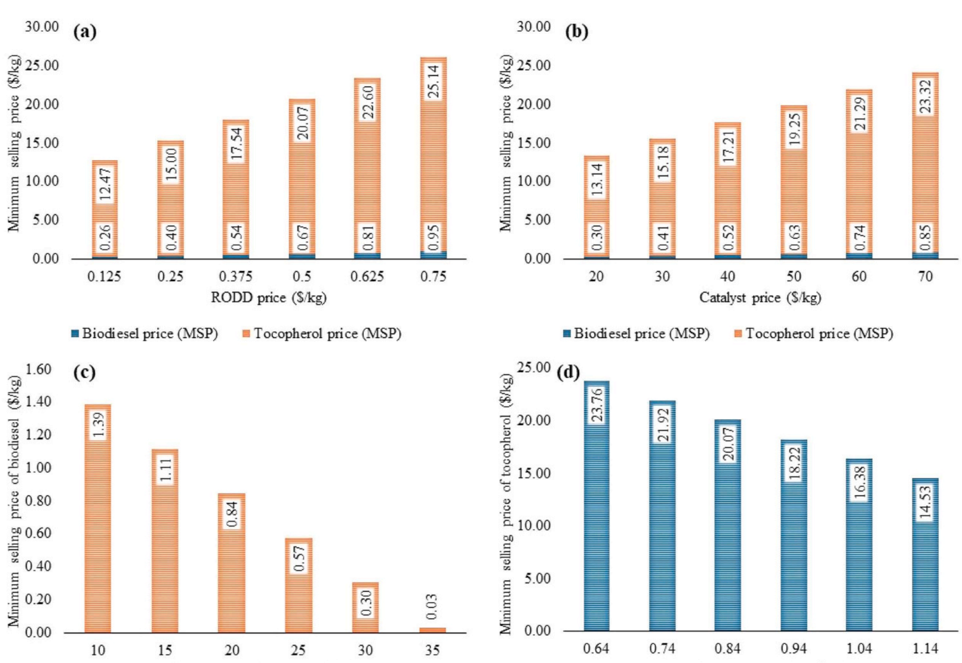

Fig. 3. Minimum selling price (a) RODD price on biodiesel and tocopherol minimum selling price; (b) catalyst price on biodiesel and tocopherol minimum selling price; (c) tocopherol price on biodiesel minimum selling price; (d) biodiesel price on tocopherol minimum selling price.

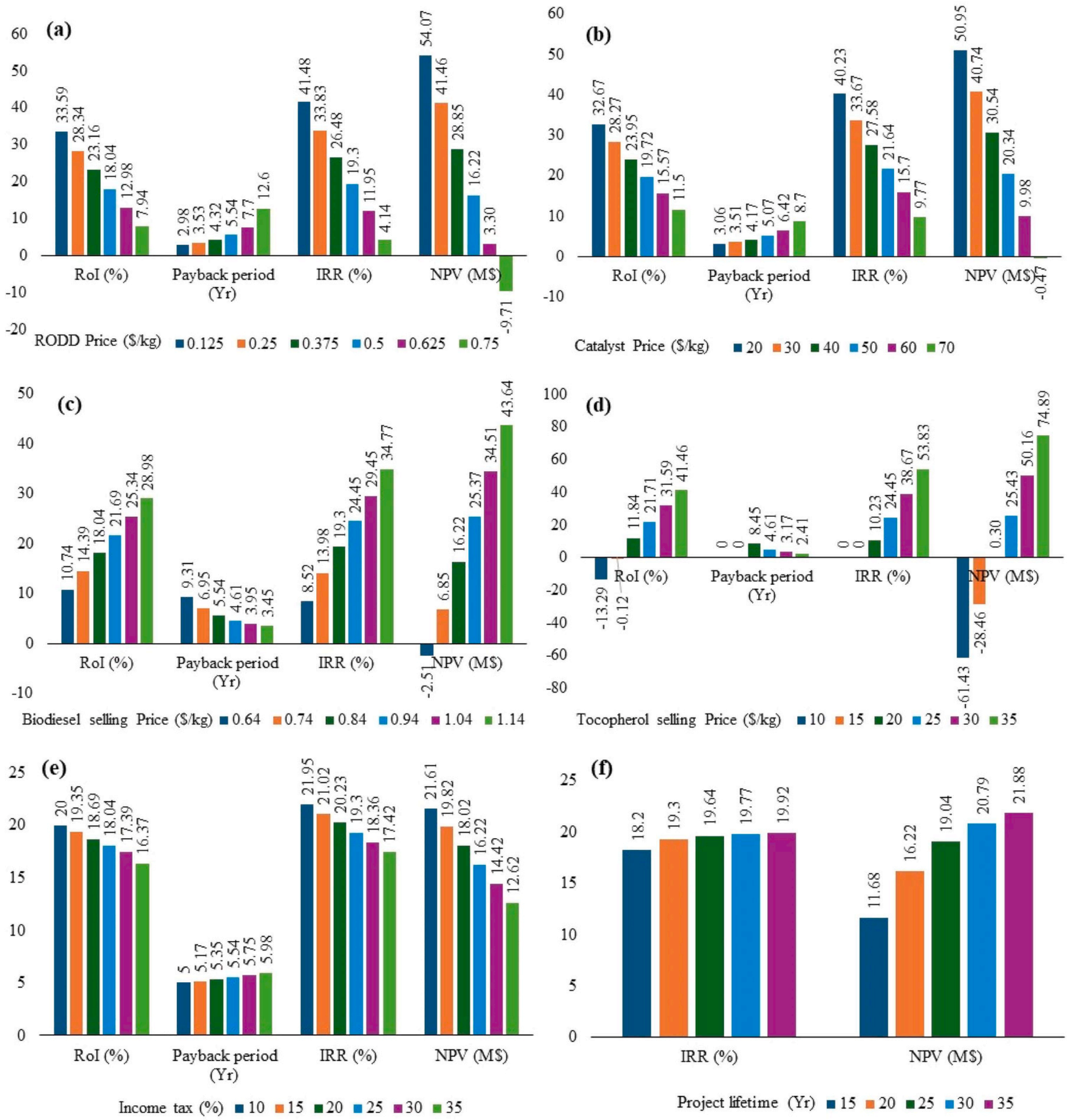

Fig. 4. Sensitivity analysis of economic factors: (a) RODD price, (b) catalyst price, (c) biodiesel selling price, (d) tocopherol selling price (e) income tax, and (f) project lifetime.

for biodiesel production (Srikumar et al., 2024) and tocopherol separation shows low environmental impact.

4. Conclusions

This study demonstrates the economic viability and environmental benefits of using RODD as feedstock, highlighting the cost-effectiveness and sustainability of the integrated process. In operating costs, enzyme catalysts have a significant impact. Reducing catalyst costs decreases both the operating cost and the minimum selling price of biodiesel and tocopherol. Methanol and steam have the most significant impact on global warming potential. Reducing methanol utilization and incorporating alternative energy sources further decrease the environmental footprint. By utilizing low-cost and waste feedstock, the study shows a reduction in both the minimum selling price and environmental impact of biodiesel and tocopherol. The reduced minimum selling prices and lower global warming potential encourage the adoption of waste valorization and circular economy principles within the biofuel and biochemical industries. The findings highlight opportunities for industry stakeholders to adopt integrated approaches which enhance economic viability while minimizing environmental impact. This study serves as a model for future research and industrial practices, promoting multi-product processes which boost profitability and reduce environmental impact.

CRediT authorship contribution statement

Jeehoon Han: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Baskar Gurunathan:** Writing – review & editing. **R. B. Sherly Priyanka:** Writing – original draft, Methodology, Investigation. **Naveenkumar Rajendran:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2024.119304.

References

Al-Mawali, K.S., Osman, A.I., Al-Muhtaseb, A.H., Mehta, N., Jamil, F., Mjalli, F., Vakili-Nezhaad, G.R., Rooney, D.W., 2021. Life cycle assessment of biodiesel production utilising waste date seed oil and a novel magnetic catalyst: a circular bioeconomy approach. Renew. Energy 170, 832–846. https://doi.org/10.1016/j.renene.2021.02.027.

Bouriakova, A., Mendes, P.S.F., Elst, K., de Clercq, J., Thybaut, J.W., 2020. Techno-economic evaluation of squalene recovery from oil deodorizer distillates. Chem. Eng. Res. Des. 154, 122–134. https://doi.org/10.1016/j.cherd.2019.12.003.

Chozhavendhan, S., Vijay Pradhap Singh, M., Fransila, B., Praveen Kumar, R., Karthiga Devi, G., 2020. A review on influencing parameters of biodiesel production and purification processes. Curr. Res. Green. Sustain. Chem. 1–2, 1–6. https://doi.org/10.1016/j.crgsc.2020.04.002.

Dougher, M., Soh, L., Bala, A.M., 2023. Techno-economic analysis of interesterification for biodiesel production. Energy Fuels 37, 2912–2925. https://doi.org/10.1021/acs.energyfuels.2c04029.

Gholami, A., Pourfayaz, F., Maleki, A., 2021. Techno-economic assessment of biodiesel production from canola oil through ultrasonic cavitation. Energy Rep. 7, 266–277. https://doi.org/10.1016/j.egyr.2020.12.022.

Gupta, R., McRoberts, R., Yu, Z., Smith, C., Sloan, W., You, S., 2022. Life cycle assessment of biodiesel production from rapeseed oil: influence of process parameters and scale. Bioresour. Technol. 360, 127532 https://doi.org/10.1016/j.biortech.2022.127532.

Gutiérrez Ortiz, F.J., de Santa-Ana, P., 2017. Techno-economic assessment of an energy self-sufficient process to produce biodiesel under supercritical conditions. J. Supercrit. Fluids 128, 349–358. https://doi.org/10.1016/j.supflu.2017.03.010.

Gutiérrez-López, A.N., Mena-Cervantes, V.Y., González-Espinosa, M.A., Sosa-Rodríguez, F.S., Vazquez-Arenas, J., Rodríguez-Ramírez, R., Hernández-Altamirano, R., 2022. Green and fast biodiesel production at room temperature using soybean and *Jatropha curcas L.* oils catalyzed by potassium ferrate. J. Clean. Prod. 372, 133739 https://doi.org/10.1016/j.jclepro.2022.133739.

Jafarian Asl, P., Niazmand, R., 2020. Modelling and simulation of supercritical CO_2 extraction of bioactive compounds from vegetable oil waste. Food Bioprod. Process. 122, 311–321. https://doi.org/10.1016/j.fbp.2020.05.005.

Jiang, S.T., Shao, P., Pan, L.J., Zhao, Y.Y., 2006. Molecular distillation for recovering tocopherol and fatty acid methyl esters from rapeseed oil deodoriser distillate. Biosyst. Eng. 93, 383–391. https://doi.org/10.1016/j.biosystemseng.2006.01.008.

Johnsson, F., Kjärstad, J., Rootzén, J., 2019. The threat to climate change mitigation posed by the abundance of fossil fuels. Clim. Policy 19, 258–274. https://doi.org/10.1080/14693062.2018.1483885.

Longati, A.A., Campani, G., Furlan, F.F., Giordano, R. de C., Miranda, E.A., 2022. Microbial oil and biodiesel production in an integrated sugarcane biorefinery: Techno-economic and life cycle assessment. J. Clean. Prod. 379, 134487 https://doi.org/10.1016/j.jclepro.2022.134487.

Lv, W., Wu, C., Lin, S., Wang, X., Wang, Y., 2021. Integrated utilization strategy for soybean oil deodorizer distillate: synergically synthesizing biodiesel and recovering bioactive compounds by a combined enzymatic process and molecular distillation. ACS Omega 6, 9141–9152. https://doi.org/10.1021/acsomega.1c00333.

Martins, P.F., Batistella, C.B., Maciel-Filho, R., Wolf-Maciel, M.R., 2006. Comparison of two different strategies for tocopherols enrichment using a molecular distillation process. Ind. Eng. Chem. Res 45, 753–758. https://doi.org/10.1021/ie050614i.

Mofijur, M., Rasul, M.G., Hassan, N.M.S., Nabi, M.N., 2019. Recent development in the production of third generation biodiesel from microalgae. Energy Procedia 156, 53–58. https://doi.org/10.1016/j.egypro.2018.11.088.

Naveenkumar, R., Baskar, G., 2020a. Optimization and techno-economic analysis of biodiesel production from *Calophyllum inophyllum* oil using heterogeneous nanocatalyst. Bioresour. Technol. 315 https://doi.org/10.1016/j.biortech.2020.123852.

Naveenkumar, R., Baskar, G., 2020b. Optimization and techno-economic analysis of biodiesel production from *Calophyllum inophyllum* oil using heterogeneous nanocatalyst. Bioresour. Technol. 315, 123852 https://doi.org/10.1016/j.biortech.2020.123852.

Naveenkumar, R., Baskar, G., 2021b. Process optimization, green chemistry balance and technoeconomic analysis of biodiesel production from castor oil using heterogeneous nanocatalyst. Bioresour. Technol. 320, 124347 https://doi.org/10.1016/j.biortech.2020.124347.

Naveenkumar, R., Baskar, G., 2021a. Process optimization, green chemistry balance and technoeconomic analysis of biodiesel production from castor oil using heterogeneous nanocatalyst. Bioresour. Technol. 320 https://doi.org/10.1016/j.biortech.2020.124347.

Omidkar, A., Xu, H., Li, Z., Haddadian, K., Song, H., 2023. Techno-economic and life cycle assessment of renewable diesel production via methane-assisted catalytic waste cooking oil upgrading. J. Clean. Prod. 414, 137512 https://doi.org/10.1016/j.jclepro.2023.137512.

Pérez-López, P., González-García, S., Ulloa, R.G., Sineiro, J., Feijoo, G., Moreira, M.T., 2014. Life cycle assessment of the production of bioactive compounds from Tetraselmis suecica at pilot scale. J. Clean. Prod. 64, 323–331. https://doi.org/10.1016/j.jclepro.2013.07.028.

Posada, L.R., Shi, J., Kakuda, Y., Xue, S.J., 2007. Extraction of tocotrienols from palm fatty acid distillates using molecular distillation. Sep Purif. Technol. 57, 220–229. https://doi.org/10.1016/j.seppur.2007.04.016.

Rajendran, N., Han, J., 2021. Integrated polylactic acid and biodiesel production from food waste: process synthesis and economics. Bioresour. Technol., 126119 https://doi.org/10.1016/j.biortech.2021.126119.

Rajendran, N., Han, J., 2022. Techno-economic analysis of food waste valorization for integrated production of polyhydroxyalkanoates and biofuels. Bioresour. Technol. 348, 126796 https://doi.org/10.1016/j.biortech.2022.126796.

Rajendran, N., Kang, D., Han, J., Gurunathan, B., 2022. Process optimization, economic and environmental analysis of biodiesel production from food waste using a citrus fruit peel biochar catalyst. J. Clean. Prod. 365, 132712 https://doi.org/10.1016/j.jclepro.2022.132712.

Shao, P., Jiang, S.T., Ying, Y.J., 2007. Optimization of molecular distillation for recovery of tocopherol from rapeseed oil deodorizer distillate using response surface and artificial neural network models. Food Bioprod. Process. 85, 85–92. https://doi.org/10.1205/fbp06048.

Srikumar, K., Tan, Y.H., Kansedo, J., Tan, I.S., Mubarak, N.M., Ibrahim, M.L., Yek, P.N.Y., Foo, H.C.Y., Karri, R.R., Khalid, M., 2024. A review on the environmental life cycle assessment of biodiesel production: Selection of catalyst and oil feedstock. Biomass Bioenergy. https://doi.org/10.1016/j.biombioe.2024.107239.

Stančin, H., Mikulčić, H., Wang, X., Duić, N., 2020. A review on alternative fuels in future energy system. Renew. Sustain. Energy Rev. 128 https://doi.org/10.1016/j.rser.2020.109927.

Straits Research, 2024. Tocopherol Market Size is Expected to Reach USD 2,288.73 million by 2030, Growing at a CAGR of 8.75%. GlobeNewswire. ⟨https://www.globenewswire.com/news-release/2024/04/24/2868801/0/en/Tocopherol-Market-Size-is-Expected-to-Reach-USD-2-288-73-million-by-2030-Growing-at-a-CAGR-of-8-75-Straits-Research.html⟩.

Usman, M., Cheng, S., Boonyubol, S., Aziz, M., Cross, J.S., 2023. Socio- and techno-economic analyses of biodiesel production from sewage sludge in Tokyo, Japan. J. Clean. Prod. 425, 138551 https://doi.org/10.1016/j.jclepro.2023.138551.

Vohra, K., Vodonos, A., Schwartz, J., Marais, E.A., Sulprizio, M.P., Mickley, L.J., 2021. Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: results from GEOS-Chem. Environ. Res. 195, 110754 https://doi.org/10.1016/j.envres.2021.110754.

www.bulknaturaloils.com, 2024. D-Alpha Tocopherol Price. ⟨https://bulknaturaloils.com/d-alpha-tocopherol-1-000-i-u-per-gram-v6000.html⟩.

www.mopng.gov.in, 2022. National Policy on Biofuels-2018, Amendment-2022. Ministry of Petroleum and Natural Gas, Gov. of India. ⟨https://mopng.gov.in/files/article/articlefiles/Notification-15-06-2022-Amendments-in-NPB-2018.pdf⟩.

www.ppac.gov.in, 2024. Snapshot of India's oil and gas data - January 2024. Petroleum Planning & Analysis Cell (Ministry of Petroleum & Natural Gas). ⟨https://ppac.gov.in/uploads/rep_studies/1709717627_monthly-ready-recknor-jan-24.pdf#page=33⟩.

Yaashikaa, P.R., Keerthana Devi, M., Senthil Kumar, P., Pandian, E., 2022. A review on biodiesel paroduction by algal biomass: outlook on lifecycle assessment and techno-economic analysis. Fuel 324. https://doi.org/10.1016/j.fuel.2022.124774.

Yusuf, N.N.A.N., Kamarudin, S.K., 2013. Techno-economic analysis of biodiesel production from *Jatropha curcas* via a supercritical methanol process. Energy Convers. Manag. 75, 710–717. https://doi.org/10.1016/j.enconman.2013.08.017.

Zheng, J.L., Zhu, Y.H., Dong, Y.Y., Chen, Y., Zhu, M.Q., 2023a. Techno-economic analysis and life cycle assessment of industrial production of ammonia via bio-oil conversion. Energy 280. https://doi.org/10.1016/j.energy.2023.128223.

Zheng, J.L., Zhu, Y.H., Su, H.Y., Sun, G.T., Kang, F.R., Zhu, M.Q., 2022. Life cycle assessment and techno-economic analysis of fuel ethanol production via bio-oil fermentation based on a centralized-distribution model. Renew. Sustain. Energy Rev. 167 https://doi.org/10.1016/j.rser.2022.112714.

Zheng, J.L., Zhu, Y.H., Zhang, W., Sun, G.T., Zhu, M.Q., 2023b. Life cycle assessment and techno-economic analysis of joint extraction of Eucommia powder, gum, water-soluble polysaccharide and alkali-extractable polysaccharide from Eucommia leaves. Process Biochem. 124, 235–244. https://doi.org/10.1016/j.procbio.2022.11.025.

Zhu, Z., Xu, L., Zhang, H., Yan, Y., 2013. Efficient production of biodiesel from rapeseed oil deodorizer distillate: one-pot esterification and transesterfication with compound lipases. Appl. Mech. Mater. 291–294, 267–275. https://doi.org/10.4028/www.scientific.net/AMM.291-294.267.