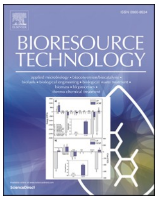
Bioresource Technology 360 (2022) 127532

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech



Life cycle assessment of biodiesel production from rapeseed oil: Influence of process parameters and scale

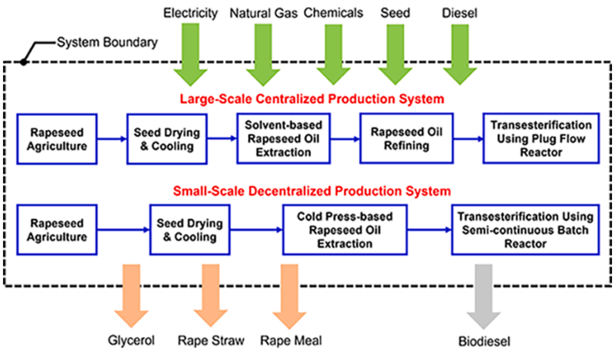
Rohit Gupta [1], Ruairidh McRoberts [1], Zhibin Yu, Cindy Smith, William Sloan, Siming You *

James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

HIGHLIGHTS

- Life cycle assessment of rapeseed oil-based biodiesel (BD) production was presented.
- Influences of process operating conditions and production scales were investigated.
- The systems had GWP of 2.63 (large-scale) and 2.88 (small-scale) tCO_2-eq/tBD.
- Rapeseed agriculture stage caused more than 65% of the CO_2 emissions.
- The alternative scenario reduced GWP by 14.1% (large-scale) and 33.6% (small-scale).

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Biodiesel
Rapeseed Oil
Life Cycle Assessment
Global Warming Potential
Sustainable Development

ABSTRACT

Biodiesel has the potential to mitigate the fossil fuel-related carbon emission and energy insecurity challenges. There are limited studies examining the impacts of biodiesel production scales on the environmental impacts, while such information will be valuable for guiding practical system design. This work applied the approach of life cycle assessment to evaluate the environmental impacts of biodiesel production from rapeseed oil which accounts for 80% of the European biofuel market. It was shown that the centralized large-scale and localized small-scale biodiesel production schemes have annual global warming potential (GWP) of 2.63 and 2.88 tCO_2-eq/t biodiesel, where the rapeseed agriculture stage caused more than 65% carbon emissions. Sensitivity analysis revealed a high dependence of GWP on rapeseed yields, glycerol re-utilization strategy, and nitrogen nutrient in fertilizer. An alternative scenario was proposed for the large- and small-scale systems that could reduce carbon emissions by 14.1% and 33.6%.

1. Introduction

Rising concerns related to greenhouse gases (GHG) including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emitted from heating and transportation sectors have caused a paradigm shift towards alternative energy sources such as biodiesel and bioethanol. Besides mitigating the global warming potential (GWP) biodiesel showed potential to decrease the sectors' dependence on fossil fuels during

---

* Corresponding author.

E-mail address: siming.you@glasgow.ac.uk (S. You).

[1] The authors contribute equally.

https://doi.org/10.1016/j.biortech.2022.127532
Received 26 May 2022; Received in revised form 22 June 2022; Accepted 23 June 2022

political and economic turmoil. In particular, the biodiesel sector in the UK was constantly uprising with a demand of 126 million litre of biodiesel solely for the transportation sector in 2020 (Puricelli et al., 2021).

Biodiesel can be produced from a wide variety of biomass feedstocks such as algae, raw and waste cooking oil (WCO), food waste, or animal fats (Schmidt, 2015). However, in UK approximately 50% of the biodiesel production was resourced from rapeseed oil (RO) due to its enhanced cold flow properties and oxidation stability (Malça et al., 2014), while fitting adequately within the UK and European legislation of biodiesel usage. There was approximately 331 ha of land used to grow oilseed rape in the UK (DEFRA, 2020b), which as of 2020 had an average yield of 2.7 t/ha (DEFRA, 2020a). Due to the opportunities of its cultivation strictly for biodiesel production, oilseed rape and raw RO have experienced significant attention in recent years.

Biodiesel production from RO comprised of salient stages such as rapeseed agriculture, seed preparation process, oil extraction, and biodiesel production (Abbaszaadeh et al., 2012). The production process relied on the transesterification of vegetable oil with an alcohol in presence of a base catalyst, producing biodiesel and glycerol (Stephenson et al., 2008). Material and energy flows across each of these stages ultimately affected the GWP of the whole process and led to variations of carbon emissions upon different types of deployments. The whole process also generated by-products which must be disposed of such as rape straw from agriculture process, rape meal from oil extraction, and glycerol from biodiesel reactor, that caused additional environmental and economic footprints (Stephenson et al., 2008). Hence it is possible to develop alternative strategies to utilize process by-products for the reduction of cumulative energy demand (CED) and GWP.

Existing biodiesel life cycle assessment (LCA) literature is mainly focused on leading biodiesel regions such as the European Union (EU) (Brinkman et al., 2018; Dufour et al., 2013; Fridrihsone et al., 2020; Malça et al., 2014; Malça & Freire, 2010), Middle East (Khanali et al., 2018; Rehan et al., 2018), USA (Chen et al., 2018), China (Syafiuddin et al., 2020), and India (Bhonsle et al., 2022). Some of these works quantified a wide range of environmental impact categories such as GWP, water footprint, land use, acidification potential, ozone formation, eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, CED, human carcinogenic toxicity, abiotic depletion potential, etc. Among these the most translational categories of interest were GWP and CED (Firrisa et al., 2014).

A case study for Latvia in Northern Europe showed a seasonal variation of GWP for rapeseed-based biodiesel production as 1.27 and 1.06 tCO_2-eq/tBD for spring and winter, respectively (Fridrihsone et al., 2020). The highest GWP was contributed by the mineral fertilizer application and diesel consumption during the agricultural stage. Assessments carried out for Portugal applied sensitivity analysis to explore alternative countries to mitigate GWP and identified environmental hotspots (Malça et al., 2014; Malça & Freire, 2010). A case study for Denmark compared rapeseed-based biodiesel production with four other vegetable oils such as sunflower, palm, soybean, and peanut (Schmidt, 2015). The biodiesels derived from rapeseed and sunflower oils had the smallest environmental impact. There were several LCA studies in context of Spain that compared rapeseed biodiesel with Cardoon (Dufour et al., 2013), sunflower oil, and soybean oil (González-García et al., 2013; Requena et al., 2011). It was showed that the GHG emissions could be reduced by 74% as compared to diesel production from fossil fuels. A case study for Indian biodiesel production from vegetable oil showed that the GWP of a conventional process (i.e., at elevated temperature) was 5 times of a novel room temperature process (Bhonsle et al., 2022). The reason for this improvement was the reduce of heat required in the biodiesel production process. For other countries such as Iran, Saudi Arabia, China, and USA, the state-of-the art in biodiesel production were reviewed (Chen et al., 2018; Khanali et al., 2018; Rehan et al., 2018; Syafiuddin et al., 2020).

Although researchers explored alternative geographical locations for biodiesel development to reduce GWP, the supply-chain policies of biodiesel across international borders are perplexing (TE, 2021). Different countries tend to be independent and self-sustained producers of biodiesel. The interplay of production technology improvement, optimal process design and operation, and decentralization in biodiesel production within a nation can offer significant benefits towards the mitigation of GWP (Rehan et al., 2018). In particular, the by-product utilization from the system can significantly vary based on the production scale of biodiesel, which could be tuned to effectively mitigate the overall GWP.

Typically, centralized large-scale biodiesel production plants produced more than 50,000 tonnes (t) annually, while localized small-scale systems had production capacities much lesser (Stephenson et al., 2008). Since the disposal (or reuse) of by-products, transportation distances of various raw materials (such as reactants, fertilizers etc.), agricultural land usage, energy usage depend on the scale of the production system, it was essential to quantify the influences of production scale towards improved deployment planning. Additionally, the choice of process operating conditions would affect the overall performance of the system, which was required to be understood for improved operation planning.

To address these, the present work compared environmental impacts (CED and GWP) of centralized large-scale and localized small-scale biodiesel production systems based on raw rapeseed-derived oil. A detailed life cycle model of various stages ranging from rapeseed agriculture to final biodiesel production (cradle to gate) was provided for the UK (Section 2). The energy and environmental hotspots were identified across the entire production chain for the baseline scenario (Section 3.1). Sensitivity analysis was carried out to assess the influences of process parameters, by-product usage, and production scales to imply for mitigation of carbon emissions (Section 3.2). Finally, an alternative scenario was designed to reduce the GWP of both large- and small-scale systems (Section 3.3).

2. Materials and methods

The LCA carried out examined the environmental impact of raw rapeseed-derived biodiesel production schemes with two different capacities, namely (a) large-scale and (b) small-scale, in the UK. The large-scale systems were defined to have a production capacity above 50,000 t of biodiesel (tBD) per annum and received raw RO from an oil extraction facility supplied with seed from various farms. In contrast, the small-scale systems had production capacities less than 50,000 t per annum and are localized, i.e., relied on rapeseed feedstock grown by nearby farms. According to ISO 14040, a well-defined LCA must have four stages: (1) defining goal and scope (e.g., functional unit (FU) and system boundary), (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) data interpretation.

2.1. Goal and scope

This work focused on system-level assessment and identified contribution from sub-processes associated from rapeseed cultivation to biodiesel production. Therefore, the LCA adopted applies a cradle-to-gate approach, where the processes beyond the biodiesel factory gate (i.e., the application of biodiesel) were not considered. 1 tBD produced is assigned as the FU.

The large-scale production system followed a centralized biodiesel production concept, where a seed crushing plant in Hull, UK received raw rapeseed from several farming locations. The location of Hull facilitated the development of a centralized plant to source rapeseed from around the UK and satisfied the criteria of handling seed crushing for more than 50,000 tBD yield (e.g., there has been a seed crushing plant developed in the city). The transesterification and other related stages were carried out at a biodiesel production plant located in Immingham, UK. On the other hand, the location for small-scale biodiesel production was Suffolk, UK, an area with leading rapeseed farming with well-established facilities like self-sustaining rapeseed agriculture, seed crushing plant, and on-site biodiesel reactors, which made it a favourable site for decentralized biodiesel production.

A description of these sub-processes and associated life cycle inventory (LCI) data collection methodologies were described in the Section 2.2. Fig. 1 showed the system boundaries of the biodiesel production schemes. It was assumed that the land used for rapeseed agriculture would not be used for other farming purposes, therfore dedicated to rapeseed farming only (Stephenson et al., 2008). As per Fig. 1 the by-products from both the schemes were (1) rape straw generated during rapeseed agriculture, (2) rape meal produced in oil extraction facility, and (3) glycerol generated from the trans-esterification process. The rape straw, which would otherwise have been wasted was used as the feedstock to generate thermal and electrical energy using a biomass boiler. This formed the basis of considering rape straw-based process heating in the alternative scenario presented in Section 3.3. Rape meal produced in the oil extraction process was usually disposed of because of its low calorific value, thus not offering any economic or energetic value. Glycerol produced from the trans-esterification process was an essential value-added product. For the large-scale system it was assumed that the glycerol was supplied to a pharmaceutical industry, while for the small-scale system it was supplied to a purification plant. Since the processes are outside the factory gate, the associated transportation and downstream processes were omitted from the LCA system boundary.

2.2. Life cycle inventory for baseline scenario

Sequential processes ranging from rapeseed agriculture to biodiesel production were detailed in this section. An extensive data collection from literature and communication with several industries were performed to build up a comprehensive LCI scaled as per FU (see Table 1). Salient stages in the life cycle for large-scale production system included (a) rapeseed agriculture, (b) seed drying and cooling, (c) oil extraction, (d) oil refining, and (e) biodiesel production. For the small-scale system all the stages were present except the oil refining process since the produced biodiesel was immediately bottled (Stephenson et al., 2008).

2.2.1. Rapeseed agriculture

Several key regions were identified for growing rapeseed in the UK including the central belt of Scotland, Northern England, Surrey,

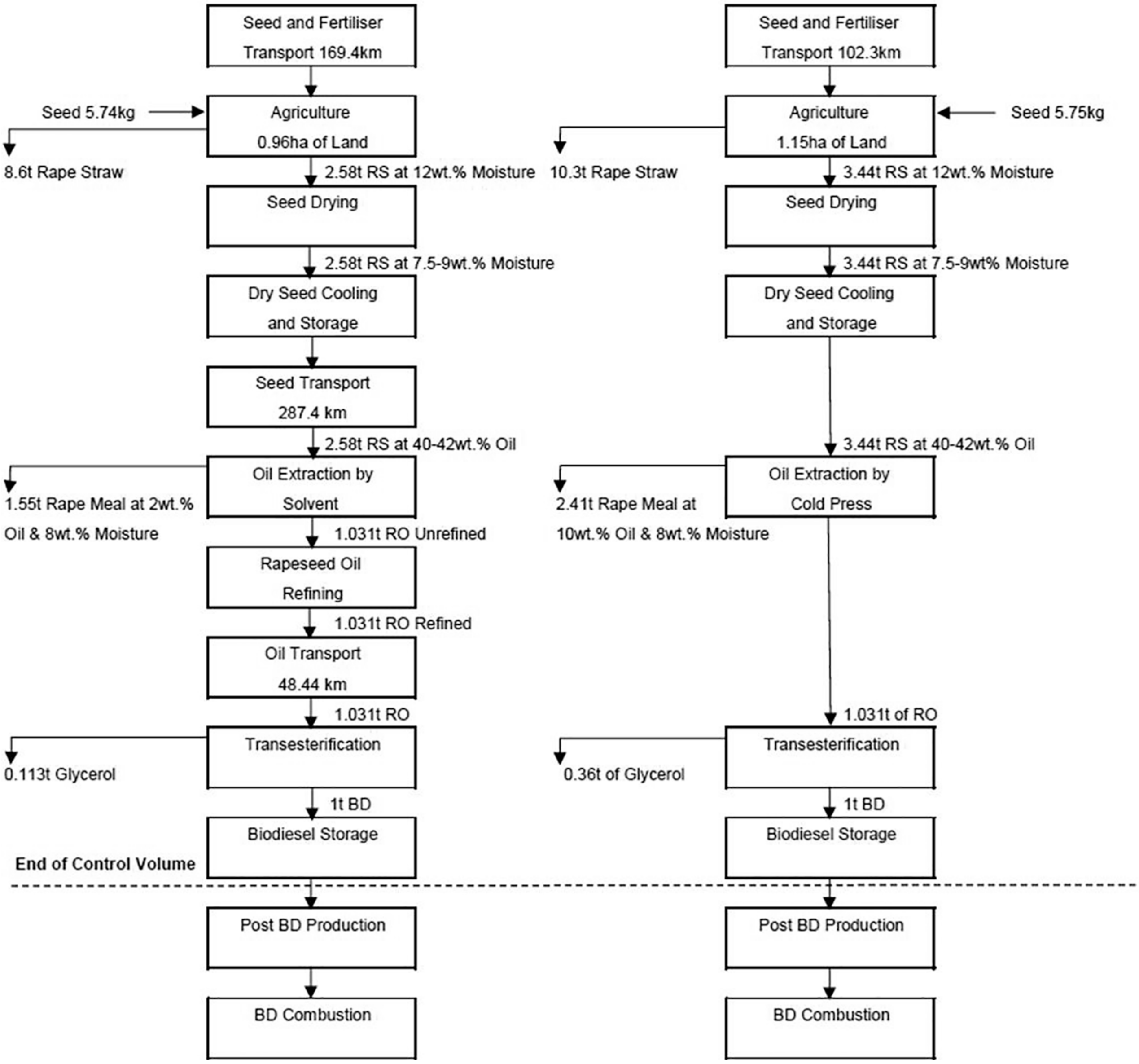


Fig. 1. Detailed process flow for the baseline large-scale (left) and small-scale (right) biodiesel production schemes from rapeseed.

Table 1
Life cycle inventory for baseline biodiesel production systems with large-scale and small-scale capacities. The entire life cycle inventory is scaled for the functional unit i.e., 1 tBD.

Process	Parameter	Unit	Large-scale	Small-scale
Rapeseed agriculture	Land	ha/tBD	0.96	1.15
	Diesel	l/tBD	90	84.1
	Nitrogen	kg N/tBD	129	172.5
	Phorphorus Pentoxide	kg P_2O_5/tBD	69	92
	Potassium Oxide	kg K_2O/tBD	60	80.5
	Sulfur	kg S/tBD	60	80.5
Rapeseed drying and cooling	Diesel	l/tBD	12.9	17.3
	Electricity	kWhr/tBD	52.8	52.8
RO extraction	Electricity	kWhr/tBD	113.3	150
	Thermal energy from natural gas	kWhr/tBD	648.6	–
	Water	kg H_2O/tBD	2321	–
	Hexane	kg C_6H_{14}/tBD	2.54	–
RO refining	Electricity	kWhr/tBD	30.93	–
	Thermal energy from natural gas	kWhr/tBD	137.2	–
	Water	kg H_2O/tBD	112.7	–
	Phosphoric acid	kg H_3PO_4/tBD	1.06	–
	Sodium hydroxide	kg NaOH/tBD	1.55	–
Biodiesel production	Electricity	kWhr/tBD	124	939
	Thermal energy from natural gas	kWhr/tBD	453.5	–
	Methanol	kg CH_3OH/tBD	219.8	252.5
	Sulphuric acid	kg H_2SO_4/tBD	10.4	23
	Potassium hydroxide	kg KOH/tBD	15.5	16.5
	Water	kg H_2O/tBD	200	1136.4

Suffolk, and the Cotswolds (DEFRA, 2020a). The agricultural methods were modelled based on the Canola and Rapeseed production guidelines provided by New Holland Agriculture (NHA, 2016). For adapting these datasets to the UK context, the Farm management Handbook 2020–2021 was used (Beattie, 2020).

For the large-scale system, the rapeseed agriculture began by subsoiling with a diesel consumption of 21 l/ha, conducted in every four years in UK (Beattie, 2020). Subsequently, ploughing and minimum light tillage of soil consumed 29.75 and 4.02 l/ha diesel, respectively (Beattie, 2020). Afterwards, the seeds were sown and rolled onto the grounds. The seed drilling rate was 6 kg/ha (NHA, 2016) and diesel consumptions were 9.95 l/ha for drilling and 2.88 l/ha for rolling (Beattie, 2020). The average distance between seed growing locations and rapeseed farms was 68.8 km, used to calculate the transportation emissions. Fertilizers were used twice, while pesticides were applied six times for each cycle of farming with diesel consumptions 3.14 l/ha and 11.76 l/ha, respectively (Beattie, 2020). Various nutrients present in the fertilizer were 135 kg/ha Nitrogen, 72 kg/ha Phosphorus Pentoxide (P_2O_5), 63 kg/ha Potassium Oxide (K_2O), and 63 kg/ha Sulphur (NHA, 2016). These quantities were based on a yield of 3.0 t/ha and were adjusted for the analysis of this work based on a UK rapeseed yield of 2.7 t/ha (DEFRA, 2020a). The average fertilizer transportation distance was 100.6 km based on a fertilizer manufacturing company in the UK. For harvesting purposes, a combined harvester was assumed with approximate diesel consumption of 11.63 l/ha (Beattie, 2020). A waste product of the technique was rape straw that consisted of stalks, pods, and leaves. Upon being harvested, the straw was removed and either used for livestock purposes or permanently disposed. Rapeseed harvesting generated 9.0 t/ha of straw based on a seed yield of 3.0 t/ha, which was again scaled for the UK yield of 2.7 t/ha (DEFRA, 2020a).

For the farming associated to small-scale production system, a company located in Suffolk was selected. To better represent the farming model and associated parameters in Suffolk, they were altered in accordance with Canola and Rapeseed production guidelines provided by New Holland Agriculture (NHA, 2016) and the Farm management Handbook 2020–2021 (Beattie, 2020). Literature suggested that the soil conditions in Suffolk area was more fertile than other rapeseed farming regions in the UK. Various farming processes that occurred in small-scale production system were seed drilling, crop protection, and harvesting. All the pre-drilling stages were assumed to be as same as the large-scale process and the sub-soiling processes was excluded as suggested by the Farm management Handbook 2020–2021 (Beattie, 2020). Since the soil in Suffolk was more fertile than other locations in UK, there was an increase in the germination rate (NE, 2014). Therefore, the seed drilling rate was lowered to 5 kg/ha with an average seed yield of 3.0 t/ha. The distances for seed and fertilizer transportation for small-scale system were 26.1 and 76.2 km, which was considerably less than the large-scale system. A comprehensive list of process parameters used for the agricultural model were detailed in the Table 2.

2.2.2. *Seed drying and cooling*

The harvested rapeseed generally contained 12 wt.% moisture (NHA, 2016), which was required to be reduced to 7.5–9 wt.% prior to the oil extraction process (HGCA, 2006). For both large- and small-scale production systems an on-site seed drying process was assumed prior to the respective oil extraction processes. A grain drier with 12–20 t capacity (MD, 2017) was selected for the analysis. The dryer ran via a power takeoff shaft connected to a tractor of minimum 70 HP capacity and typically consumed 35 l/hr diesel. This corresponded to approximately 5 l diesel requirement per t of grain (MD, 2017). Following the seed drying process, a cooling process was required which employed a set of cooling fans. For both the small- and large-scale systems two fans each of 2.3 kW were considered (P&C, 2021). Typically, grain cooling was carried out with fans operating for a total of 12 h. Once both the drying and cooling stages were complete the rapeseed contained 40–44 wt.% oil, 7.5–9.0 wt.% moisture, and 47–51 wt.% protein (HGCA, 2006).

2.2.3. *Oil extraction and refining*

For the large-scale oil extraction, the seed crushing plant had a capacity of 750 t rapeseed per day, which produced 420 t of rape meal and 323 t of RO (Cargill, 2022). The process involved seed cleaning, cooking,

Table 2
Parameters for the agricultural model used for large-scale and small-scale rapeseed agriculture.

Input quantity	Unit	Large-scale	Small-scale	Ref.
Distance (seed merchant to farm)	km	68.8	26.1	Calculated
Distance (fertilizer merchant to farm)	km	100.6	76.2	Calculated
Grain drilling rate	kg/ha	6.0	5.0	(NHA, 2016)
Seed Yield	t/ha	2.7	3.0	(DEFRA, 2020a; NHA, 2016)
Nitrogen	kg N/ha	135	150	(NHA, 2016)
Phosphorus Pentoxide (P_2O_5)	kg P_2O_5/ha	72	80	(NHA, 2016)
Potassium Oxide (K_2O)	kg K_2O/ha	63	70	(NHA, 2016)
Sulphur (S)	kg S/ha	63	70	(NHA, 2016)
Number of fertilizer spreads	–	2	2	(Beattie, 2020)
Number of pesticide spreads	–	6	6	(Beattie, 2020)
Diesel	l/ha	94.13	73.13	(Beattie, 2020)

and flaking followed by a mechanical press that extracted a pre-specified amount of RO. Subsequently, the rape meal contained 10 wt.% oil, which further underwent a counter-current solvent extraction process to reduce the oil content to 2 wt.%. The remainder rape meal contained 20–25 wt.% hexane (C_6H_{14}) which was removed by a steam-operated desolventizer. The rape meal then was passed through drying and cooling processes. The extracted oil was further distilled to remove impurities such as hexane and water. This phase was concluded when a continuously operating centrifuge separated oil and water. Following the oil extraction process a refining stage was conducted onsite at Hull. The process began with phosphoric acid (H_3PO_4)-mediated removal of lipophilic phospholipids from the oil originated from the rapeseed wall. Phospholipids that remained further were neutralized by sodium hydroxide (NaOH) creating soap and was ultimately removed by centrifugation from the oil.

For the small-scale biodiesel production, the plant located at Suffolk had an onsite cold press oil extraction process that avoided transportation of rapeseed over long distances. The process chain included cleaning, cold processing, filtering, and storage (Hillfarm, 2021). Cleaning involved a 4.25 kW grain cleaner with 3 t/hr capacity, which removed any foreign particle present in the raw rapeseed. Upon completion, the cleaned seeds were fed by a hopping process into 6YL-130 screw press. This equipment had a rated power consumption of 18.5 kW and could press 9–12 t of rapeseed per day (Oil-Expeller, 2022). This was done by two screw presses with operation times 8 hr/day. Subsequently, the extracted oil was filtered through a plate and frame filter which did not consume any additional electricity or chemicals. It was worth mentioning that small-scale system did not include any oil refining process unlike the large-scale process. A comprehensive list of process parameters used for the large and small-scale oil extraction systems were provided in the Table 3.

Table 3
Parameters for the large-scale and small-scale RO extraction-refining processes at Hull and Suffolk, respectively.

Process	Input quantity	Unit	Value	Ref.
Large-scale RO extraction	Distance (from farming locations to Hull)	km	287.4	Calculated
	Electricity	kWhr/t RS	43.9	(Cargill, 2022)
	Thermal energy from natural gas	kWhr/t RS	254.9	(Cargill, 2022)
	Water	l/l RO	2.06	(Cargill, 2022)
	Hexane (C_6H_{14})	kg C_6H_{14}/t RO	2.47	(Cargill, 2022)
Large-scale RO refining	Electricity	kWhr/t RO	30	(Cargill, 2022)
	Thermal energy from natural gas	kWhr/t RO	133.1	(Cargill, 2022)
	Water	l/l RO	0.1	(Cargill, 2022)
	Phosphoric acid (H_3PO_4)	kg H_3PO_4/t RO	1.03	(Cargill, 2022)
	Sodium hydroxide (NaOH)	kg NaOH/t RO	1.50	(Cargill, 2022)
Small-scale RO extraction	Power rating of grain cleaner	kW	4.25	(Hillfarm, 2021)
	Operating hours of grain cleaner per day	hr	8	(Hillfarm, 2021)
	Power rating of screw press	kW	18.5	(Oil-Expeller, 2022)
	Number of screw presses	–	2	Calculated
	Operating hours of screw presses per day	hr	8	(Hillfarm, 2021)

2.2.4. Biodiesel production

2.2.4.1. Large-scale production scheme. Upon completion of the oil extraction and refining processes for large-scale production system, the RO was transported to the biodiesel production plant located in Immingham (designed specifically for raw vegetable oils), producing 140,000 tBD per annum (Alberici & Toop, 2014). Most of the biodiesel production systems were based on transesterification of vegetable oil or RO with an alkali catalyst (Rutz & Janssen, 2007). For the present case the production layout was resourced from the biofuel technology handbook (Rutz & Janssen, 2007) and another relevant literature (Van Gerpen, 2005). Salient stages of the production system were transesterification reaction of the raw RO, biodiesel purification, glycerol recovery, and methanol (CH_3OH) recovery. Essential mechanical components of this production layout were (a) general purpose storage tank, (b) transesterification reactor parts and auxiliaries (reactors, pumps, and centrifuges), (c) purification equipment (centrifuge, pumps, washing columns, dryer), and (d) glycerol and methanol recovery equipment (centrifuge, pumps, distillation columns). A comprehensive schematic of the large-scale biodiesel production system was shown in Fig. 2a.

Methanol, potassium hydroxide (KOH) catalyst, and RO were combined and mixed in a reactor at 60 °C temperature and 60–80 bar pressure for approximately one hour. Following the reactor, a gravity settling decanter was utilized to separate the biodiesel slurry and glycerol slurry. This stage was depicted as the separator process in Fig. 2a. Subsequently, the biodiesel slurry was flashed at 150 mbar pressure that removed excess water and methanol (Rutz & Janssen, 2007; Van Gerpen, 2005). The methanol and water were then distilled, separated, and reused in the process in a cyclic manner. Thereafter, the biodiesel was washed using water and dilute sulphuric acid (H_2SO_4) to remove any unwanted impurities. The clean biodiesel was then dried and pumped to the storage volume. The glycerol slurry resulted from the separation process contained glycerol, potassium hydroxide, methanol, and biodiesel. Sulphuric acid was added to the glycerol slurry to neutralize the potassium hydroxide catalyst, but subsequently a reaction occurred with the remainder biodiesel in the slurry that generated free fatty acids. Therefore, additional sulphuric acid was necessary to esterify the free fatty acids, which created more biodiesel. This biodiesel was then returned to the transesterification mixer and reactor block (see Fig. 2a). During this process a centrifugation step separated potassium sulphate and generated a slurry containing glycerol, methanol, and water. Further distillation and purification produced crude glycerol, which could be sold to the pharmaceutical industry. The present work assumed that the Glycerol production rate is 0.113 t/tBD (Stephenson et al., 2008). Again, the remaining methanol and water was distilled and fed back to the process.

The consumption rate of methanol during transesterification was estimated at 22 wt.% of the feedstock (Chaturvedi et al., 2013). This work further assumed a transesterification conversion rate of 97% (Meher et al., 2006), meaning that 1.031 t of RO was required to generate 1 tBD. This resulted to a methanol consumption rate of 226.8 kg/t RO. The catalyst i.e., Potassium Hydroxide was required at approximately 1.5 wt.% of the oil (Van Gerpen, 2005). Therefore, 1.031 t of raw RO had Potassium Hydroxide consumption of 15.5 kg/tBD for the transesterification reaction. Other essential parametric inputs included water used in the washing and biodiesel purification stages, and acid used in the glycerol recovery stage. The resulting values for water and sulphuric acid consumption were 200 kg/t BD and 10.4 kg H_2SO_4/tBD, respectively for a plant with capacity 250,000 tBD (Stephenson et al., 2008). The electricity consumption and heat input (from natural gas) for this process was calculated as 122 kWhr/tBD and 453.5 kWhr/tBD (Saville, 2006; Stephenson et al., 2008). A list of process parameters used for the large-scale biodiesel reactor was provided in the Table 4.

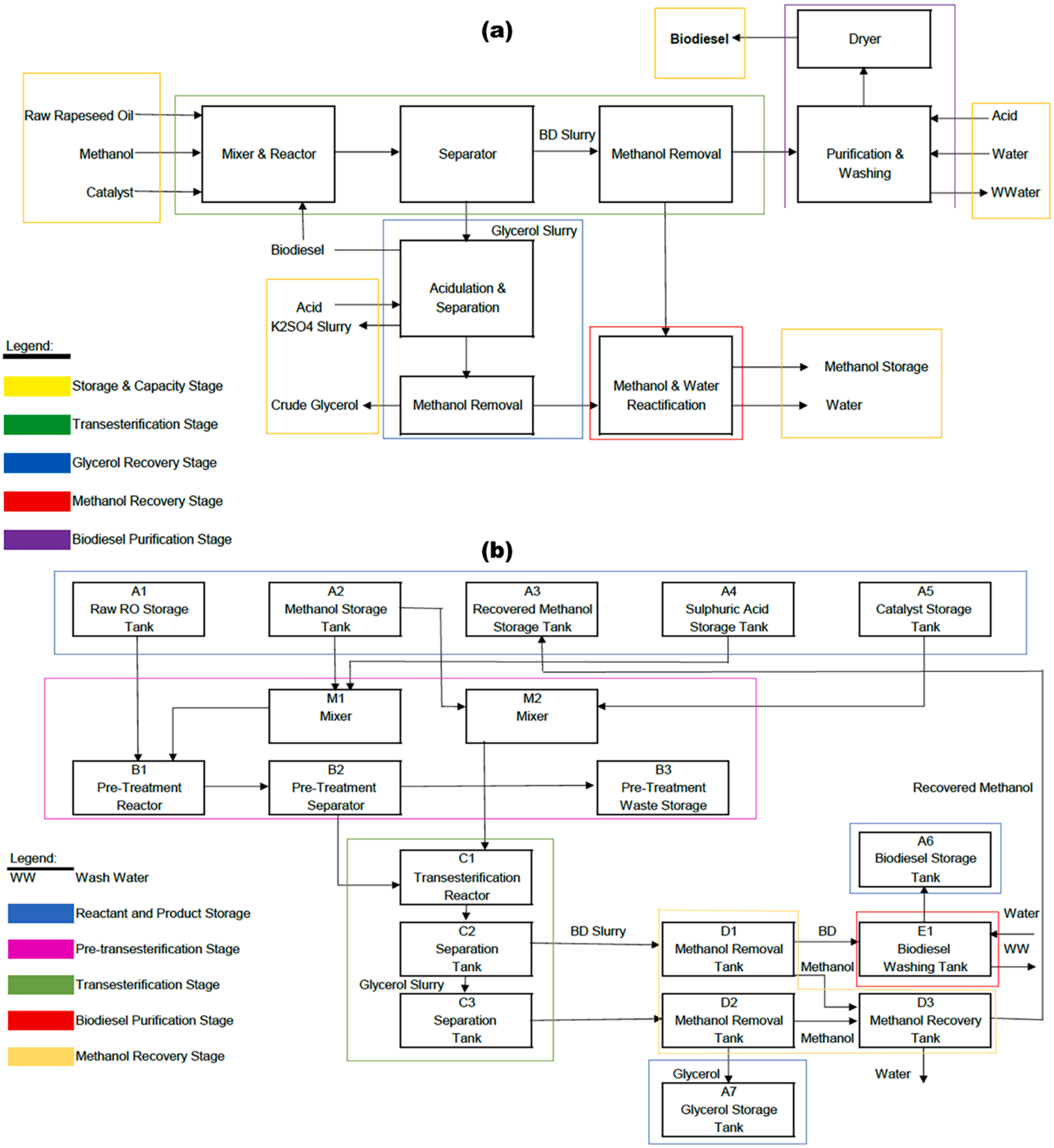


Fig. 2. Process flow for (a) plug flow biodiesel reactor (Van Gerpen, 2005) used by large-scale and (b) semi-continuous batch biodiesel reactor (Chaturvedi et al., 2013) used by the small-scale biodiesel production schemes.

2.2.4.2. Small-scale production scheme. For the small-scale biodiesel production process at Suffolk. an on-site biodiesel reactor was required to be installed. For this purpose, a 100-liter semi-continuous batch biodiesel reactor was considered suitable for rural applications (Chaturvedi et al., 2013). Daily, the reactor could produce approximately 100 L of biodiesel over two ten-hour shifts that resulted up to 30 tBD annually. The size of Suffolk was estimated as the average in East England, 121 ha with 79% of the land was arable (DEFRA, 2021). Therefore, it was estimated that in Suffolk, each crop rotation utilized 95.6 ha land. Based on the rapeseed yield (see Section 2.2.1) of 3 t/ha a maximum of 286.8 t rapeseed yield was estimated, relevant for reactor sizing. Typically, 40 wt.% oil was available within the rapeseed (Malça et al., 2014). However, the cold press technique considered here was only capable the seed to an oil content of 10 wt.%. As a result, in Suffolk up to 86.04 t of RO from the cold press process would be produced. Similar to the large-scale transesterification process, a 97% conversion efficiency was assumed (Meher et al., 2006). Hence, for producing 30 t of biodiesel, the biodiesel reactor would require 31 t of RO. This value amounted to 36% of Suffolk's raw RO production capacity and therefore the choice of the biodiesel reactor was found suitable.

Based on the manufacturer specification the 100-liter semi-continuous batch biodiesel reactor contained the following stages (a) general storage and reactant preparation section, (b) reactant pre-transesterification segment, (c) transesterification reaction zone, (d)

Table 4
Parameters for the large-scale biodiesel production system deployed at Immingham.

Input quantity	Unit	Value	Ref.
Distance (Hull to Immingham)	km	48.44	Calculated
Electricity	kWhr/tBD	122	(Saville, 2006; Stephenson et al., 2008)
Thermal energy from natural gas	kWhr/tBD	453.5	(Saville, 2006; Stephenson et al., 2008)
Methanol	kg CH_3OH/tBD	113.52	(Chaturvedi et al., 2013)
Sulphuric acid	kg H_2SO_4/tBD	10.4	(Stephenson et al., 2008)
Potassium hydroxide	kg KOH/tBD	15.5	(Van Gerpen, 2005)
Water	kg H_2O/tBD	200	(Stephenson et al., 2008)
Biodiesel storage electricity	kWhr/tBD	1.67	(Van Gerpen, 2005)
Glycerol yield	kg/tBD	113	Calculated
Transesterification efficiency	%	97	(Meher et al., 2006)

biodiesel purification section, and (e) methanol recovery unit. A comprehensive schematic of the small-scale biodiesel production system was shown in Fig. 2b.

The biodiesel reactor was separated into five distinct stages as shown in Fig. 2b. The pre-transesterification stage began at the mixing of methanol and sulphuric acid in tank M1. Alongside, methanol and Potassium Hydroxide catalyst were mixed in tank M2. RO entered reactor B1 and was mixed with the methanol and sulphuric acid. This slurry then entered the separator B2 where impurities were removed into storage B3. The treated oil slurry was then subjected to the transesterification reaction in reactor C1. This was achieved by mixing the slurry with the methanol and catalyst mix from M2 that generated biodiesel and glycerol. The biodiesel and glycerol slurry were passed into the separation tanks C2 and C3. Here the biodiesel and glycerol were separated and treated in D1 and D2 to remove any methanol. This methanol was further recovered and distilled in D3 before being recycled back to storage tank A3. The biodiesel slurry from D1 was passed into the washing tank E1 where it was mixed with water to remove impurities. The by-product of this process was wash water containing methanol, soap, potassium sulphate and potassium hydroxide. This wash water could then be discharged by treatment with barium ions (at a low pH) or through anaerobic digestion (Chaturvedi et al., 2013). As the methods presented were not directly involved in the biodiesel production, they were excluded from the LCA. Following washing and purification, the biodiesel was stored in tank A6. The glycerol from D2, after methanol removal, was stored in A7. Approximately 220 kg of glycerol was produced in one week by the reactor. This glycerol was not refined and contained traces of biodiesel, methanol, catalyst, and soap. The manufacturer's report suggested that due to the complexity involved with glycerol purification the process would not occur onsite. Instead, the glycerol was sent to specific waste facilities for proper purification (Chaturvedi et al., 2013). The present LCA assumed that this would occur onsite at Suffolk, thus the process of Glycerol purification and disposal was omitted from the LCA. It was also important to note that the reactor operated for 20 h a day in spanned across two ten-hour shifts.

Methanol, being one of the primary reactants should be fed in correct volume the transesterification stage. Specifications suggested (Chaturvedi et al., 2013) that the methanol consumption was 22 wt.% of the feedstock, which resulted to 22.2 kg per batch of methanol. With unavoidable methanol losses an additional 11% by weight adjustment of methanol was required, which resulted to 44.38 kg methanol per batch and 155.4 kg methanol per week. Sulphuric acid and potassium hydroxide requirements were 14.14 kg per week and 10.16 kg per week, respectively (Chaturvedi et al., 2013). Weekly electricity and water consumptions were 577.5 kWhr and 700 l. The total weekly biodiesel yield was 0.616 t and a multiplication factor of 1.62 was used to scale all quantities for a biodiesel yield of 1 t (62.34% increase). A list of process parameters used for the small-scale biodiesel reactor was provided in the Table 5.

2.3. *Emission factors for life cycle impact assessment*

Since our focus was to examine the GHG emissions and energy consumption for the raw rapeseed-derived biodiesel production chain, GWP and CED were chosen as the life cycle impact (LCI) category by following the CML 2001 – August 2016 methodology. The emissions were measured in terms of GWP over 100 years (GWP100) in accordance with IPCC norms and expressed as carbon dioxide equivalent per tBD ($kgCO_2$-eq/tBD) produced. Three types of emissions were considered, indirect emissions, direct emissions from transport process, and direct emissions from fertilizer usage during rapeseed agriculture.

2.3.1. *Indirect emissions*

The indirect emission factors were used to convert the various quantities usages from LCI in Table 1 to its associated carbon emissions in $kgCO_2$-eq/tBD. Table 6 listed all such conversion factors resourced from relevant literature.

2.3.2. *Direct emissions from transport processes*

Direct emissions from transport processes that impacted the GWP (such as CH_4, CO_2, and N_2O) were estimated based on the diesel requirement of a 7.5 – 17.0 t heavy goods vehicle (HGV). The emission conversion factor for this vehicle was obtained as 0.5447 $kgCO_2$-eq/km by using the UK government GHG conversion factors dataset (BEIS, 2022). This value was related to the operation of the HGV at 6% laden weight. The total transportation distance for large-scale and small-scale biodiesel production schemes were 505.24 km and 102.3 km, respectively.

2.3.3. *Direct emissions from fertilizer usage*

GHG emissions from agricultural soil, notably CO_2 and N_2O contributed to the GWP augmentation. The constituents in the agricultural soil were dictated by the fertilizers used during rapeseed farming according to the guidelines from New Holland company. The fertilizers were Urea (U) with 46% Nitrogen, Triple Super-Phosphate (TSP) with 48% P_2O_5, Muriate of Potash (MP) with 60% K_2O, and Ammonium Sulphate (AS) with 21% Nitrogen and 24% sulphur (Brentrup et al., 2016).

The masses of direct nutrients required (see Table 2) were used to calculate the amount of specific fertilizers required, which in turn, caused GHG emissions. Due to two fertilizers containing nitrogen, the total values were separated appropriately. Out of the total nitrogen

Table 5
Parameters for the small-scale biodiesel production system deployed at Suffolk.

Input quantity	Unit	Value	Ref.
Electricity	kWhr/tBD	937.51	(Chaturvedi et al., 2013)
Methanol	kg CH_3OH/tBD	252.5	(Chaturvedi et al., 2013)
Sulphuric acid	kg H_2SO_4/tBD	23	(Chaturvedi et al., 2013)
Potassium hydroxide	kg KOH/tBD	16.5	(Chaturvedi et al., 2013)
Water	kg H_2O/tBD	1136.4	(Chaturvedi et al., 2013)
Biodiesel storage electricity	kWhr/tBD	1.67	(Chaturvedi et al., 2013)
Glycerol yield	kg/tBD	360	(Chaturvedi et al., 2013)
Transesterification efficiency	%	97	(Meher et al., 2006)

Table 6

Carbon emission conversion factors and energy conversion factors in kgCO_2-eq/unit quantity and MJ/unit quantity of the life cycle inventory (Table 1).

Input quantity	Unit	GWP conversion factor (kgCO_2-eq/Unit)	Ref.	Energy conversion factor (MJ/unit)	Ref.
Diesel	l	2.7	(BEIS, 2022)	36	(BEIS, 2022)
Electricity	kWhr	0.212		3.6	
Natural gas (net calorific value)	kWhr	0.2		3.6	
Water supply	kg H_2O	1.49×10^{-4}		–	–
Hexane production	kg C_6H_{14}	0.62	(Veolia, 2011)	51.6	(Stephenson et al., 2008)
Phosphoric acid production	kg H_3PO_4	1.45		36	(Stephenson et al., 2008)
Sodium hydroxide production	kg NaOH	1.12		3.5	(Hong et al., 2014)
Methanol production	kg CH_3OH	0.66		40.32	(Renó et al., 2011)
Sulphuric acid production	kg H_2SO_4	0.14		12	(Stephenson et al., 2008)
Potassium hydroxide production	kgKOH	1.94		43.4	(Stephenson et al., 2008)
Urea	kg U	5.15	(Brentrup et al., 2016)	23.45	(Brentrup et al., 2016)
Triple super phosphate	kg TSP	0.27		0.18	
Muriate of potash	kg MP	0.25		3	
Ammonium sulphate	kg AS	2.3		14.02	

requirement (129 kgN/tBD for large-scale and 172.5 kgN/tBD for small scale), 70% was within Urea and 30% within Ammonium Sulphate. Subsequently the following equation provided the mass of specific fertilizer required per tBD (Rose, 2004),

$$\text{Fertilizer Mass (kg/tBD)} = \frac{\frac{\text{kg Nutrient}}{\text{ha}} \times \frac{\text{ha}}{\text{tBD}}}{\frac{\text{\% Nutrient in fertilizer}}{100}} \tag{1}$$

The resultant values for various fertilizer masses for large-scale biodiesel production were (a) 196 kg/tBD U, (b) 143 kg/tBD TSP, (c) 100 kg/tBD MP, and (d) 219 kg/tBD AS. Likewise, these values for the small-scale production system were (a) 262.5 kg/tBD U, (b) 191.6 kg/tBD TSP, (c) 134 kg/tBD MP, and (d) 294 kg/tBD AS. Applying the fertilizers would cause GHG emission through several key processes namely CO_2 emissions from Urea hydrolysis, N_2O emitted by nitrification/denitrification of soil, N_2O emitted from NH_3 volatilization, and N_2O emitted from NO_3 leaching to agricultural systems. Various emission factors of the fertilizers required for LCA were listed in Table 6.

2.4. *Data interpretation*

Based on the LCIAs adopted in Section 2.3, the environmental impacts (GWP and CED) for both the baseline large- and small-scale systems were discussed, which included identification of carbon emission and energy consumption hotspots (Section 3.1). Subsequently, a sensitivity analysis was performed to assess the influence of input parameter variations and by-product (rape straw, glycerol, and rape meal) utilization methods. The result obtained from the sensitivity analysis was shown in terms of carbon emission abatement (or augmentation) with respect to the baseline scenario (Section 3.2). Finally, based on the outcome of sensitivity analysis, an alternative operation strategy was proposed that could reduce the GWP (Section 3.3).

3. Results and discussion

3.1. *Environmental Impact: Baseline scenario*

The environmental impacts for the baseline scenarios described in Section 2.2 were expressed by two metrics: CED in GJ/tBD and GWP in tCO_2-eq/tBD for the large- and small-scale systems (see Fig. 3). Fig. 3a revealed that the rapeseed agriculture and biodiesel production (transesterification) stages were the two highest consumers of energy (72% for large-scale and 92% for small-scale). Other significant energy consumers in the large-scale system were the RO extraction stage (9%) and transportation component (15%). The CED totalled to 32.1 and 30.8 GJ/tBD, respectively for the small- and large-scale systems. Fig. 3b showed that the highest GWP contributor for both the schemes was the rapeseed agriculture stage, which accounted for 69% and 81% for the large- and small-scale systems, respectively. The overall GWP for the large- and small-scale systems were annually 2.63 and 2.89 tCO_2-eq/tBD. It was worth mentioning that the CED for the large-scale system was 1.3 GJ/

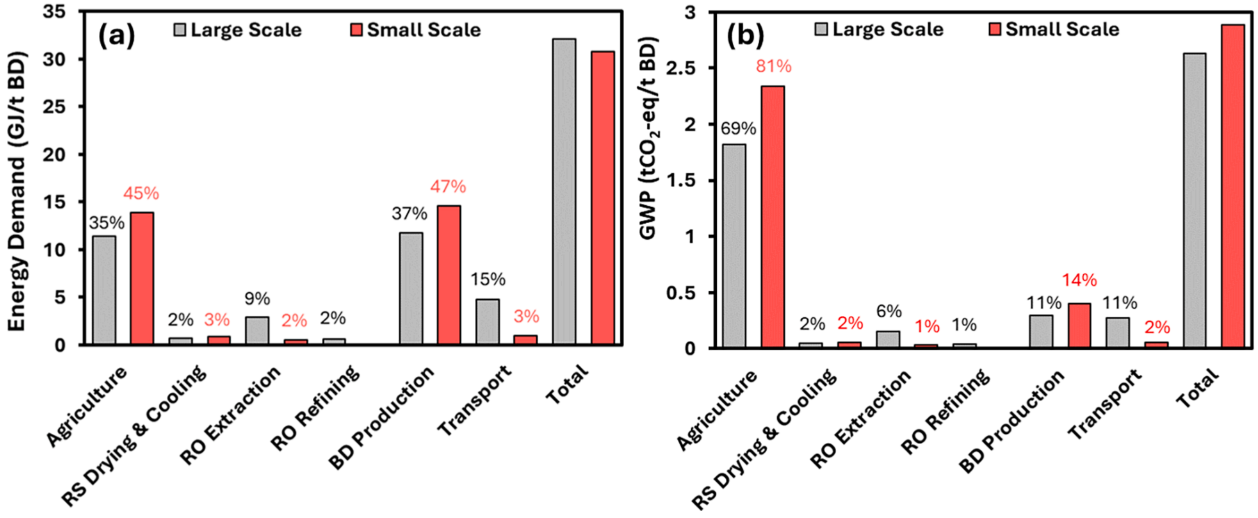


Fig. 3. (a) Cumulative ED (CED) in GJ/t BD and (b) GWP in tCO_2-eq/t BD for various stages of the large-scale and small-scale biodiesel production. The values of total energy demand for the large-scale and small-scale systems are 32.15 GJ/t BD and 30.82 GJ/t BD, while GWP are 2.63 tCO_2-eq/t BD and 2.88 tCO_2-eq/t BD, respectively.

tBD greater than the small-scale (i.e., 4% higher), while the GWP for the same was 0.26 tCO_2-eq/tBD lesser (i.e., 9.9% lower). Existing case studies of rapeseed-based biodiesel production showed a wide range of GWP across different countries, such as 1.48 tCO_2-eq/tBD for Finland, 0.82–5.9 tCO_2-eq/tBD for Italy, 1.06–1.27 tCO_2-eq/tBD for Latvia, 0.79 for Poland, 1.18 tCO_2-eq/tBD for Iran, 0.2–0.35 tCO_2-eq/tBD for Slovenia, and 2.21 tCO_2-eq/tBD for India (Bhonsle et al., 2022; Fridrihsone et al., 2020). The environmental impacts could be further reduced by fivefold using a room temperature-based production method (Bhonsle et al., 2022).

The contributions from the seed drying and cooling stage, oil extraction, and oil refining stages were comparably small, which is inline with the existing literature (Chen et al., 2018). A significant difference due to production scale was observed in the transportation component for both the CED and GWP metrics. Since the large-scale system was associated with longer transportation distances between the farming location, seed crushing plant at Hull, and biofuel production plant at Immingham, it caused higher emissions and consumes more energy. In contrast, the small-scale system located entirely at Suffolk avoided such long-distance transportation processes. To investigate the reason of dominance of rapeseed agriculture and biodiesel transesterification stages from both CED and GWP perspective a detailed impact breakdown of the subcomponents was discussed.

For the agricultural stage of the large-scale system, fertilizer applications (U, TSP, MP, and AS) consumed approximately 8 GJ/tBD (70% of agriculture) energy and caused 1.58 tCO_2-eq/tBD (87% of agriculture) GWP. In contrast, the diesel usage in large-scale farming application had CED 3.4 GJ/tBD (30% of agriculture) and GWP 0.24 tCO_2-eq/tBD (13% of agriculture). Similarly for the small-scale system, fertilizer applications consumed nearly 10.7 GJ/tBD (77% of agriculture) CED and had a GWP of 2.11 tCO_2-eq/tBD (90.3% of agriculture). Associated diesel usage contributed to 3.2 GJ/tBD (23% of agriculture component) CED and 0.22 tCO_2-eq/tBD GWP (9.7% of agriculture component). Among different fertilizers, the U and AS showed the highest CED and GWP footprints for both the schemes due to their N_2O emission potential. Similar case studies reported in the literature showed GWP contributions in the range of 70–90% from the agricultural fertilizer application and diesel usage during farming (Fridrihsone et al., 2020).

It was also found that for the small-scale system that the environmental footprint was larger than its large-scale counterpart. This was because the small-scale system related farming site had a greater yield (3.0 t/ha) and required higher fertilizer usage (NHA, 2016), while the large-scale yield was the UK average of 2.7 t/ha (DEFRA, 2020a). It is essential to note that the value of rapeseed yield could significantly vary across different countries, at e.g. 3.0 t/ha in France, 3.5 t/ha in Denmark, 2.5 t/ha in Latvia (Fridrihsone et al., 2020), 1.5 t/ha in Canada, 2.3 t/ha in France, and 3.75 in Germany (Malça et al., 2014). Some additional factors included the capability limitation of the cold press oil extraction technique used in the small-scale system, that extracted only 30 wt.% as compared to the solvent extraction technique with 40 wt.% capability in the large-scale system (Stephenson et al., 2008). As a result, the small-scale system needs more land area (1.15 ha) than the large-scale system (0.96 ha), which incur more fertilizer application. The diesel consumption-associated GWP was slightly greater (0.02 tCO_2-eq/tBD) for the large-scale system due to inclusion of the sub-soiling process using farming machineries (Beattie, 2020).

Another essential environmental hotspot was the biodiesel transesterification process, that contributed up to 47% of the CED and 14% of the GWP. In the large-scale system, the transesterification GWP components in decreasing order were methanol 0.145 tCO_2-eq/tBD (49.3%), thermal energy 0.091 tCO_2-eq/tBD (31%), potassium hydroxide 0.03 tCO_2-eq/tBD (10.2%), electricity 0.026 tCO_2-eq/tBD (8.8%), and sulphuric acid 0.001 tCO_2-eq/tBD (0.7%). While for the small-scale system the GWP components in decreasing order were electricity 0.2 tCO_2-eq/tBD (49.8%), methanol 0.167 tCO_2-eq/tBD (41.6%), potassium hydroxide 0.032 tCO_2-eq/tBD (8%), and sulphuric acid 0.003 tCO_2-eq/tBD (0.6%). The total GWP associated with transesterification were 0.294 and 0.401 tCO_2-eq/tBD for the large- and small-scale systems, respectively. A higher GWP of the small-scale transesterification stage was due to increased methanol consumption that was used to balance out the methanol losses through the glycerol waste stream. This was because the plug flow type biodiesel reactor for the large-scale system was equipped with a glycerol recovery facility (see Figs. 1 and 2a), while the semi-continuous batch biodiesel reactor did not offer this advantage (see Figs. 1 and 2b). The choice of production scale also dictated the CED. This was due to the small-scale systems relying on electrical energy and large-scale systems are predominantly gas-based (Stephenson et al., 2008).

3.2. Sensitivity analysis

Influences of various process parameters and internal utilization of various co-products were investigated through a sensitivity analysis where, GWP was considered as the decisive metric. A comprehensive sensitivity map for various parametric/scenario variations was shown in Fig. 4. All the investigations performed in this section were compared with respect to the respective baseline scenarios for the large- and small-scale systems.

3.2.1. Agricultural nitrogen fertilizer and diesel Input

From earlier discussions of the baseline LCA result, it was revealed that the most dominant component of GWP was the rapeseed agriculture stage due to high nitrogen-based fertilizer application such as U and AS. Therefore, the impact of nitrogen content on the GWP was investigated. Prior work in the literature (Liu et al., 2020) correlated rapeseed yields (y) as a function of nitrogen nutrient input (x) for the large- and small-sale systems given by Eqs. (2) and (3), respectively.

$$y = \frac{-0.023x^2 + 14.0667x + 1223.5}{1000} \tag{2}$$

$$y = \frac{-0.025x^2 + 14.992x + 1303.98}{1000} \tag{3}$$

During the sensitivity analysis all other constituents in the fertilizers such as P_2O_5, K_2O, and S were kept unchanged. The agricultural land and farming-associated diesel requirement were varied in correlation to support the rapeseed yield predicted by Eqs. (2) and (3). The large-scale system in the baseline scenario had a nutrient application rate of 135 kgN/ha for a corresponding yield of 2.7 t/ha, and a corresponding GWP 2.63 tCO_2-eq/tBD. The nutrient application rate was decreased to 65 kgN/ha (a 52% decrease) and the corresponding rapeseed yield was found to be 2.04 t/ha (Eq. (2)). This resulted in a GWP of 2.26 tCO_2-eq/tBD and indicated a 14% decrease. Similarly for the small-scale system the baseline scenario corresponded to a nutrient application rate of 150 kgN/ha for a rapeseed yield of 3.0 t/ha. When this value was changed to 75 kgN/ha (i.e., 50% decrease), a seed yield of 2.29 t/ha was resulted. This decrement in the nitrogen application rate reduced the GWP to 2.33 tCO_2-eq/tBD signifying a 19.1% reduction.

If the nitrogen nutrient content was reduced, the amount of diesel required would be increased. To support this additional diesel requirement, prior works recommend substituting the agricultural fuel with B20 biodiesel blend, since diesel engines can operate using this fuel without modifications. Besides the energy content in the B20 biodiesel blend was only 1% lesser per gallon than the petroleum diesel (US-DoE, 2022). The emission factor used for B20 was 2.486 $kgCO_2$-eq/l of the biodiesel produced from the RO. These considerations were further investigated upon the description of the alternative scenario in Section 3.3.

3.2.2. Fluctuations of rapeseed yield

The rapeseed yield could fluctuate annually, and its impact was worth investigation. In a related work (Stephenson et al., 2008) for

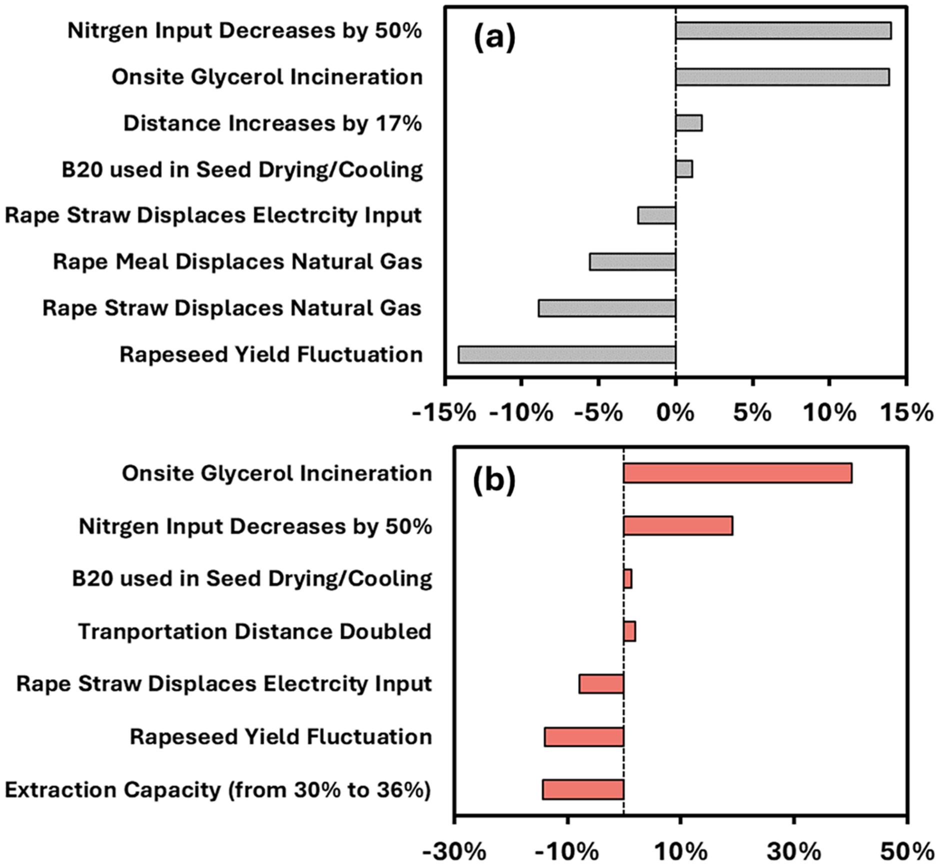


Fig. 4. Sensitivity maps showing percentage of GWP change with respect to the baseline scenario for various analysis performed in Section 3.2 for (a) large-scale and (b) small-scale systems.

large- and small-scale rapeseed-based biodiesel production systems, the yields were 3.4 t/ha and 3.6 t/ha, respectively. This led to a GWP 2.26 and 2.48 tCO_2-eq/tBD for the large and small-scale systems respectively, which suggested a 14.1% GWP reduction for both the systems.

3.2.3. *B20 alternative fuel Input*

The baseline scenario used petroleum diesel to supply the energy demand during seed drying and cooling processes. If this was replaced by B20 biodiesel blend (20% biodiesel and 80% petroleum diesel), then the GWP would be reduced by 1.1% (large-scale) and 1.2% (small-scale).

3.2.4. *Oil extraction methods*

Prior discussion on the oil extraction methods (i.e., solvent extraction for large-scale and cold pressing for small-scale) indicated that the process limitations could significantly affect the GWP of the overall system. Solvent extraction methods were much efficient with an oil leftover content of 0.5–2.0 wt.% in the rape meal. In contrast, small-scale facilities utilizing the cold oil pressing method produced rape meal with oil leftover content in the range of 4.0–10.0 wt.%, which impacted the biodiesel production capacity significantly (Hillfarm, 2021; Oil-Expeller, 2022). As a result, higher amount of rapeseed cultivation and associated land were required to produce a certain amount of oil, which ultimately increased the fertilizer and farming-associated diesel usage. The effect of cold oil press extraction capacity on the overall GWP was investigated by altering the extraction capability from 30 wt.% (baseline scenario) to 36 wt.%. An oil press with extraction capability of 36 wt.% resulted in a GWP 2.47 tCO_2-eq/tBD which was 14.3% smaller than the baseline scenario with 30 wt.% oil press.

3.2.5. *Influence of transportation distance*

An essential factor of the transport process was the transportation distance that significantly impacted the GWP. For the large-scale system, the total transportation distance was 505.24 km. If the case study was performed for the central belt of Scotland, the total distance would be 593.1 km (17.4% increase). This resulted to a GWP of 2.675 tCO_2-eq/tBD which was 1.7% higher compared to the baseline scenario. For the small-scale system, the transportation distance was 102.3 km since most of the processes occurred locally at Suffolk. Therefore, even doubling the transportation distance increased the GWP only by 1.9%, to 2.942 tCO_2-eq/tBD.

3.2.6. *Alternative thermal energy Input*

Most of the energy content of the large-scale system was resourced from natural gas and the GWP contributions from thermal energy/natural gas was approximately 30.7% of the total GWP. One of the prior works (Stephenson et al., 2008) suggested supplying this thermal energy demand by utilizing a biomass-fired boiler using rape meal or straw. Using a calorific value of 17.6 MJ/kg for rape meal (Stephenson et al., 2008) and a biomass boiler of an 80% efficiency (Vakkilainen, 2016), a total of 357 kg rape meal was required to supply the entire thermal energy demand. Based on an emission factor of 0.317 $kgCO_2$-eq/kg (Kindred et al., 2008), this would lead to a GWP of 2.48 tCO_2-eq/tBD, which was 5.6% smaller than the baseline scenario. Alternatively, if rape straw with a calorific value of 14.5 MJ/kg (FR, 2022) was used in the biomass boiler (Vakkilainen, 2016), a total of 384.6 kg of rape straw would be required to supply the entire thermal energy demand. Using emission data of the rape straw as 0.04924 $kgCO_2$-eq/kg (BEIS, 2022), the updated system would have a GWP of 2.39 tCO_2-eq/tBD (8.9% decrease). Findings from this sensitivity analysis was further used in developing the alternative scenario for large-scale production system (see Section 3.3).

3.2.7. *Alternative electrical energy Input*

Both the large- and small-scale systems required electrical energy during various stages of the process. Rape straw as a by-product of the process was used in natural gas fired station to supply a fraction of this electricity (Stephenson et al., 2008). A power station with a 45% efficiency was assumed (Storm, 2021) and supplied with rape straw of a calorific value of 14.5 MJ/kg (BEIS, 2022). To displace the entire electrical demand of the large-scale system, 177.17 kg/t BD rape straw was needed, which would result to a GWP of 2.56 tCO_2-eq/tBD (i.e., 2.43% lower than that of the baseline scenario). Similarly, for the small-scale system, the rape straw requirement was 629.73 kg/t BD to displace the entire electricity demand that resulted to a GWP of 2.66 tCO_2-eq/t BD (7.86% lower than baseline scenario).

3.2.8. *Influence of glycerol disposal*

In the baseline scenario, it was assumed that the glycerol as co-product was supplied to a pharmaceutical industry for the large-scale system, while the small-scale system supplied glycerol to a purification site (Stephenson et al., 2008). If this was not the case, the emissions associated with glycerol incineration and disposal should be accounted for in the LCA. Considering an emission factor of 3.23 $kgCO_2$-eq/kg for glycerol (BEIS, 2022), this would result in a GWP of 2.99 (13.9% higher) and 4.05 (40.3% higher) tCO_2-eq/tBD for large- and small-scale production systems, respectively. The influence of the glycerol disposal stage was found to be more pronounced for the small-scale system due to its larger amount of glycerol generation during transesterification (approximately 3.2 times higher than large-scale).

3.3. *Environmental Impact: Alternative scenario*

Based on the findings from sensitivity analysis, an alternative scenario was designed with minor changes in the large- and small-scale biodiesel production systems as shown in Fig. 5. This alternative scenario considered internal recovery of value-added product which would have otherwise been sent to the environment. For the large-scale system, the allocated changes were (1) switching to eco-friendly low nitrogen nutrient methods for rapeseed cultivation, (2) utilization of the biodiesel product in the B20 fuel blend and displace usage of conventional petroleum in rapeseed farming and seed drying/cooling, and (3) replacing natural gas-based process heating in oil extraction, refining, and transesterification stages by utilizing rape straw. For the small-scale production system, an additional allocation was considered in the alternative scenario where the cold oil press would press the seed to an oil content of 4 wt.%, that indicated 6 wt.% additional oil extraction than the baseline scenario (see Fig. 1). The percentage of GWP augmentation or reduction of the alternative scenario was discussed and compared to the baseline scenario using the metric λ as follows.

$$\lambda = \frac{\mathrm{GWP_{baseline}} - \mathrm{GWP_{alternative}}}{\mathrm{GWP_{baseline}}} \times 100 \tag{4}$$

A positive value of λ signified a reduction in the GWP and was desirable. Fig. 6a showed the GWP breakdown for the large- and small-scale systems, while Fig. 6b revealed the distribution of λ for various stages in the production systems. The GWP of the alternative scenario was 2.25 and 1.91 tCO_2-eq/tBD for the large- and small-scale biodiesel production systems, which were 14.1% and 33.6% lower than the baseline scenario. The GWP reductions were realized from (a) low nitrogen rapeseed agriculture fed with the B20 biodiesel blend (16.8% for

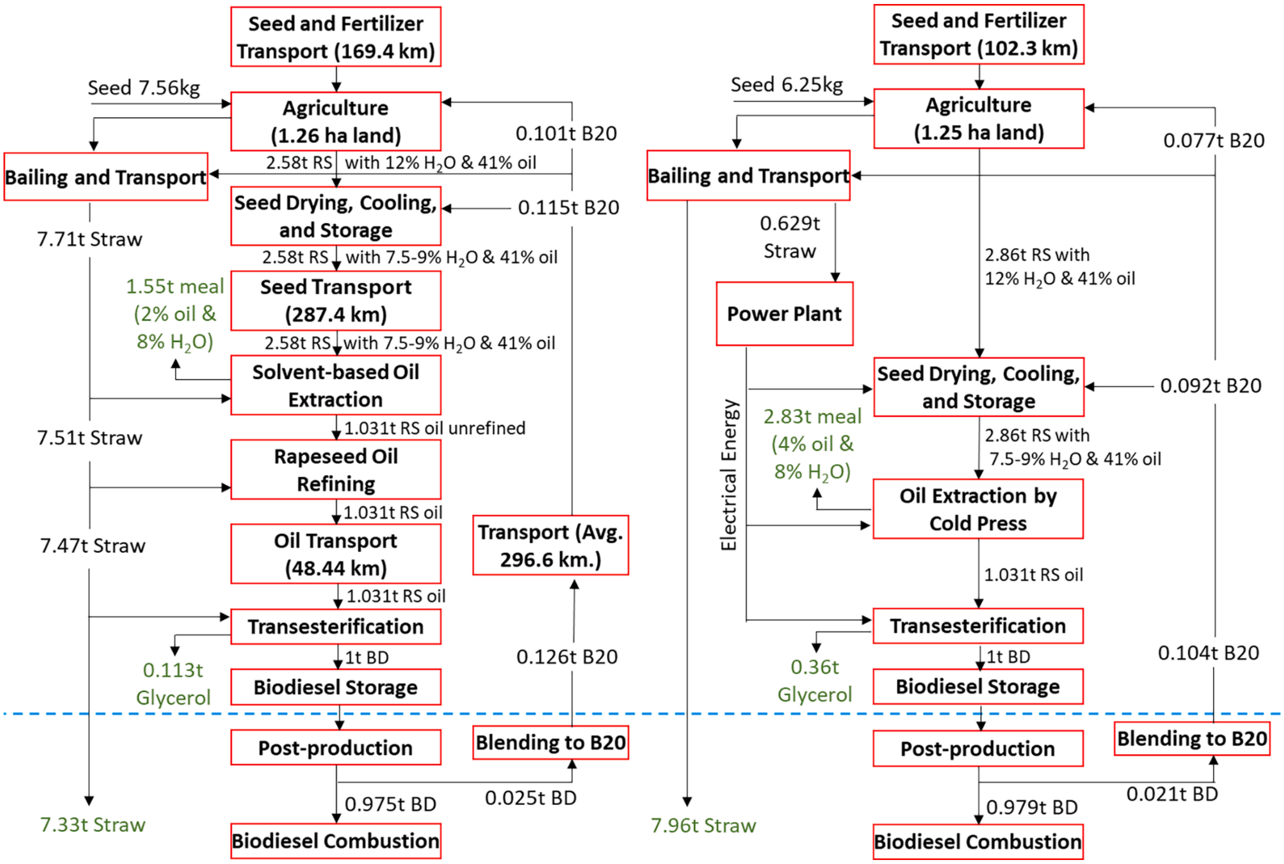


Fig. 5. Detailed process flow for the alternative scenario large-scale (left) and small-scale (right) biodiesel production schemes from rapeseed. The blue dotted line signifies end of LCA control volume where processes beyond this stage are not considered. Shown in green are the by-products from the biodiesel production processes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

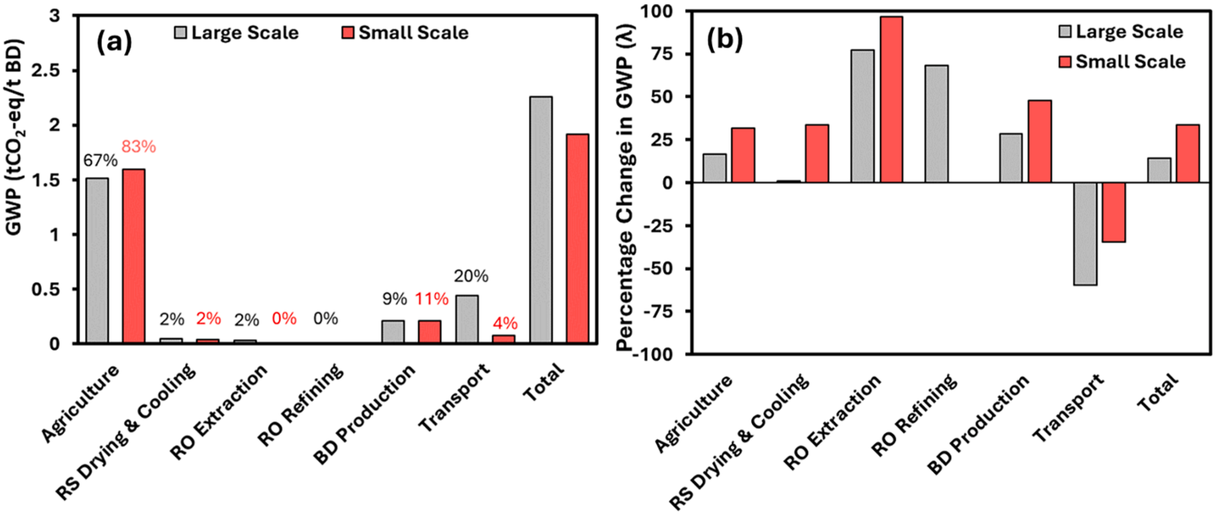


Fig. 6. (a) GWP breakdown for various stages in the large- and small-scale production chains for the alternative scenario, (b) Percentage of relative change in GWP (λ) for the alternative scenario in various stages of the large- and small-scale biodiesel production. The positive values suggest that the GWP for the alternative scenario is less than the baseline scenario, ultimately leading to carbon footprint reduction.

large-scale and 31.9% for small-scale); (b) rape straw and the B20 blend that supplied energy demand in seed drying/cooling process (1.3% for large-scale and 31.7% for small-scale), RO extraction process (77.1% for large-scale and 96.6% for small-scale), and RO refining process (77.1% for large-scale). Since the RO refining stage was not present in the small-scale system, the λ metric was not applicable for the stage. Energy generation from rape straw was also supplied to the biodiesel transesterification process and resulted in GWP reductions of 28.5% and 47.9% in the modified scenario. The only detrimental component was the GWP contributions from the transportation process. For the large-scale system, longer transportation distances (average 296.6 km) associated with B20 utilization impacted the GWP drastically and increased the carbon emissions for the alternative scenario by 59.6%. This in turn nullified the advantages gained by using B20. For the small-scale system, since the B20 mixing was carried out on-site, the associated transportation process became a minor factor. However, in the small-scale system, the rape straw transportation to the power plant increased the GWP by 34.6%, which was unfavourable. This offset effect was less pronounced in the small-scale system than the large-scale system, which ultimately led to more GWP reduction for the small-scale system with the modified production scenario.

The development of this alternative scenario with the benefits of decentralized rapeseed-based biodiesel production is significant due to its major market share in the biodiesel sector. In the EU, rapeseed-derived biodiesel had approximately 36% percent contribution in 2020, and most of the rapeseed was resourced indigenously within the EU (TE, 2021). These practices (e.g., low nitrogen rapeseed culture, exploring alternative utilization of by-products, and switching between production scales) will also motivate the rapeseed-based biodiesel development in UK and enable self-sustainable biodiesel production. Biodiesel production plants in UK should be placed close to the industries that can be benefited from the by-products (such as rape straw, glycerol, rape meal, etc.). Rape straw and meal can be utilized in anaerobic digesters as feedstocks to produce biogas or biomethane (Gupta et al., 2022), which can enable on-site combined heat and power (CHP) generation. This will mitigate the environmental impacts related to by-product disposal and contribute to material recycling and a circular bioeconomy (Abbaszaadeh et al., 2012; Puricelli et al., 2021; Rehan et al., 2018; Syafiuddin et al., 2020). In future, it will be interesting to explore a wide range of by-product utilization scenarios and investigate their influences on different environmental impacts via a normalization approach.

4. Conclusions

The work investigated energy (CED) and environmental impact (GWP) of rapeseed-derived biodiesel production processes. The centralized large-scale production system emitted 2.63 tCO_2-eq/tBD with energy demand 32.15 GJ/tBD. In contrast, the localized small-scale production system had 2.88 tCO_2-eq/tBD emissions with energy consumption 30.82 GJ/tBD. Sensitivity analysis revealed high dependence on factors such as glycerol disposal, rape straw or rape meal-based energy production, nitrogen nutrient content in fertilizer, rapeseed yield fluctuation, and limitations of oil extraction capacity. The proposed alternative scenario had a GWP of 2.26 (14.1% lower) and 1.92 (33.6% lower) tCO_2-eq/tBD for large- and small-scale production systems, respectively.

CRediT authorship contribution statement

Rohit Gupta: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. **Ruairidh McRoberts:** Conceptualization, Data curation, Methodology, Software. **Zhibin Yu:** Funding acquisition, Project administration, Supervision. **Cindy Smith:** Funding acquisition, Project administration, Supervision. **William Sloan:** Funding acquisition, Project administration, Supervision. **Siming You:** Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing, Supervision.

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

A related statement was added in the Acknowledgements section.

Acknowledgments

The authors would like to acknowledge the financial support from the Engineering and Physical Sciences Research Council (EPSRC) Programme Grant (EP/V030515/1). Siming You would like to thank the financial support from the Royal Society Research Grant (RGS\R1

\211358) and International Exchange Scheme (EC\NSFC\211175). All data supporting this study are provided in full in the 'Methodology' and 'Results and Discussion' sections of this paper.

References

Abbaszaadeh, A., Ghobadian, B., Omidkhah, M.R., Najafi, G., 2012. Current biodiesel production technologies: A comparative review. Energy Convers. Manage. 63, 138–148. https://doi.org/10.1016/j.enconman.2012.02.027.

Alberici, S., Toop, G. 2014. Overview of UK biofuel producers. Ecofys UK ltd. by order of Department of Transport. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308142/uk-biofuel-producer.pdf.

Beattie, A. 2020. The Farm Management Handbook 2020/21. SAC Consulting. URL: https://www.fas.scot/downloads/farm-management-handbook-2020-21/.

Beis, 2022. Conversion factors 2021: condensed set (for most users) - revised January 2022. E.I.S, Department for Business. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1049332/conversion-factors-2021-condensed-set-most-users.xls.

Bhonsle, A.K., Singh, J., Trivedi, J., Atray, N., 2022. Comparative LCA studies of biodiesel produced from used cooking oil using conventional and novel room temperature processes. Bioresource Technology Reports 101072.

Brentrup, F., Hoxha, A., Christensen, B., 2016. Carbon footprint analysis of mineral fertilizer production in Europe and other world regions. Conference Paper, The 10th International Conference on Life Cycle Assessment of Food (LCA Food 2016).

Brinkman, M.L.J., van der Hilst, F., Faaij, A.P.C., Wicke, B., 2021. Low-ILUC-risk rapeseed biodiesel: Potential and indirect GHG emission effects in Eastern Romania. Biofuels. 12 (2), 171–186.

Cargill. 2022. Hull, UK. URL: https://www.cargill.co.uk/en/hull-location.

Chaturvedi, O.P., Mande, S., Rajan, P., Kundu, K., 2013. Biodiesel plant design for rural application. ZENITH International Journal of Multidisciplinary Research 3 (9), 46–52.

Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., O'Connor, D., Duffield, J., 2018. Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. Bioresour. Technol. 251, 249–258.

DEFRA. 2021. Defra Statistics: Agricultural Facts England Regional Profiles. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/972103/regionalstatistics_overview_23mar21.pdf.

DEFRA. 2020a. Farming Statistics – final crop areas, yields, livestock populations and agricultural workforce at 1 June 2020 United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/946161/structure-jun2020final-uk-22dec20.pdf.

DEFRA. 2020b. Farming Statistics – provisional arable crop areas at 1 June 2020 England. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910585/structure-jun2020provcrops-eng-20aug20.pdf.

Dufour, J., Arsuaga, J.s., Moreno, J., Torrealba, H., Camacho, J. 2013. Comparative life cycle assessment of biodiesel production from cardoon (Cynara cardunculus) and rapeseed oil obtained under Spanish conditions. *Energy & fuels*, **27**(9), 5280-5286.

Firrisa, M.T., van Duren, I., Voinov, A., 2014. Energy efficiency for rapeseed biodiesel production in different farming systems. Energ. Effi. 7 (1), 79–95. https://doi.org/10.1007/s12053-013-9201-2.

FR. 2022. Carbon emissions of different fuels. UK Forest Research Department. URL: https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/.

Fridrihsone, A., Romagnoli, F., Cabulis, U., 2020. Environmental life cycle assessment of rapeseed and rapeseed oil produced in Northern Europe: A Latvian case study. Sustainability 12 (14), 5699.

González-García, S., García-Rey, D., Hospido, A., 2013. Environmental life cycle assessment for rapeseed-derived biodiesel. Int. J. Life Cycle Assess. 18 (1), 61–76. https://doi.org/10.1007/s11367-012-0444-5.

Gupta, R., Miller, R., Sloan, W., You, S., 2022. Economic and environmental assessment of organic waste to biomethane conversion. Bioresour. Technol. 345, 126500.

HGCA. 2006. Drying and storing rapeseed successfully. 89. URL: http://adlib.everysite.co.uk/resources/000/151/377/TS89.pdf.

Hillfarm. 20Pressing Matters: The Story of Our Two New Presses. Hillfarm Oils ltd. URL: https://hillfarmoils.com/blog/pressing-matters-the-story-of-our-two-new-presses/.

Hong, J., Chen, W., Wang, Y., Xu, C., Xu, X., 2014. Life cycle assessment of caustic soda production: a case study in China. J. Cleaner Prod. 66, 113–120.

Khanali, M., Mousavi, S.A., Sharifi, M., Nasab, F.K., Chau, K.-W., 2018. Life cycle assessment of canola edible oil production in Iran: a case study in Isfahan province. J. Cleaner Prod. 196, 714–725.

Kindred, D., Mortimer, N., Sylvester-Bradley, R., Brown, G., Woods, J., Alliance, P. 2008. Understanding and Managing Uncertainties to Improve Biofuel GHG Emission Calculations. HGCA. URL: https://ahdb.org.uk/understanding-and-managing-uncertainties-to-improve-biofuel-ghg-emissions-calculations.

Liu, S., Yang, X., Guan, Q., Lu, Z., Lu, J., 2020. An Ensemble Modeling Framework for Distinguishing Nitrogen, Phosphorous and Potassium Deficiencies in Winter Oilseed Rape (Brassica napus L.) Using Hyperspectral Data. Remote Sens. 12 (24), 4060. https://doi.org/10.3390/rs12244060.

Malça, J., Coelho, A., Freire, F., 2014. Environmental life-cycle assessment of rapeseed-based biodiesel: Alternative cultivation systems and locations. Appl. Energy 114, 837–844. https://doi.org/10.1016/j.apenergy.2013.06.048.

Malça, J., Freire, F., 2010. Uncertainty analysis in biofuel systems: an application to the life cycle of rapeseed oil. J. Ind. Ecol. 14 (2), 322–334. https://doi.org/10.1111/j.1530-9290.2010.00227.x.

MD. 2017. Mobile & Static Grain Driers, 10 To 56 Ton. Master Driers. URL: https://www.masterfarm.co.uk/wp-content/uploads/Master-Farm-Driers-Brochure-June-2017.pdf.

Meher, L., Dharmagadda, V.S., Naik, S., 2006. Optimization of alkali-catalyzed transesterification of Pongamia pinnata oil for production of biodiesel. Bioresour. Technol. 97 (12), 1392–1397. https://doi.org/10.1016/j.biortech.2005.07.003.

NE. 2014. NCA Profile: 83 South Norfolk and High Suffolk Claylands (NE544). Natural England. 978-1-78367-104-5. URL: http://publications.naturalengland.org.uk/file/5427224945623040.

NHA. 2016. Canola or Rapeseed Production Guidelines. New Holland Agriculture. URL: https://assets.cnhindustrial.com/nhag/apac/en-ph/assets/pdf/agronomy/canola-or-rapeseed-agronomy-brochure-apac-en.pdf.

Oil-Expeller. 2022. Introduction to Screw Oil Press. URL: https://oil-expeller.net/edible-oil-press-machine/screw-oil-press.html.

P&C. 2021. 2.2kW Aluminium Centrifugal Fan Product Catalog. Plug & Cool. URL: https://www.plugandcool.co.uk/app/uploads/2021/04/Ali-Fan-Data-Sheets-A5-2021-2.2-kW-1.pdf.

Puricelli, S., Cardellini, G., Casadei, S., Faedo, D., Van den Oever, A., Grosso, M., 2021. A review on biofuels for light-duty vehicles in Europe. Renew. Sustain. Energy Rev. 137, 110398 https://doi.org/10.1016/j.rser.2020.110398.

Rehan, M., Gardy, J., Demirbas, A., Rashid, U., Budzianowski, W., Pant, D., Nizami, A., 2018. Waste to biodiesel: A preliminary assessment for Saudi Arabia. Bioresour. Technol. 250, 17–25.

Renó, M.L.G., Lora, E.E.S., Palacio, J.C.E., Venturini, O.J., Buchgeister, J., Almazan, O., 2011. A LCA (life cycle assessment) of the methanol production from sugarcane bagasse. Energy 36 (6), 3716–3726.

Requena, J.S., Guimaraes, A., Alpera, S.Q., Gangas, E.R., Hernandez-Navarro, S., Gracia, L.N., Martin-Gil, J., Cuesta, H.F., 2011. Life Cycle Assessment (LCA) of the biofuel production process from sunflower oil, rapeseed oil and soybean oil. Fuel Process. Technol. 92 (2), 190–199. https://doi.org/10.1016/j.fuproc.2010.03.004.

Rose, C. 2004. Fertiliser Calculations. NSW Department of Primary Industries. URL: https://www.dpi.nsw.gov.au/_data/assets/pdf_file/0004/166153/fertiliser-calculations.pdf.

Rutz, D., Janssen, R. 2007. *Biofuel technology handbook*. WIP Renewable energies. URL: https://www.osti.gov/etdeweb/biblio/21214116.

Saville, B., 2006. Feasibility Study for a Biodiesel Refinery in the Regional Municipality of Durham. BBI Biofuels, Canada. URL: https://seda.sk.ca.52-60-208-4.objectified.live/wp-content/uploads/agri-business_2_2244362475.pdf.

Schmidt, J.H., 2015. Life cycle assessment of five vegetable oils. J. Cleaner Prod. 87, 130–138. https://doi.org/10.1016/j.jclepro.2014.10.011.

Stephenson, A., Dennis, J., Scott, S., 2008. Improving the sustainability of the production of biodiesel from oilseed rape in the UK. Process Saf. Environ. Prot. 86 (6), 427–440. https://doi.org/10.1016/j.psep.2008.06.005.

Storm, K., 2021. Chapter 6 - Combined cycle power plant (1× 1) labor estimate. in: *Industrial Construction Estimating Manual* Vol. 4887, 95–159. https://doi.org/10.1016/B978-0-12-823362-7.00006-5.

Syafiuddin, A., Chong, J.H., Yuniarto, A., Hadibarata, T., 2020. The current scenario and challenges of biodiesel production in Asian countries: A review. Bioresour. Technol. Rep. 12, 100608.

TE. 2021. 10 years of EU fuels policy increased EU's reliance on unsustainable biofuels. URL: https://www.transportenvironment.org/wp-content/uploads/2021/08/Biofuels-briefing-072021.pdf.

US-DoE. 2022. Biodiesel blends. URL: https://afdc.energy.gov/fuels/biodiesel_blends.html.

Vakkilainen, E.K., 2016. Steam generation from biomass: construction and design of large boilers. Butterworth-Heinemann.

Van Gerpen, J., 2005. Biodiesel processing and production. Fuel Process. Technol. 86 (10), 1097–1107. https://doi.org/10.1016/j.fuproc.2004.11.005.

Veolia. 2011. Winnipeg sewage treatment program: South end plant (Process selection report). URL: https://www.winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/PSR_rev%20final.pdf.