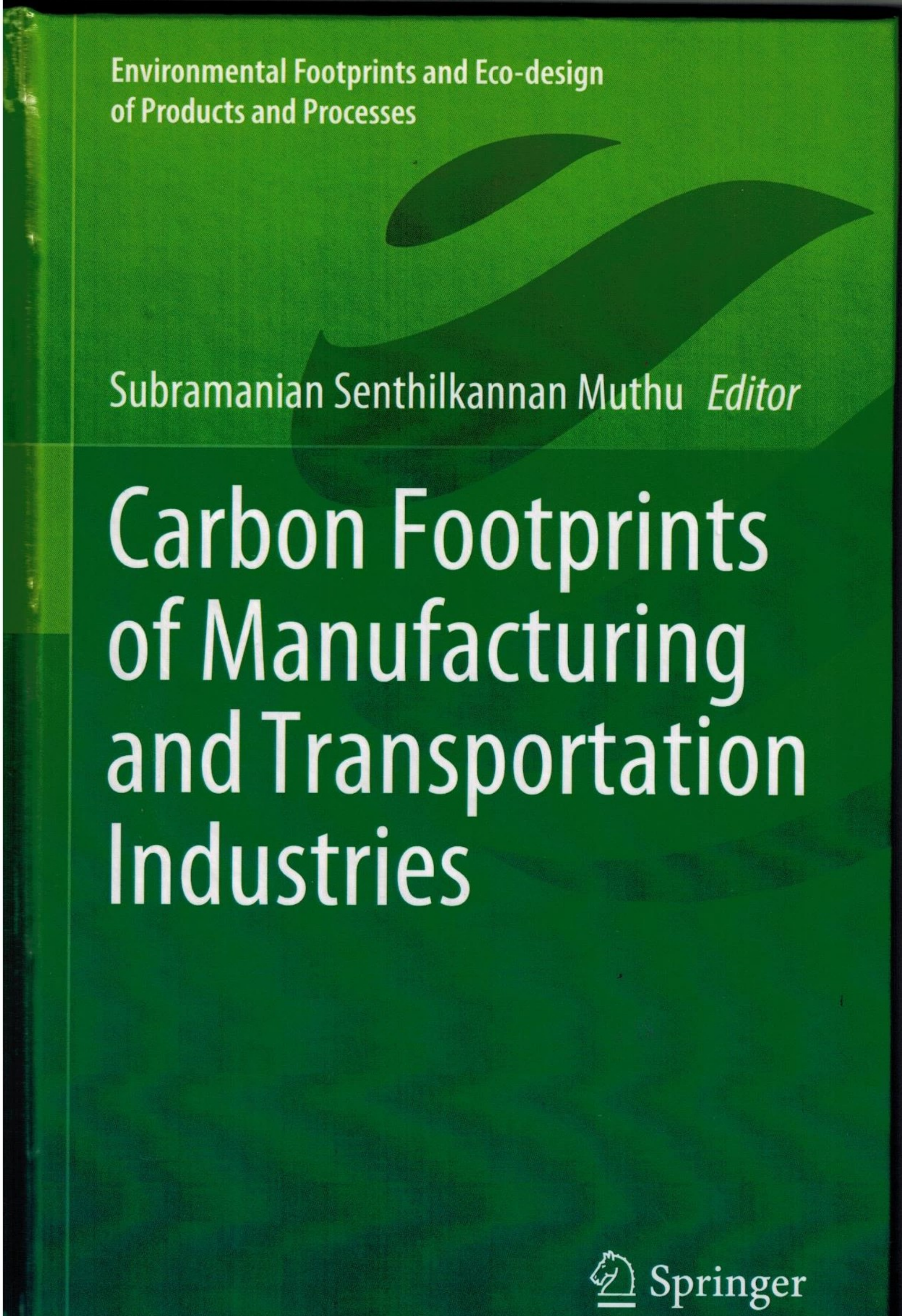

Environmental Footprints and Eco-design
of Products and Processes

Subramanian Senthilkannan Muthu *Editor*

Carbon Footprints of Manufacturing and Transportation Industries

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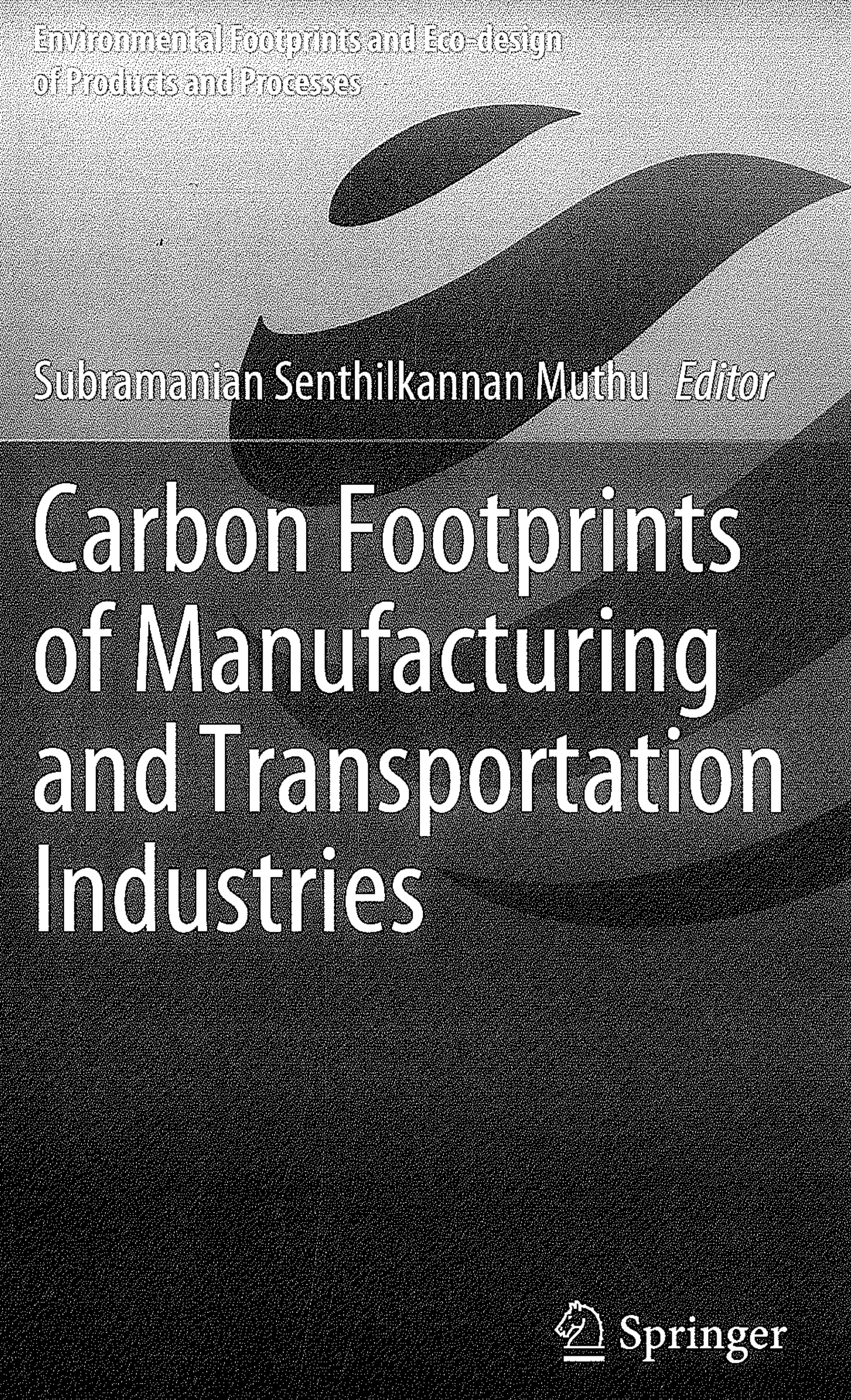

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Contents

Carbon Footprint Assessment of Palm, Jatropha, and Microalgal Biodiesel

G. Saranya and T. V. Ramachandra

Abstract Diminishing fossil fuel reserves, escalating oil prices, higher greenhouse gas footprint, and the adverse effects of climate change have propelled increased research focus during the twenty-first century on sustainable renewable energy transitions. Algal biofuel is gaining global interest due to its potential to convert biomass into a range of bioenergies and other value-added products. Life Cycle Assessment (LCA) aids in quantifying the environmental benefits of algal biodiesel over plant-oil-based biodiesel. The present chapter presents the environmental footprint of biodiesel from microalgae. It is compared with the terrestrial oil yielding feedstocks of first- (palm) and second-generation (Jatropha)-derived biodiesel by considering the mass and energy of production processes starting from feedstock generation to biodiesel production (cradle to gate analysis). The lifecycle impact of different generations of the biodiesel was assessed using OpenLCA software to understand the potential health and environmental implications (GHG, etc.)/soundness. Process-wise energy expenditure estimation shows a 68% and 45% reduction in energy expenditure and GHG emissions in algal biodiesel compared to first- (palm) and second-generation (jatropha) biodiesel, respectively. Results also reveasled a GHG mitigation potential in terms of direct GHG emission savings of 84, 90, and 95% for palm, Jatropha, and microalgal biodiesel compared to conventional fossil diesel.

Keywords Greenhouse gas footprint · Cradle-to-gate LCA · Net energy ratio · Lifecycle emissions · Palm · Jatropha · Microalgal biodiesel · Impact assessment

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1 Introduction

Energy is a vital resource, and the economic development of a region depends on its potential and access to energy. Increasing global energy security concerns and rapid environmental deterioration with the escalating greenhouse gas (GHG) due to burgeoning fossil fuel combustion have necessitated the development of sustainable, economic, and renewable energy alternatives [1]. The economic burden due to fossil fuel imports is evident from the import of 198 million tonnes of petroleum in 2020–2021 [2]. Currently, India is consuming 8.2 kg of oil equivalent (kgoe) per dollar of GDP as of 2014 in terms of purchasing power parity [3]. Additional demand in the primary energy supply of at least 3–4 times from their 2011 levels [4] is projected with the economic growth target of 8–9% by 2031–2032. In this regard, the nation must adopt at least 5–6% renewable energy share by 2031 as the strategic national energy policy. Renewable resources such as biodiesel, biogas, bioethanol, biohydrogen, etc., primarily biomass-based bioenergies, would play a crucial role in providing economical and sustainable energy as biomass feedstocks replenish and require a shorter cycling and processing time [5]. Biofuels are biodegradable, low-sulfur, and nontoxic fuels with a significantly lower GHG footprint than fossil fuels. Blending biodiesel with conventional diesel has lowered the fossil fuel requirement and tail-pipe emissions [3]. However, the prospects of scaling up renewable energy resources require research and the development of efficient processes and technologies that would considerably reduce environmental footprints [3, 5, 6].

Biodiesel is produced by extracting oil from oilseeds of terrestrial plants harvesting solar energy and storing it in seeds as chemical energy. Biodiesel extracted from oilseeds of terrestrial plants is categorized as first- and second-generation biodiesel based on its end-use value. First-generation biodiesel is derived from food crops, whereas second-generation biodiesel focuses on non-edible oilseeds with no associated food use-value. Conversion of food crops and the use of arable lands for biofuel feedstock production received resistance as these approaches were considered as major threats to uninterrupted food supply, known to trigger higher deforestation rate, and loss of biodiversity [2]. The current biodiesel supply is just 0.3% of the existing transportation fuel demand. Yet, using arable lands for increased biofuel production would adversely affect the global food supply. Other criticisms of first- and second-generation biodiesel produced from land-based oilseeds include changes in land use, fertilizer consumption, and the requirement for freshwater [7].

Microalgae, on the other hand, is emerging as a potential alternative to traditional fuel resources due to their ability to produce a variety of fuels and other value-added bio commodities [7]. Thus, assessing the environmental footprint of biodiesel feedstock will aid in prioritizing feedstock for the scaled-up production of biofuel. This chapter evaluates the environmental footprint of feedstocks palm, Jatropha, and microalgae.

Palm (*Elaeis guineensis*) belongs to the Arecaceae family, is native to Africa, and is naturalized in India and other Southeast Asian countries. Oil palms are known for their higher oil yields per unit area than any oil-producing crop worldwide. It gives nine times more oil per unit area than soy and 4.5 times more oil than rapeseed. India imports 46% of the edible oil to cater to its domestic needs. Palm oil now accounts for 33% of the global vegetable oil production and caters to the domestic and export markets of many countries like India, China, the European Union (EU), Thailand, Malaysia, and Indonesia [8]. Due to its affordable price, high oxidative stability, and simple processing steps, palm oil has broad applicability in food, cosmetics, plastics, detergents, personal hygiene products, and biofuel. As per global annual statistics 2021, palm oil has shown a worldwide consumption of 75.4 MT (million tonnes). In India, palm oil constituted 60% of the total vegetable oil import, with 0.5 MT in March 2021. In India, oil palm is cultivated in about 13 states covering about 3,50,000 ha. under irrigated conditions. India has strongly encouraged domestic palm oil production under the unique government programme "National Mission on Oilseeds and Oil Palm" (NMOOP) since 2014. India's crude palm oil production as of 2018 is about 0.27 million Mt (nfsm.gov.in).

Jatropha (*Jatropha curcas* L.) belongs to the family Euphorbiaceae and is a tropical perennial plant. Almost all plant parts of Jatropha, including stem, roots, leaves, and bark, are well known for their use in traditional and folk medicine. Oil seeds are a purgative for expelling intestinal parasites [4]. Jatropha produces seeds containing about 30–40% oil, and however, due to its highly toxic nature, it is considered unsuitable for food or livestock feed [9]. The average lifespan of Jatropha is 50 years, and it grows well in marginal/poor soil due to its drought-resistant characteristics. Jatropha plant starts fruiting from the second year onwards, while the yield stabilizes from the 4th or 5th year onwards. Jatropha yields about 2 kg of seeds per plant, with a productivity of 4–6 MT per hectare per year. The oil yield from 4 to 6 MT of Jatropha seeds is estimated as 1.6 Mt/ha/year, out of which 1.35–1.4 MT of biodiesel is possible [10]. In 2009, the National Biodiesel Mission programme launched by the Union Government of India, identified *Jatropha curcas* as the most favorable terrestrial oilseed crop for biodiesel production to help achieve a B-20 (20%) biodiesel blend with conventional diesel by the year 2017. As per the Government of India survey, 90 million hectares are identified as wastelands that can effectively be used for non-edible oil seed feedstock production. Among the various oil seeds, *Jatropha curcas* possesses many favorable characteristics, including drought resistance and favorable fatty acid profiles for biodiesel. According to the Planning commission, 13.4 million hectares (Mha) of land are required for Jatropha cultivation to achieve a 20% biofuel blending target [11].

Microalgae have been emerging as potential biofuel feedstocks owing to their rich energy content, remarkable carbon sequestration capacity, faster growth rates, enhanced cell density, and efficient culturing approaches [12]. Microalgal biomass productivity of 36–54 tonnes/ha/year is reported in the literature when algae are cultivated as a single species in raceway ponds with nutrient inputs in the form of fertilizers [8]. Dry algal biomass as high as 165 tonnes/ha/year is reported in biofilm-based multispecies algal turf scrubbing systems constructed near large watersheds as tertiary water treatment systems at different river shores in the USA [13].

LCA is a methodological tool to quantify the energy requirement of a product/service and subsequent environmental emission that is inevitable due to its production. LCA considers the energies involved in a product's production right from raw material extraction until the manufacture of the final product. LCA provides critical information on the environmental performance of a product/system, which significantly helps ecological management, monitoring, and making policy-oriented decisions. According to the ISO 14000 series technical framework of LCA, the life-cycle analysis consists of four phases: (1) goal scope and definition; (2) Inventory analysis; (3) Impact assessment; (4) Interpretation.

2 Materials and Methods

2.1 The Goal, Scope, and Definition

This study aims to evaluate the environmental footprint of biodiesel production using different generation feedstocks such as palm oil, Jatropha oil, and algal oil. The functional unit (FU) considered for this study is 100 kg biodiesel produced from each feedstock and considers feedstock production, harvesting, transportation to the factory, and their transformation into biodiesel (pretreatment, oil extraction, and transesterification). The environmental impacts are measured as per the CML-IA baseline method. The system boundary for this LCA study is modelled by considering the following parameters for cradle to the gate, starting with feedstock cultivation to be the cradle stage to biodiesel production as the gate stage.

- The 'cradle' stage for palm and Jatropha oil begins with a plantation (considering the use of arable land without deforestation), followed by harvesting, transport, and milling operation to extract oil from oilseeds and transesterification.
- The 'cradle' stage for algal biodiesel begins with raceway pond cultivation of microalgae *Chlorella* sp. (considering 1 ha area), harvesting, followed by transportation of the harvested biomass drying and transesterification.
- Lipid extraction from microalgal biomass is carried out using the solvent hexane, and complete recovery and reuse of the solvent are assumed for the LCA analysis.
- The biodiesel production from oil/lipids is carried out using methanol and alkali (NaOH) as the catalyst for palm and Jatropha biodiesel, while diluted H_2SO_4 (mineral acid) is considered as a catalyst for algal oil transesterification.

2.2 System Boundary

The life cycle of palm oil biodiesel consists of five stages. (i) plantation (agricultural) operations; (ii) harvesting; (iii) transportation; (iv) milling operations; (v) transesterification. Figure 1 outlines the system boundaries for (a) palm, (b) Jatropha biodiesel, (c) algal biodiesel.

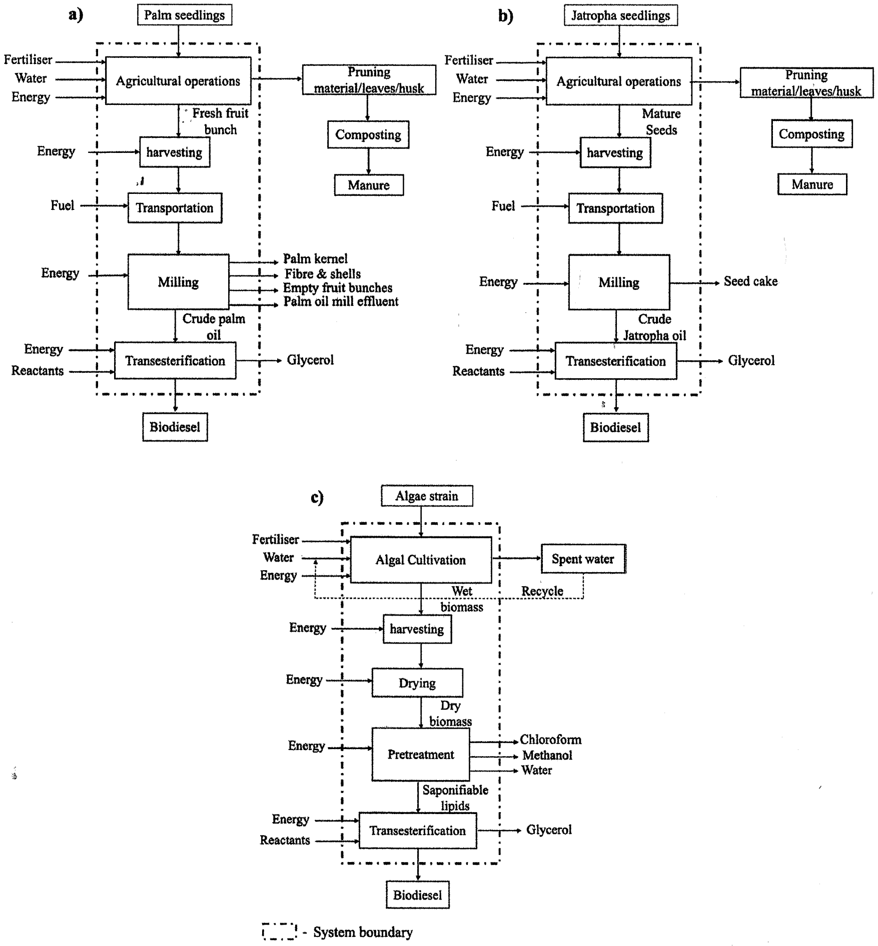

Fig. 1 System boundaries for **a** palm, **b** Jatropha biodiesel, **c** algal biodiesel

The agricultural operations for oil palm include site preparation, nursery establishment, sowing and maintenance, harvesting, and collection of fruit bunches. Sowing seeds takes 3–4 months to form saplings, after which the saplings are transferred to large poly-grow bags where it is maintained until 12–13 months before field plantation [3, 8]. The next step is the plantation, where field establishment of palm is carried out by planting the mature saplings at a density of 136–148 plants per hectare. The plantation density usually depends on the type of soil in which the saplings are planted. The average lifespan of palms is 24–30 years, while oil palms will be ready for harvesting 2.5–3 years after field plantation. Inflorescence of both male and female flowers happens in the same tree after 14–18 months of plantation. However, removing flowers during the initial 2–3 years is recommended to ensure stem girth and a strengthened string root system. This process of removal of flowers from oil palm is known as 'ablation.' After proper fertilization and maintenance, the oil palm yield would be between 10–12 tonnes/ha during the first 4–8 years, and the yield would vary between 20 and 25 tonnes/ha after 8th year until its entire life span.

The crude palm oil (CPO) yield from the fresh fruit bunches (FFBs) ranges between 4 and 5 tonnes/ha. Fresh fruit bunches formed are harvested and processed almost immediately by transporting the fruits to the nearby palm oil mills to prevent the rapid rise of free fatty acids (FFA), which could adversely affect the quality of crude palm oil (CPO) [6]. CPO processing in a mill involves sterilization, threshing, fruit stripping, digestion, and oil extraction [8]. The sterilization process is carried out using live steam, and it helps loosen the fruits from the bunch. After sterilization, a rotary drum is used to strip off the fruits from its bunch. Once the fruits are stripped, they are continuously fed into a digester that converts the fruits into a homogenous oil mash to enable easy pressing of the content to extract oil. The extracted oil is then trans-esterified to produce biodiesel.

Jatropha oil production involves four stages, i.e., establishment and production of Jatropha seeds, harvest and processing of Jatropha oil, transesterification of oil into biodiesel, purification, transport, and distribution of biodiesel. Jatropha plants are established by seedling, cutting, and propagation. The plantation is usually drought-prone, with the necessity of watering just twice a week. Fertilizers are applied once in three years. On average, 625 kg of NPK fertilizers is used every year (Table 1). Herbicide application is assumed to average glyphosate (3 L) and paraquat (2 L) per ha per year [8]. Jatropha starts to yield fruits only from the fifth year onwards, while the yield is not significant before that. The seed yield varies between 2.8 and 12.5 t/ha/yr. [14]. The treatment of Jatropha seed involves harvesting ripe fruits that are dried under the sun and de-husked. The dried fruits are separated from the peels using a cracking machine with a feed rate of 100–120 kg seeds per hour. The dried seeds are then subjected to mechanical extraction using a filtering machine (150–170 L oil per hour) to separate oil from the sources [5]. Before mechanical extraction, the seeds are solar dried for a day or two. The extracted oil is then trans-esterified with methanol to produce biodiesel.

Photobioreactors and raceway ponds are the most studied large-scale production systems of algae. Algae cultivation in raceway ponds was considered for this study as it is relatively less expensive than photobioreactors and well-suited for Indian climatic conditions. The selected algal strain (*Chlorella* sp.) with total lipid content of 25% that was cultivated in 1000 L brackish water was considered. The cultivated algal biomass was assumed to have an inoculum volume of 125 L, with a biomass density of 0.5 g/L. The total volume of the raceway pond is 1500 L, with a working volume of 1000 L. The areal productivity was considered as 25 g/m^2/day. Dewatering was carried out by centrifugation until the biomass content was 15% [7]. Biodiesel is produced from the harvested biomass after extracting oil from the harvested algal cells through chemical extraction using hexane [18, 19]. Alkali catalyzed transesterification using KOH as a catalyst in the presence of methanol was used for algal biodiesel production.

Table 1 Material inputs at various stages of feedstock conversion to biodiesel

Processes	Inputs	Palm Biodiesel[a]	Jatropha Biodiesel[b]	Microalgal biodiesel[c]
Cultivation	N (Kg/ha)	166	60	88
	P (Kg/ha)	56	80	79.2
	K (kg/ha)	122	75	65
	Pesticides (kg/ha)	1.1	3.6	–
	Water (kg)		20.6	2,21,750
Solvent extraction	Hexane (kg/ton of seed)	5	4	2.95
	Steam (kg/ton of seed)		280	–
	Electricity (KWh/ton of seed)	534	55	0.08
	Water (kg/ton of seed)	8250	12,000	9200
Biodiesel production	Oil (kg/ton of biodiesel)	987	1050	1050
	Methanol (kg/ton biodiesel)	136.8	117	124.9
	NaOH (kg/ton biodiesel)	6	12.8	10.5
	Sulfuric acid	–	–	15.8
	Electricity (KWh/ton biodiesel)	156.2	36.1	41
	Steam (kg/ton biodiesel)	5.3	660	–
	Circulated water (kg)	250	550	140
	Glycerol (kg/ton biodiesel)	156	125	113
	Oil content of seeds (wt%)	50	35	45
	Oil extraction efficiency (%)	99	91	87
Transportation	From mill to biodiesel industry (km)	50	50	50
	From the biodiesel industry to fuel stations (km)	50	50	50

[a] [14, 15];
[b] [8, 13, 16];
[c] [6, 17]

2.3 Lifecycle Inventory (LCI)

2.3.1 Inventory

To produce 100 kg palm biodiesel, 512.3 kg fresh fruit bunches must be sterilized in an autoclave at ~2 bar at 125 °C for 50 min [15]. The fresh fruit bunches are then stripped and digested under steam conditions, yielding a crude palm oil (CPO) of ~987 kg of pulp, which is purified, and stored at 60 °C for further processing. The CPO is trans-esterified to biodiesel using methanol and sodium hydroxide as catalysts. For every 100 kg of palm biodiesel produced, a 11 kg crude glycerol is also produced. During transesterification, triglycerides are converted into methyl esters with the addition of methanol. The energy consumption (MJ/kg of biodiesel) for the production of fertilizer, herbicide, diesel, and electricity use for each downstream process and its corresponding GHG emission (kg CO_2e) is listed in Table 2.

In the case of Jatropha biodiesel, the seed yield was taken as 1.5 t/ha/yr. Consider rain-fed cultivation in arid conditions as the plantation is known to be drought-prone. Herbicide consumption of 2.4 kg/ha/yr. was used in this present study [14]. Fertilizer application at 60, 85, and 70 kg/ha/yr. was considered for the analysis. Jatropha cultivation as a perennial plantation was considered as it required less maintenance and less fertilizer. The energy consumption for the production of Jatropha biodiesel alone was considered. In contrast, energy consumption and generation through co-products such as fruit hulls, seed cakes produced during oil extraction, and energy from dry leaves generated were omitted in this energy analysis.

A raceway pond inoculated with strain *Chlorella vulgaris* was considered with a light: dark cycle of 12 h for microalgae cultivation, the culture period of 6 days was considered for the algal cells to reach the final cell density. Considering a cell density of 0.5 g/L, in 1000 L culture volume, a biomass of 0.5 kg will be produced. Energy consumption in different processes of algal biodiesel production is listed in Table 3. The energy required for CO_2 pumping (2% CO_2) was estimated as 0.22 kWh per kg of CO_2, which is 0.58 MJ/kg of biodiesel. Mixing in raceway ponds was effected by paddle wheels which consume 1.15 MJ to achieve a biomass density of 25 g/m^2/day. Centrifugation was considered for harvesting the algal biomass with a requirement of energy of about 1.12 MJ/kg of algal biomass harvested with a solid content of 15%. Algal biomass of 4.44 kg is required to produce 1 kg biodiesel considering 90% lipid conversion to biodiesel. The total energy needed for producing 1 kg biodiesel was estimated with 25% lipid content as 22.5 MJ/kg of biodiesel. The harvested biomass is then subjected to solvent extraction to extract lipids. A solvent ratio of 3:1 chloroform and methanol is used. The extracted lipids are trans-esterified to methyl esters. The energy demand for transesterification was considered as 5.4 MJ/kg of biodiesel [13, 17].

Table 2 Life cycle inventory of energy and carbon footprint of palm and jatropha biodiesel production

Process	Palm biodiesel[a]		Jatropha biodiesel[b]	
	Energy factors (MJ/100 kg of biodiesel)	GHG emission (kg CO_2 eq)	Energy factors (MJ/100 kg of biodiesel)	GHG emission (kg CO_2 eq)
Fertilizer production				
Nitrogen (N)	51.5	18.8	87.6	6.7
Phosphorus (P)	9.2	5.2	26.4	0.71
Potassium (K)	6	15.3	10.5	0.46
Diesel use				
Energy expenditure for diesel production	50	1.84	11.29	3.7
Sodium hydroxide (NaOH)	1.5	0.47	19.8	1.2
Palm/Jatropha biodiesel			37.3	
Seed cake			21.5	
Herbicide production				
Glyphosate	319	1.14	452	5.4
Paraquat	–		458	
Insecticide	325	1.7	–	
Electricity use (kwh)	7.4	9.7	28	0.81
Methanol	33.5	1.56	38.08	1.95
Crude glycerine	15.6	22.8	26	31.4

[a] [5, 8];
[b] [13, 17, 20]

Table 3 Energy consumption in different processes of algal biodiesel production

Process	Energy input (MJ/kg of biodiesel)[a]
Raceway pond operation	4.6
CO_2 pump	0.58
Harvesting	1.12
Dewatering	0.14
Lipid extraction	3.8
Methanol	3.2
Transesterification	5.4

[a] [14]

2.3.2 GHG Emission Estimation from Fertilizers

The functional unit (FU) of 100 kg biodiesel production used in this study. The life-cycle inventory associated with the carbon footprints generated for producing palm, Jatropha, and microalgal biodiesel was estimated using the 2006 IPCC guidelines for National Greenhouse Gas Inventories. The carbon dioxide equivalent emissions associated with each feedstock (palm, Jatropha, and microalgae) from land preparation, chemical fertilizer application, seed planting, and running farm machineries were estimated by considering the NO_x, CH_4, and CO_2 emissions. NH_3, NO_x (indirect and direct N_2O) emissions due to N-based fertilizers, nitrate and phosphate percolation into the ground and surface water due to N and P fertilizers application to the field. Ammonia, N_2O, and nitrate emissions were calculated following [26] in Eqs. (1)–(3).

$$NH_3 = \left(\frac{17}{14}\right) \times \sum_{m=1}^{M} (EFa_m \times P \times N_{min} + EFb_m \times (1-p) \times N_{min}) \quad (1)$$

where,

NH_3 represents the ammonia volatilization due to mineral N fertilizer application. EF_a and EF_b are emission factors (kg NH_3-N/Kg N) with respect to soil pH. EF_a is used if the soil pH is $< \,= 7$, while EF_b is used if pH is > 7. ‘p’ is the fraction of the soil with pH $< \,= 7$. NO_x fraction is calculated after subtracting N, which is volatilized in the form of ammonia.

$$N_2O = \left(\frac{44}{28}\right) \times \left(0.01\left(N_{tot} + N_{cr} + \left(\frac{14}{17}\right) \times NH_3 + \left(\frac{14}{46}\right) \times NO_2\right) + 0.0075 \times \left(\frac{14}{62}\right) \times NO_3\right) \quad (2)$$

where,

N_{tot} = total nitrogen in mineral and organic fertilizer; N_{cr} = Nitrogen in crop residues; NH_3 = ammonia emissions; NO_2 = Nitrogen dioxide emissions; NO_3 = Nitrate leaching.

Nitrate leaching was estimated based on Eq. (3).

$$N = 21.37 + \frac{P}{c \times L}[0.0037 \times S + 0.0000601 \times N_{org} - 0.00362 \times U] \quad (3)$$

where,

N = NO_3-N percolation in (kg N ha/year); P = total water supplied by irrigation and precipitation (mm/year); c = amount of clay content (in percentage); L = length of the roots; S refers to nitrogen supply after eliminating NH_3, NO_x and N_2O emissions (kg N/ha). N_{org} = organic nitrogen content; U = nitrogen uptake by the crop.

Phosphate leaching to groundwater was estimated using a constant factor of 0.07 kg (P/ha*a), while phosphate run-offs to surface water were calculated using Eq. (4).

$$P_{ro} = P_{rol} \times \left(\frac{1 + 0.2}{80 \times P_2O_{5min}} \right) \tag{4}$$

where,

P_{ro} = P lost through run-off (kg/ha yr.)

P_{rol} = P lost through run-off for a selected land use category (0.175 kg P/ha yr.)

P_2O_{5min} represents the quantity of P_2O_5 present in mineral fertilizer.

2.3.3 Estimation of Net Energy Ratio

The net energy ratio is the ratio of net energy output from the system to the non-renewable energy input. The energy inputs for different biodiesels include the energy expended in cultivation, harvesting, and biodiesel production, while energy output represents the energy produced by burning the biodiesel.

$$NER = 1 + \frac{Net\ Energy}{Energy\ Input} = \frac{Energy\ Output}{Energy\ Input}$$

2.3.4 Savings in GHG Emission

Savings that are possible in GHG emission are defined as the reduction in environmental burden, commonly expressed as direct savings that are possible when biodiesel is used in the place of conventional fossil diesel [34].

$$GHG\ Savings = \frac{(FD - BD)}{FD} \times 100$$

where FD is the GHG as CO_{2e} emissions caused by the conventional diesel and BD is the CO_{2e} emission due to biodiesel.

2.3.5 Lifecycle Impact Assessment

Lifecycle impact assessment (LCIA) helps in the evaluation of potential impacts of a product system/process streams on the environment [16, 20]. LCIA follows the critical steps of impacts being classified, characterized, normalized, and weighted [3, 13]. Resource consumptions and various environmental impacts related to emissions were enumerated to evaluate the various lifecycle impact categories. A 100 kg biodiesel manufactured using different second- and third-generation biodiesel feedstocks was used as the functional unit for the assessment of lifecycle impacts. OpenLCA software version (v1.10.3) with Ecoinvent® 3.6 (academic free license version for non-OECD countries) database has been used for assessing LCIA of biofuel from various feedstocks. The impact categories relevant for each feedstock's biodiesel production were estimated as per CML–IA baseline method, developed by the Leiden University (The Netherlands). The LCIA was aimed at assessing the impacts at eleven different impact categories including terrestrial ecotoxicity (kg 1,4 DB eq), marine ecotoxicity (kg 1,4 DB eq), human toxicity (kg 1,4 DB eq), global warming (GWP 100a kg CO_2e), ozone layer depletion (kg CFC-11 eq), photochemical oxidation (kg C_2H_4 eq), eutrophication (kg PO_4 eq), freshwater ecotoxicity (kg 1,4 DB eq), acidification (kg SO_2 eq), abiotic depletion (fossil fuel) (MJ), abiotic depletion (kg Sb eq). The relative contributions of each process and its associated pollutants were determined through contribution analysis by allocating total impact scores per impact category.

3 Results and Discussions

3.1 Comparison of Energy Expenditure

Figure 2 illustrates the energy expenditure related to each process and its comparison for different biodiesel feedstocks. While considering a 100 kg biodiesel as the functional unit, the energy expended for cultivation, pretreatment, oil extraction, and biodiesel production was found to be the highest for palm biodiesel (2898 MJ/100 kg), followed by Jatropha (1696 MJ/ 100 kg) and the least energy expenditure was recorded for microalgae (926 MJ/100 kg). It should be noted that the transportation energy expenditure as diesel use was included in the pretreatment and oil extraction stage for all three types of biodiesel. There was an energy expenditure of 2402.5 MJ/ha of palm fruit brunches produced, while 14,689 MJ per 100 kg crude palm oil processing and 91,670 MJ/100 kg biodiesel [15]. For Jatropha plantation, an energy of 1279 MJ/100 kg of biodiesel was required during the cultivation stage, while 1250 MJ/kg for oil refining and 2340 MJ/ 100 kg during biodiesel production [20]. The overall energy expenditure is comparable to the present study. The overall energy expenditure was the least for each unit's operations for microalgae. Handling microalgae in raceway ponds are easier than energy plantations like palm and Jatropha. Thus, the energy consumption from the microalgal cultivation, pretreatment, and biodiesel production was the least compared to all other feedstocks.

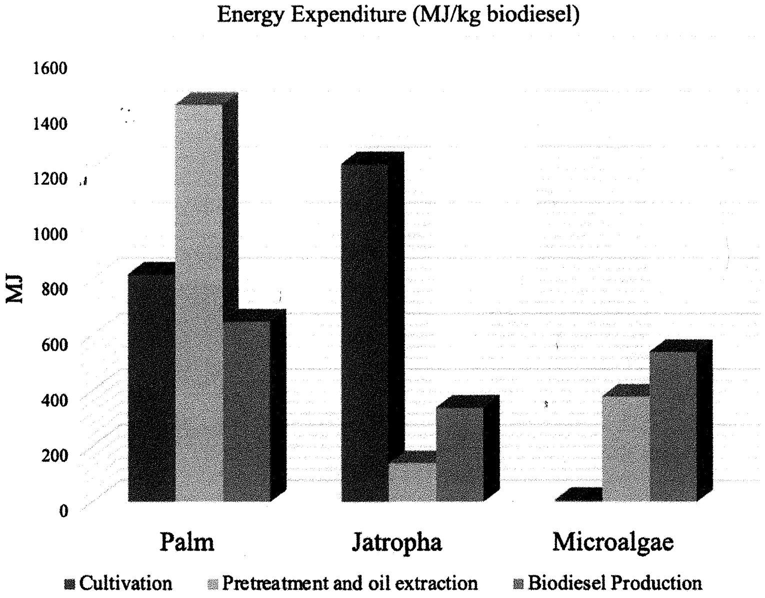

Fig. 2 Energy expenditures of biodiesel derived from different feedstocks

3.2 *Estimation of GHG Emission*

Figure 3 illustrates GHG emission share for different feedstocks during different stages of the biodiesel production process. The GHG emission (as kg CO_{2e}) was least for microalgal biodiesel (111.3 kg CO_{2e}/100 kg of biodiesel) and highest for palm biodiesel (348.5 kg CO_{2e}/100 kg of biodiesel), with a maximum share for pretreatment processes contributing to 49% emission out of the total. In all the biodiesel production using different land-based feedstocks, the GHG emission of palm biodiesel was higher (172 kg CO_{2e}/100 kg of biodiesel) in the pretreatment stage, while for Jatropha biodiesel, the cultivation stage was found to release environmental loads as GHG emission with 142 kg of CO_{2e}/100 kg of biodiesel produced. In the case of microalgal biodiesel, the trans-esterification (biodiesel production) process was found to be environmentally burdening (64 kg CO_{2e}/100 kg biodiesel) due to the use of organic volatiles such as methanol and hexane. The significant share of GHG emissions (72%) for Jatropha during cultivation was from fertilizer application and fertilization induces soil acidification, thus leading to eutrophication and reduced soil fertility. However, adopting optimal production of microalgal biomass using wastewater has been shown to reduce the environmental burden through bioremediation [13, 17]. Algal cultivation when integrated with wastewater treatment demonstrated a significant reduction in lifecycle emissions, when carried out in a biofilm-based microalgal biorefinery [3] and open pond reactors [13]. Thus,

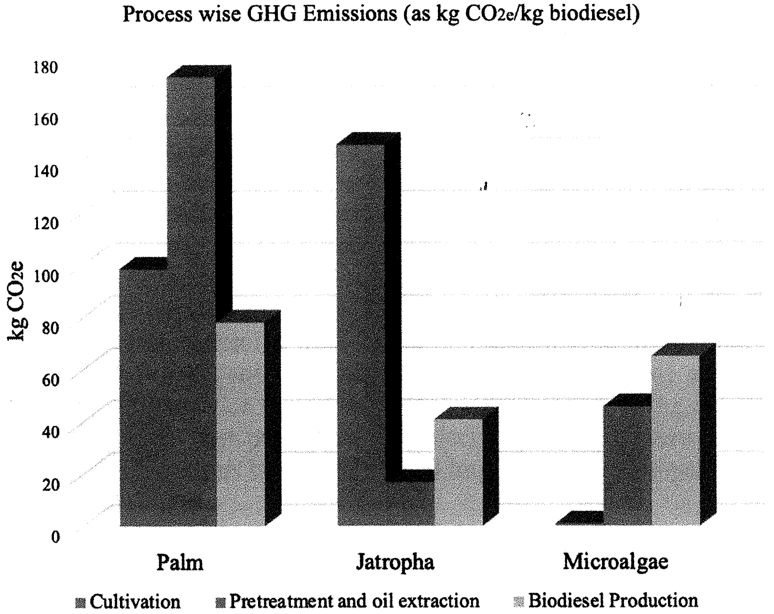

Fig. 3 Process-wise GHG emissions for biodiesel production from different feedstocks

microalgal biodiesel exhibits better environmental performance when compared to palm and Jatropha biodiesel in terms of GHG emission reduction potential per unit of energy production.

3.3 *Net Energy Ratio*

Any biofuel production system is considered economically viable if Net Energy Ratio (NER) > 1. NER of different feedstocks are illustrated in Fig. 4. NER was determined by considering the total energy output possible from biodiesel manufactured using respective oils as feedstocks. The energy content of biodiesel for palm, Jatropha, and microalgae considered for calculation was 36.5 MJ kg^{-1}, 39.4 MJ kg^{-1}, and 39 MJ kg^{-1}, respectively. NER for all kinds of biodiesel depicted a positive energy system with net energy ratio greater than 1,. The result demonstrated the highest NER for microalgal biodiesel (NER = 4.2), which is almost comparable to the NER = 5.26 of conventional fossil based diesel. The result could be from lesser fertilizer inputs during microalgae cultivation, followed by lower grid electricity and chemical inputs during the trans-esterification process. NER of 2.3 and 1.2 was estimated for Jatropha and palm-derived biodiesels, respectively. The least NER for palm could be attributed to its higher energy requirement in downstream operations of pretreatment and oil extraction.

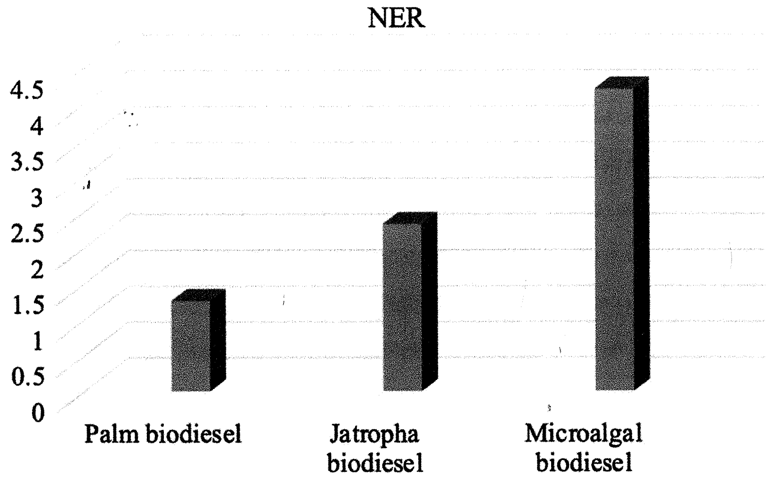

Fig. 4 NER of different feedstocks derived biodiesel

3.4 *Lifecycle Impact Assessment*

3.4.1 Abiotic Resource Depletion Potential (ADP)

ADP expressed in kg of Antimony equivalents (kg Sb-eq) is defined as the amount of non-renewable natural resources that are depleted due to a certain anthropogenic activity. The ADP of palm, jatropha and microalgal biodiesel production varied between 1.64E-07 kg Sb-eq/100 kg and 0.0225 kg Sb-eq/100 kg biodiesel. The abiotic resource depletion estimated for microalgal biodiesel production exhibited 0.0023 kg Sb-eq [21] which is comparably higher to that of the ADP estimated in the present study (1.64E-07 kg Sb-eq/100 kg biodiesel).

3.4.2 Abiotic Depletion Potential (ADP) Fossil Fuel

ADP fossil fuel refers to the measure of scarcity of a substance, especially due to the non-renewable resource consumption such as fossil fuels. In this study, the fossil resource depletion evident due to coal consumption in conventional grid-based electricity generation is considered as the major impact category, followed by the use of a base catalyst such as NaOH, and petroleum derivatives such as n-hexane and Me-OH (methyl alcohol) for biodiesel production as ancillary impact categories that are likely to enhance the fossil fuel consumption. The above mentioned utilization of resources (abiotic) is collated and characterized as MJ equivalent factors of energy (as the CML–IA baseline (ISO 14042 LCA).

Figure 5 illustrates the different impact categories on palm, Jatropha, and microalgal biodiesel. The abiotic fossil resource depletion ranged between 0.20 and

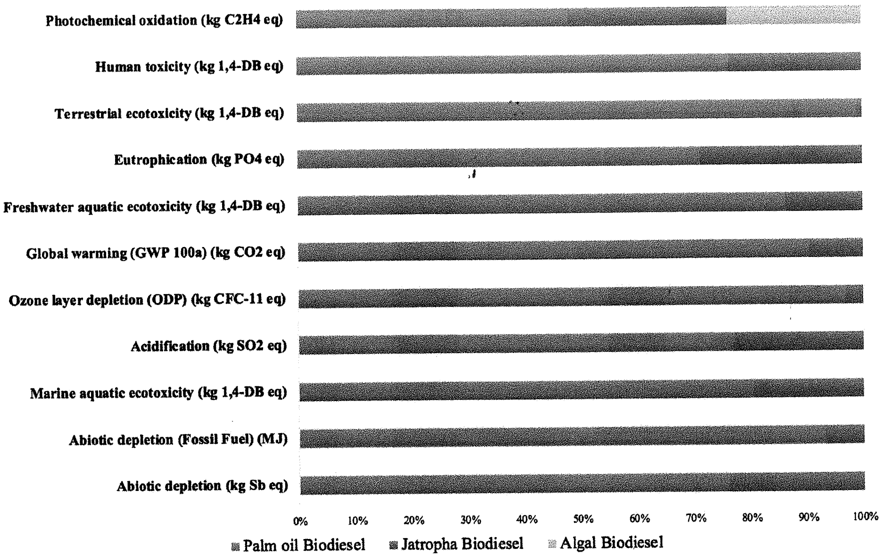

Fig. 5 Lifecycle impacts of biodiesel produced using different feedstocks

8.33E + 04 MJ/100 kg of biodiesel, with the least abiotic depletion potential for microalgal biodiesel compared to palm and Jatropha. The resource depletion of an analyzed ethanol project that utilized cane sugar derived bagasse ranged between 0.003 MJ/kg of bioethanol (Rocha et al. 2014), and the fossil resource depletion estimated for microalgal biodiesel was found to be 3.9 MJ/100 kg of biodiesel, much higher than the ADP (fossil fuel) estimates of the current study (2.60 MJ/100 kg of biodiesel). Lifecycle assessment of biogas production using microalgae as feedstock showed an ADP primarily influenced by grid-based electricity spent on harvesting microalgae [22]. Lifecycle impact categories for different terrestrial and microalgal biodiesel are given in Table 4. Earlier studies have also demonstrated a 45% less consumption of abiotic resources in biodiesel than in conventional fossil fuel [18].

3.4.3 Human Toxicity Potential (HTP)

Human toxicity in biodiesel production is significantly contributed by the use of chemicals, heat, and electricity during its production, and it is expressed as 1, 4 dichlorobenzene equivalent (1, 4 DB eq). In India, coal is the primary source of electricity production that contributes to the excessive release of heavy metals and hydrogen fluoride during coal processing. In palm and Jatropha biodiesel, the use of fertilizers, herbicides, and insecticides mandate electricity during its production, which is reflected as the prime impact category during lifecycle impact assessment. The HTP of palm biodiesel production was found to be the maximum (1556 kg 1,4-DB eq/FU), followed by Jatropha (481 kg 1,4-DB eq/FU), and the least HTP was

Table 4 Lifecycle impact categories for different terrestrial and microalgal biodiesel

Name	Palm biodiesel	Jatropha biodiesel	Algae biodiesel	Unit
	Impact result	Impact result	Impact result	
Abiotic depletion	0.0225	0.00708	1.64E-07	kg Sb eq
Marine aquatic ecotoxicity	2.37E + 06	5.75E + 05	18.57	kg 1,4-DB eq
Acidification	46.84	13.98	0.0001	kg SO_2 eq
Ozone layer depletion (ODP)	1.06E-03	3.38E-05	2.14E-09	kg CFC-11 eq
Freshwater aquatic ecotoxicity	1952.72	309.17	0.0098	kg 1,4-DB eq
Eutrophication	12.83	5.17	3.34E-05	kg PO_4 eq
Terrestrial ecotoxicity	468.20	4.29	6.04E-05	kg 1,4-DB eq
Photochemical oxidation	5.24508	3.08	2.60	kg C_2H_4 eq
Human toxicity	1556.2	481.79	0.01	kg 1,4-DB eq
Abiotic depletion (fossil fuels)	8.33E + 04	6169.95	0.20	MJ
Global warming (GWP100a)	6904.05	714.50	0.018	kg CO_2 eq

observed in microalgal biodiesel (0.01 kg 1,4-DB eq/FU). This negligible environmental impact of microalgal biodiesel could be attributed to the absence or non-use of toxic agricultural chemicals during microalgal cultivation.

3.4.4 Environmental Ecotoxicity Potential

Environmental ecotoxicity is calculated as three stand-alone impact entities that affect marine, freshwater, and land. It is defined as the assessment of maximum tolerable concentrations of toxic elements in water that disrupt the ecosystem's sanity through emission of toxic heavy metals to the receiving ecosystem. It provides a method to evaluate the toxic substances' fate, exposure, and effects on the environment. The damage caused by such toxic chemicals to the environment would be biodiversity loss and species extinction. The marine aquatic and freshwater ecotoxicity of palm biodiesel was the highest with 2.37E + 06 kg 1,4-DB eq/FU and 1952.7 kg 1,4-DB eq/FU, respectively. Jatropha and microalgae's impact was relatively lower compared to palm due to its environmental competitiveness towards lesser use of agrochemical inputs for its growth and sustenance.

3.4.5 Acidification Potential (AP)

Intergovernmental Panel on Climate Change (IPCC) has categorized sulfur oxides (SO_x), ammonia (NH_3), and nitrogen oxides (NO_x) as potential acidic gases that react with water to produce acid rains [19]. It is expressed using a reference unit kg SO_2 eq. In the present study, the acidification potential of palm biodiesel was found to be 46.8 kg SO_2 eq/100 kg of biodiesel. Earlier studies have shown that Jatropha biodiesel's acidification potential was 5850 kg SO_{2e}/100 kg of biodiesel [5] which is way much higher compared to the present study (13.9 kg SO_{2e}/kg of biodiesel). In yet another study [17] an ADP of 1380 kg SO_{2e}/100 kg of soybean biodiesel was estimated. The acidification potential of microalgal biodiesel was estimated to be 0.023.4 kg SO_{2e}/kg of biodiesel produced, with impact level greater than the value estimated in this present study (0.0001 kg SO_2/kg of biodiesel) [21].

3.4.6 Eutrophication Potential

Eutrophication refers to the chemical nutrients build-up in an ecosystem, leading to excessive plant and algal productivity and severe deterioration in water quality and animal populations. Eutrophication potential in the lifecycle of biodiesel production is mainly due to upstream emissions of nitrogen and phosphorus to ground and surface waters and through ammonia and NO_x emissions to air as a result of fertilizer usage. Wastewater utilization for algal growth is considered credit for reducing the environmental impacts as N and P uptake by microalgae during its development reduces eutrophication from the environment. The eutrophication potential of the present study ranged from 3.34E-05 to 12.83 kg PO_4 eq/100 kg biodiesel.

3.4.7 Photochemical Oxidation Potential (POCP)

The photochemical oxidation potential is otherwise known as photochemical ozone creation potential, which implies the potential of certain toxic gases such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), ammonium, nitrogen, and sulfur oxides (NO_x and SO_x) formed as a result of the reaction between VOC's and NO_X in the presence of heat and sunlight. It is expressed in reference units as equivalents of ethylene (kg C_2H_4 eq). POCP was highest once again for palm biodiesel (5.24 kg C_2H_4 eq/kg biodiesel), attributed to the fertilizer input during its cultivation and the use of hexane during its oil extraction. The POCP for microalgal biodiesel was found to be negligible as the use share of hexane is the least (2.95 kg/ton of biomass). An earlier study has shown the photochemical oxidation potential was heavily influenced by the use of hexane when Jatropha, microalgae and soybean were used as biodiesel feedstocks with 28.0, 26.9 and 33.1 kg C_2H_4 eq. per 100 kg of biodiesel due [21].

3.4.8 Ozone Layer Depletion Potential (ODP)

All halogenated gases in their chlorinated and brominated forms, like CFCs, HCFCs, and other halons, can cause potential hazard to the atmospheric ozone layer and reduce its capacity to block the harmful UV (ultraviolet) radiation from penetrating into the earth's atmosphere. The ozone depletion potential of different gases is expressed using chlorofluorocarbon–11 as a reference unit (kg CFC-11 eq). The ozone depletion potential of biodiesel is significantly lesser than the conventional fossil diesel, as the use of biodiesel can reduce the dependence on the extraction of crude oil, a primary source of the impact that aggravates the depletion of ozone to a large extent. In the present study, the ODP was the least for microalgal biodiesel (2.14E-09 kg CFC-11 eq/FU) and the maximum for palm biodiesel (1.06E-03 kg CFC-11 eq/FU). Thus, microalgal biodiesel has shown proven benefits through better performance by exhibiting the lowest environmental footprints among terrestrial feedstock-based biodiesel.

3.4.9 Global Warming Potential (GWP 100a)

Global warming potential refers to the ability of toxic greenhouse gases to alter the global temperature over a defined time horizon. GWP 100a refers to the changes in climatic conditions expressed for a time horizon of 100 years. Its reference unit is kg CO_2 equivalent. Global warming causes adverse and irreversible effects, primarily due to releasing greenhouse gases like NO_x, SO_x and CO_2, and CH_4 [30]. For assessing the global warming potential of each feedstock, the methane and nitrogen oxide emissions from fertilizer production were transformed as $kgCO_{2e}$ (Carbon dioxide equivalents) by considering the global warming potential (GWP) of each gas into its equivalent factors: GWP = 32 for CH_4, GWP = 298 for N_2O and GWP = 1 for CO_2, respectively, for a time horizon of hundred years [8]. For the estimation of life cycle inventory, the energy inputs and outputs from each unit operations that are involved in the conversion of oil into biodiesel were considered as impacts in addition to the ancillary energies spent on critical energy and chemical components such as diesel, electricity, production of chemicals such as sodium hydroxide (NaOH), herbicides (Glyphosate, Paraquat), insecticides and chemicals (methanol, and hexane) and fertilizers (ammonium nitrate, monoammonium phosphate). The global warming potential of palm, Jatropha, and microalgal biodiesel were 6904 kg CO_{2e}, 714 kg CO_{2e}, and 0.018 kg CO_{2e} per functional unit of 100 kg biodiesel, respectively. The GWP of Jatropha and microalgal biodiesel for an operating unit of 1 MJ biodiesel produced in an earlier study had shown 1.5E-02 and 1.1E-02 kg CO_{2e}, respectively [21].

3.5 Direct Savings in GHG Emission

The direct savings in GHG emission is calculated as the ratio between the decrease in GHG emissions while using biodiesel in the place of fossil diesel's GHG emission. The environmental burden that are potentially reduced due to CO_{2e} emission reduction is expressed as direct savings while using biodiesel in the place of conventional petroleum-based diesel. The use of alternate green renewable energies in the place of conventional fossil diesel would result in GHG emission mitigation that is commonly expressed as percentage (%).The use of microalgal biodiesel by replacing petroleum-based fossil diesel has shown a 95% direct savings in GHG emissions. Similarly, palm and Jatropha biodiesel had shown a potential reduction in GHG emissions of about 84 and 91% respectively in the form of direct GHG savings. An earlier study that assessed the lifecycle emissions from a microalgal cultivation system that operated in a hybrid mode exhibited a 42% reduction or direct savings in GHG emission [1]. Similarly, *Chlorella vulgaris* derived biodiesel that were cultivated in a raceway pond showed a 78% direct savings in GHG emission when microalgae derived biodiesel was replaced with conventional fossil diesel. Another study that utilized palm and soybean biodiesel has shown a potential GHG emission reduction of 88% and 70% when fossil diesel was replaced with vegetable oil-based biodiesel [3, 21].

4 Conclusions

The environmental footprint assessment of palm, Jatropha, and microalgal biodiesel provided essential insights into the life cycle emissions in each feedstock conversion into biodiesel. Analyses demonstrate higher energy and GHG emissions for palm than Jatropha and microalgae. Microalgal biodiesel was promising from a lifecycle perspective, mainly due to its decarbonizing ability through carbon sequestration during cultivation with minimal fertilizer inputs and fossil fuel usage reduction in the logistics and transport sector. Assessing the life cycle impacts aided in the estimation of the potential environmental deteriorations posed by the use of conventional fossil fuel use and the ecological footprint enhancement possible with diverse biodiesel feedstock. However, challenges exist in microalgal biodiesel production due to higher energy costs associated with harvesting of microalgal biomass and its subsequent downstream operations. The present study demonstrated the economic feasibility of microalgal cultivation over terrestrial land-plants-based biodiesel production. The results of the present study indicate a considerable reduction in GHG emissions in the form of direct savings of up to 95% when biodiesel produced from microalgae is used as a replacement to the conventional fossil diesel.

Moreover, the use of wastewater during its cultivation would render additional environmental benefits of wastewater remediation apart from GHG emission reduction, which gives potential scope for decentralized bioremediation prospects through microalgal bioreactors. A higher NER (4.2) for microalgal biodiesel production proves its economic viability, evident through negligible energy requirements for various upstream and downstream operations. Thus, the environmental footprint assessment of diverse feedstocks demonstrates the sustainability of the microalgal biofuel production system through sustainable bioresource utilization and bioenergy production, which helps in addressing the most pressing climate change concerns.

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