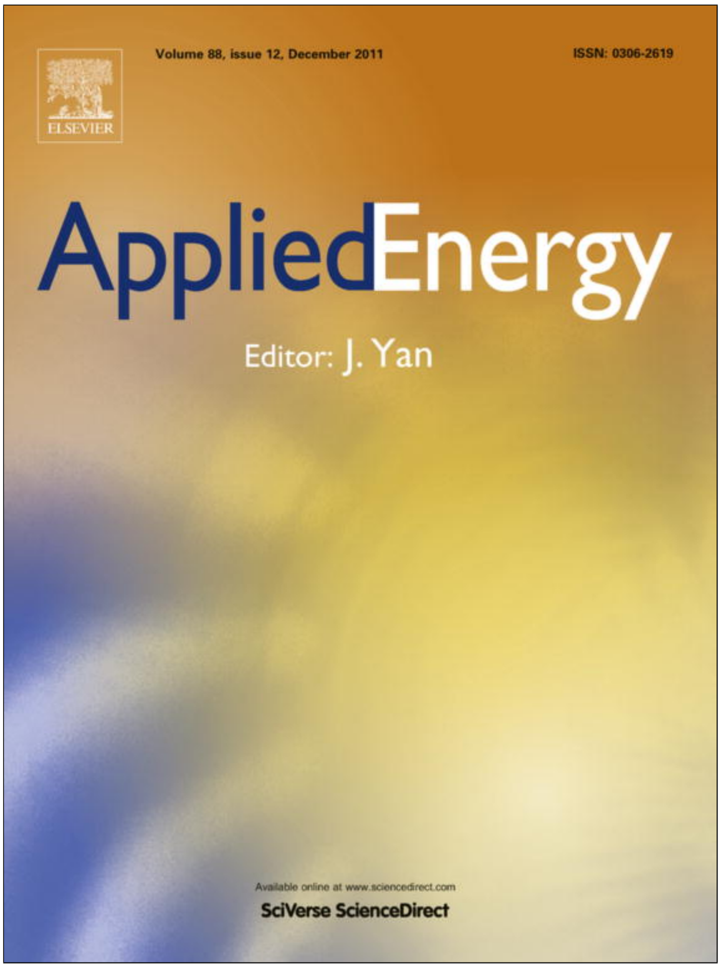
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Life cycle assessment of small-scale high-input Jatropha biodiesel production in India

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ABSTRACT

In the current scenario of depleting energy resources, increasing food insecurity and global warming, Jatropha has emerged as a promising energy crop for India. The aim of this study is to examine the life cycle energy balance for Jatropha biodiesel production and greenhouse gas emissions from post-energy use and end combustion of biodiesel, over a period of 5 years. It's a case specific study for a small scale, high input Jatropha biodiesel system. Most of the existing studies have considered low input Jatropha biodiesel system and have used NEB (Net energy balance i.e. difference of energy output and energy input) and NER (Net energy ratio i.e. ratio of energy output to energy input) as indicators for estimating the viability of the systems. Although, many of them have shown these indicators to be positive, yet the values are very less. The results of this study, when compared with two previous studies of Jatropha, show that the values for these indicators can be increased to a much greater extent, if we use a high input Jatropha biodiesel system. Further, when compared to a study done on palm oil and Coconut oil, it was found even if the NEB and NER of biodiesel from Jatropha were lesser in comparison to those of Palm oil and Coconut oil, yet, when energy content of the co-products were also considered, Jatropha had the highest value for both the indicators in comparison to the rest two.

1. Introduction

In today's milieu of rapid economic development energy, environment and food security are indeed the most talked about topics. When it comes to concern over these issues, India is not secondary to any other nation. Even the recent oil and gas discoveries in India have failed to keep pace with the energy demand. With high rate of economic growth, and 15% of the world's population, it is currently dependent on imports for 68% of its oil use and is expected to become the fourth largest net importer of oil in the world by 2025, behind the United States, China, and Japan [1].

Petroleum-based fuels are limited reserves concentrated in certain regions of the world. Biodiesel fuels are attracting increasing attention worldwide as a blending component or a direct replacement for diesel fuel [2]. In comparison with the conventional diesel fuels, biodiesel is 100% renewable [3]. It has better exhaust gas emission quality and is biodegradable [4]. Rapeseed and Sunflower in Europe, Soybean in USA and Sugarcane in Brazil are being used as raw materials for producing biofuels. However, for the country like India with world's 15% population, food security is a major concern which restricts these options, as most of the biofuels used today are from food plants which are cultivated on fertile lands. Further, the diesel fuel use in India is about five times higher than gasoline fuel [5]. So, renewable fuels, particularly biodiesel, should get more attention in India.

In the view of the above, non-edible oil from crops like Jatropha (*Jatropha curcas*) and Pongamia (*Pongamia pinnata*) are preferred for bio-diesel production, and the trend is expected to continue. Especially *J. curcas* has gained attention in tropical and sub-tropical countries and has spread beyond its center of origin [6]. Even the planning commission of India has recommended cultivation of Jatropha for its biofuel projects [7]. Initially, it was said that it could even be grown on wasteland with minimal care and minimal requirement of water and nutrients [8], but without commercial yield [9]. From experiences with Jatropha projects, it is now clear that it performs much better with adequate access to soil nutrients and water [10]. Adding some fertilizer or manure is needed to maintain good long-term seed yields, because Jatropha is not a Nitrogen-fixing crop, and substantial Nitrogen is removed with the harvesting of the seeds [10]. In spite of efforts made by Indian government, its growth did not pick up [11]. According to one study the reason for this was that basic agronomic properties of Jatropha were not thoroughly understood by many [12]. However

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later on, it was found that for a good and profitable yield, proper and careful agricultural practices are important, these include proper irrigation and fertilizing [13,14]. Another study on land availability and biomass production potential in India also supported that biomass productivity can be increased through use of genetically superior planting material, application of fertilizer and manure, by adoption of soil and water conservation practices along with water application in the areas with less rainfall [15].

1.1. Goal, scope and system boundaries

All the activities in the production of biodiesel are energy intensive, due to the virtue of which they also generate greenhouse gases, and therefore, a viability study is required to find out the suitability of the crop as a biodiesel feedstock. Many studies have already been done on different feedstocks for biodiesel [16–22], and most of them [17–19,22] have used either Net Energy balance (difference of energy output and energy input) or Net energy ratio (ratio of energy output to energy input) or both of them, as indicators for estimating the viability of the systems. In the same manner there are viability studies already done on Jatropha [23,24].

However, most of them have considered low input (with minimal care and minimal use of materials) Jatropha cultivation system. Many of them have even shown these indicators to be positive, yet the values are very less. We need to find out if we can further increase the values for these viability indicators i.e. Net energy balance and Net energy ratio, by using a high input (with adoption of the best available management practices, which include proper irrigation, pruning, weeding, and use of fertilizer and water, etc.) Jatropha cultivation system. An increase in the input of fertilizer and irrigation decreases the energy use efficiency [25]. And this increase can only be compensated by higher energy returns which are possible only if the yield can be increased to a much higher extent. For the same, we have compared the results of the current study with two previous studies [23,24] on low input Jatropha biodiesel system and one previous study on Palm oil biodiesel system which also includes Coconut biodiesel system [18].

Therefore, with reference to the above background this case specific life cycle study aims at finding out the life cycle energy balance and greenhouse gas emissions from the energy use for a small scale (1 hectare) but high input Jatropha biodiesel system. The functional unit of the study is one hectare.

The system includes Jatropha cultivation, oil extraction, biodiesel production and its end use in transportation. Focus is mainly on primary agricultural practices [26]. Non-renewable energy requirement for only fertilizer use during Jatropha cultivation has been included as fertilizer production is highly energy intensive process. The non-renewable energy requirements for items, with many years of useful life, have not been considered in this study. Instead of artificial pesticides, biopesticides were used during the cultivation of Jatropha. Though the Jatropha seeds used were not genetically modified but a proper care was taken during selection of seeds to see that they are of the best quality.

1.2. Jatropha biodiesel

Jatropha traces its roots to Central America, Mexico and Brazil [27] and is now grown in most parts of the tropical and sub tropical regions of the world [6]. It contains 170 known species [28].

It is also known as Physic Nut and Ratanjyot. It is a shrub with a height of 6 m (20 ft) and can be grown in deserts as it is resistant to even high degree of aridity. Jatropha has a life expectancy of 50 years. The plant develops a deep taproot and initially four shallow lateral roots. The taproots stabilize the landslides and prevent and control soil erosion and reclaim wasteland. The leaves are smooth, 4–6 lobed and 10–15 cm in length and width. The plant is monoecious and the terminal inflorescences contain unisexual flowers. The ratio of male to female flowers ranges from 13:1 to 29:1 and decreases with the age of the plant [27]. Jatropha seeds contain 27–40% oil and are used to produce a high-quality biodiesel fuel, usable in a standard diesel engine [29]. Oil contains sterols and triterpene alcohols which is responsible for the insecticidal properties [30]. Jatropha can even grow in gravelly, sandy and less fertile soil but should be well drained as it cannot withstand standing water. Using special techniques of plantation, it can even be grown and planted in soil with pH as high as 8.5–9.5 [29].

However there are studies, which contradict the claims of successful Jatropha plantation in arid and semi-arid regions without the need of any irrigation [31]. According to one, for good yield of up to 5 ton dry seed/ha/yr an optimal rainfall of 900–1200 mm is required and if not, can be complemented with additional irrigation. Jatropha is frost sensitive and can die in extreme and prolonged frost conditions. It grows well in humid regions with average temperature of 20–28 °C. Therefore, one should be very careful while doing site selection for Jatropha plantation [31]. Another study on response of Jatropha to water deficit showed that yield of Jatropha seed and extracted oil decreased as the water application rate decreased [32].

For proper growth, the initial years of Jatropha require more frequent irrigation which decreases later on. Although, it can survive in dry areas too, but proper irrigation is a must for obtaining good amount of fruits and seeds. The plants need more care with frequent weed removal, a must activity up to the age of 3 months after which the plant can take care of itself. Once the ripe fruits are harvested, proper pruning should be done as it increases the number of lateral branches and thus produces more fruits. Pruning is required after the age of 3 years and should be done at a height of 65 cm from the surface. Proper use of fertilizers, like DAP (Di Ammonium Phosphate), NPK (Nitrogen, Phosphorous and Potassium) and gobar (cow dung) gives good yield [29]. Once the ripe black colored seeds are harvested, they are decorticated and pressed to release the oil. The seed cake and the oil are separated, after which seed cake can be used to produce biogas. The cake can also be used as a combined fertilizer and biopesticide [21].

The neat Jatropha oil has higher density, viscosity and flash point in comparison to petroleum diesel. These properties of biodiesel cause problem during use in diesel engine as it leads to slow atomization, starting problem and engine choking [33].

In a combustion analysis of Jatropha based biodiesel, it was found that various properties of oil, obtained from Jatropha, can be improved by the process of transesterification, thus, making it comparable to petroleum diesel. It lowers the flash point, decreases the viscosity, thus making it suitable for use in diesel engine [34]. In the process of transesterification, the triglycerides of Jatropha oil and alcohol (methanol or ethanol) are reacted in the presence of catalyst ($NaOH/KOH/CH_3ONa/CH_3OK$). Methoxide catalysts (CH_3O-Na/CH_3OK) perform better. Transesterification is sensitive to parameters, like free fatty acids (FFAs), water content, molar ratio of alcohol to oil, catalyst, reaction temperature and stirring, all of which are important to achieve a high quality biodiesel which meets the regulatory standards [35,36].

The properties of biodiesel from Jatropha and its blends with petro diesel are in comparison with ASTM biodiesel standards. Because of high oxygen content, though the calorific value is a little lower than petro diesel, but then, it helps in complete combustion. Table 1 gives the various properties of Jatropha biodiesel in varying blends with petroleum diesel [37].

Use of biodiesel in place of diesel cuts down the emissions of unburned hydrocarbons, carbon dioxide, carbon monoxide, sulfates, polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons, ozone-forming hydrocarbons, and

Table 1
Various properties of Jatropha biodiesel in varying blends with petroleum diesel [37].

SN	Fuel blend	Density (kg/m^3)	Calorific value (kJ/kg)	Viscosity (cSt)	Flash point (°C)	Cloud point (°C)	Pour point (°C)
1	Diesel	850	44,000	2.87	76	6.5	3.1
2	JB20	852	43759.5	3.02	88	6.9	3.3
4	JB50	857	43,323	3.59	113	7.3	3.4
7	JB100	873	42,673	4.23	148	10.2	4.2

particulate matter (75–83%). Reductions in net Carbon dioxide emissions are estimated at 77–104 g/MJ of petroleum diesel displaced by biodiesel. These reductions increase as the amount of biodiesel blended into the diesel fuel increases. However, there is a slight increase in the NO_x emissions with commercial biodiesel compared to the petroleum diesel [2].

2. Methodology

Life cycle Assessment (LCA) has been used for the analysis of energy balance and greenhouse gas emissions from the energy use for Jatropha based biodiesel production and its use in internal combustion engine for transportation. In LCA, a product is followed from its cradle to its grave. Natural resource use and pollutant emission are described in quantitative terms [38]. This study incorporates all the major activities and various inputs/outputs in every stage of Jatropha biodiesel production. The entire life cycle has been divided into three major stages:

i. Jatropha cultivation.
ii. Oil extraction and oil processing.
iii. End combustion of biodiesel.

2.1. Method of data collection

Agreed that a lot of research has already been done on Jatropha, however, the documentation on every aspect of it is not proper. Therefore, the data and the facts about Jatropha biodiesel have been taken from three sources

i. Various studies and research papers.
ii. The detailed information about various inputs during Jatropha cultivation stage has been taken from a primary data collected from 100 acres of plantation, in Ettayapuram village of Tamil Nadu, by a company called Bharat Jatropha Garden Estate Pvt. Ltd.
iii. Parallel experiments were undertaken in Biodiesel lab at University of Petroleum and Energy Studies, Dehradun, India for various biodiesel related inputs/outputs and properties.

2.2. Assumptions

a. $CO_{2.}$ emissions from every stage of Jatropha life cycle have been considered, while N_2O emissions have only been considered from fertilizer use.
b. Greenhouse gas emissions from human activities i.e. from physiological activities of human beings at work have not been considered as our major concern is the use of depleting fossil fuels and electricity use.
c. Greenhouse gas emissions from only mineral fertilizer has been considered and not from organic fertilizer.
d. According to Indian centre for science and environment in 2007–2008, 78% of India's urea production came from natural gas as the feedstock and rest from fuel oil and naphtha contributing 11% each [39]. Since the maximum urea in India is produced from natural gas so have assumed 100% urea production from natural gas.
e. Electricity production has been assumed to be from 100% fossil fuel fired power plants in India. (Fossil fuel share in electricity generation in India is 64%. Coal is by far the most important fuel source for power generation, with 52% of electricity generated in coal-fired power plants and rest from natural gas (11%), oil (1%), hydro (23%), nuclear (3%), and renewable (10%) [40].)

2.3. Calculations and parameters considered for study

The various parameters considered for this study are given in Table 2.

2.3.1. Calculation for CO_2 emissions from biodiesel

The CHN (Carbon, Hydrogen and Nitrogen content) analysis, conducted in biodiesel lab at University of Petroleum and Energy Studies, gave 0.78 kg of Carbon/kg of biodiesel.

The formula used for CO_2 emissions is:

$$\text{Carbon dioxide emission from fuel combustion} = \text{Fuel combusted} * \text{Carbon content coefficient} * \text{Fraction oxidized} * (44/12)$$

where 44 is molecular weight of CO_2 and 12 is molecular weight of carbon.

If we consider fraction oxidized = 1 (The use of a 1.00 fraction oxidized for fuel combustion follows the guidance from Chapter 3 of the 2006 IPCC, guidelines for National Greenhouse Gas Inventories [46]).

$$CO_2 \text{ emission from 1 kg of biodiesel} = 1 * 0.78 * 1 * (44/12) = 2.86 \text{ kg of } CO_2$$

2.3.2. Calculations for direct N_2O emissions from fertilizer applied [47]

$$\text{Nitrous oxide emissions} = \text{FC} * \text{EC}$$

FC is the Fertilizer Consumption; EC is the Emission Coefficient = 17.68 kg/ton of fertilizer consumed [47]. (The emission coefficient represents the percent of nitrogen applied as fertilizer that is released into the atmosphere as nitrous oxide).

2.3.3. Calculation for NEB (net energy balance) and NER (net energy ratio)

$$\text{NEB} = \text{Total Energy Output} - \text{Total Energy Input}$$

$$\text{NER} = \text{Total Energy Output}/\text{Total Energy Input}$$

3. Jatropha cultivation at the identified site

3.1. Nursery raising

3.1.1. Polybags

Black poly-ethylene poly bags (weight per bag was 10 g) filled with soil (Equal quantity of sand, humus and soil, well mixed) were used to grow plantlets from seeds and cuttings in the nursery. It

Table 2
Various parameters considered for study.

Parameters	Value	Unit	References
Area under study	1	Hectare	
Weight of one polybag used in nursery raising	10	gram	
Spacing between plants	2∗2	meters	
Plant density	2500	Per hectare	
Density of diesel	0.85	kg/l	
Emission factor/ton plastic (LAND filled)	0.04	Mton CO_2E (metric ton carbon dioxide equivalent)	[41]
Specific energy consumption for urea production from natural gas from the best available technique	20.9	GJ/Mton	[39]
The average CO_2 emission during urea production from the various plants surveyed by Centre for science and environment	0.61	Mton CO_2/MT of urea	[39]
CO_2 emissions from diesel at oxidation factor of 0.99	10.1	kg/gallon	[42]
1 US gallon	3.79	liters	
Calorific value of diesel	44,000	kJ/kg	[37]
According to Ernest Orlando Lawrence Berkeley National Laboratory in 2001–2002 the average energy consumed per Mton of fertilizer produced in India (nitrogen and phosphorous fertilizers)	34.20	GJ/Mton of fertilizer	[43]
Effective CO_2 emission factor for fuel oil	77.4	Mton CO_2/TJ	
Effective CO_2 emission factor for naphtha	73.3	Mton CO_2/TJ	
The world average is 2.1 Mton CO_2/Mton ammonia for natural gas feedstock and 4.1 Mton CO_2/Mton ammonia for other feedstocks. And since natural gas forms 50% of feedstock and rest as another 50% so the average is	3.1	Mton CO_2/MT ammonia	[39]
Average specific energy consumption for ammonia from all the feedstocks	10.9	Gcal/Mton	[44]
CO_2 emission from electricity	980	gCO_2/kW h of electricity produced	[40]
Fossil fuel energy per 1 kW h electricity, considering the conversion efficiency (calculated as per the given data in the literature)	10.69	MJ	[45]

was observed that if watered every 3 days, it accelerated the germination and prepared the plants to be planted in the fields just at the age of 3 months. With good quality seeds the germination rate was about 70%.

At 70% germination rate number of polybags required for getting 2500 well germinated plants was estimated to be 3500 with total emission of 0.0014 Mton CO_2E (metric ton carbon dioxide equivalent), if land filled.

3.1.2. Fertilizer

Along with sand, humus and soil, 25 kg (0.025 Mton) of Urea was also used for the nursery raising for plantation in field of one hectare. Therefore, energy required for 0.025 Mton of Urea was estimated to be 0.52 GJ with 0.02 Mton of CO_2 emissions. The direct nitrous oxide emission from the use of Urea was estimated to be 0.44 kg.

3.2. Plantation in field

At the age of 3–4 months the small plantlets were planted in the prepared field, at the beginning of the rainy season, with spacing of 2∗2 m with plant density of 2500 per hectare.

3.2.1. Tilling

Field preparations involved tilling and weed removal. Tilling loosened the soil for plantation as well as uprooted the weeds too. It was found that to till one hectare of land a tractor normally took 2 h and consumed 12 l of diesel. Therefore, the total energy consumed was estimated to be 0.45 GJ and with 0.03 Mton of CO_2 emissions.

3.2.2. Pit preparation and plantation

After the field was tilled and weeds were removed, pits were dug. It was seen that 150 pits could be dug per day per man, working for 8 h a day. So, 2500 pits required 133 man hours. Thereafter the plantlets from the nursery were planted in these pits. In 8 man hours, 300 plants could be planted. Accordingly, it took total of 67 man hours to plant 2500 plants. Since both the activities of pit preparation and planting were done manually, so no fossil energy was consumed. Even if plantation is done on a large scale, due to availability of inexpensive labor in India, it can still be done manually.

Table 3
Energy share and CO_2 emissions from each feedstock in production of 0.88 Mton of fertilizer (calculated based on data given in reference number [42]).

Feedstock	Energy required (GJ)	Amount of CO_2 emitted (Mton)
Natural gas	15	0.71
Naphtha	7.5	0.55
Fuel oil	3	0.23
Ammonia	4.5	0.31
Total	30	1.8

3.2.3. Fertilizer

For initial 2 years fertilizers were used every 6 months and once every year after fruiting. The mineral fertilizer used was Di Ammonium Phosphate (DAP). 500 g of cowdung (Gobar), mixed with 50 g of DAP, was fed per plant. Thus, for 2500 plants total of 0.88 Mton of DAP and 8.75 Mton of cowdung was required.

A lot of energy is consumed to produce fertilizers, which further depends on capacity utilization, feedstocks, plant age and technology. Energy use for 0.88 Mton of DAP was evaluated to be 30 GJ. The share of various feedstocks used to produce fertilizer in India is Natural gas (50): Naphtha (25): Fuel oil (10): External ammonia (15) [42]. Based on these values the share of each of the feedstock in production 0.88 Mton of fertilizer, and CO_2 emissions from them was evaluated which is given in Table 3. The direct Nitrous oxide emission from the use of DAP was estimated to be 15.47 kg.

3.2.4. Irrigation

Irrigation was done with the help of pipe attached to water tankers. For large scale plantation drip irrigation was found to be very costly, as a lot of pressure is required to maintain the water flow in the larger area. Excluding 4 months of rainy season, a minimum of 16 times irrigation was done for initial 2 years and two times every year later on. The size of pipe used to give water was 2.5 in. and10 l of water was given to every plant. Almost 5 l got wasted from moving from one plant to another, so an average

Table 4
Total yield per hectare for initial 5 years from Jatropha plantation in the identified site.

Plantation year	Seed yield/plant (kg)	Average yield/plant (kg)	Average yield/hectare (kg)
First	Nil	Nil	Nil
Second	0.2–0.4	0.3	750
Third	0.5–2	1.25	3125
Fourth	2–4	3	7500
Fifth	4–5	4.5	11,250
Total yield/hectare (kg)			22,625

of 15 l was considered per plant. Total 37,500 l of water per irrigation was estimated for one hectare of Jatropha plantation with 2500 plants. Accordingly, in the initial 5 years, 22 times irrigation was done. 5 l of diesel was consumed by the tanker per irrigation thus a total of 110 l (93.5 kg) of diesel was consumed during the initial 5 years. Therefore, total energy input was estimated to be 4.11 GJ with 0.3 Mton of CO_2 emissions.

3.2.5. Weeding, pruning and harvesting

Weeding was regularly done, till the plants became 3 months old. Even before planting in fields, the weeds were removed by tilling.

Pruning was also done on a regular basis, after the plants became 3 years old. It gave rise to many new branches and thus, more fruits.

Harvesting was labor intensive and was done manually. Considering that all the fruits of Jatropha do not ripe at the same time, mechanical harvesting was not found to be efficient. The ripe fruits of yellow and black color were picked by hands. Table 4 gives the total yield per hectare for the initial 5 years.

It was observed that one person could harvest at rate of 8 kg of dry seeds/h. Therefore, to harvest 22,625 kg of seeds, total of 2828 h of man work was estimated.

4. Oil extraction and oil processing carried out in the biodiesel lab

4.1. Seed processing

4.1.1. Decortication

After the Jatropha fruits were harvested they were decorticated i.e. fruit shells were removed to extract the seeds. Decortication was done mechanically. For the same a decorticator (made by Indian Institute of Technology, New Delhi) of 1.5 kW was taken with capacity of 150 kg/h. Therefore, the total time to decorticate all the seeds was estimated to be 151 h with energy use of 226.5 kW h (2.42 GJ) and 0.22 Mton of CO_2 emissions.

4.1.2. Seed pressing

It was found that after decortication the weight of the seeds became 60% of the original weight of corticated seeds. Therefore, at 60% of original weight, the weight of 22,625 kg corticated seeds was estimated to be 13,575 kg. Then the seeds were pressed for oil extraction. For this purpose a screw press expeller of 5.5 kW with capacity 50 kg/h was taken. The oil content of Jatropha seeds in a literature is given to be 38% [29]. Therefore, at 100% extraction efficiency the oil yield should be around 5158.5 kg. But with the screw press used, we obtained the oil yield of 4126.8 kg i.e. the extraction efficiency of almost 80%, and that too when the seeds were pressed twice. It was estimated that it would take almost 543 h (not considering the reducing weight of the seeds after each round of pressing) with energy use of 2986.5 kW h (31.9 GJ) and 4.39 Mton of CO_2 emissions.

4.1.3. Filtering of oil

After the above process, the oil was filtered using a filter press of 1.5 kW with capacity of 600 kg/h. Total time for filtering was estimated to be 7 h with energy use of 10.5 kW h (0.11 GJ) and 0.01 Mton of CO_2 emissions.

4.2. Oil processing

Energy use for transesterification of 1 kg of Jatropha oil was evaluated experimentally and then was used to estimate energy use for transesterification of 4126.8 kg of oil. Table 5 gives the total energy use during various steps of oil processing for converting it into biodiesel. Carbon dioxide emission for 22 GJ of energy use during oil processing was estimated to be 1.87 Mton of CO_2. Further, at 95% conversion efficiency, the total biodiesel yield was expected to be 3920 kg.

5. End combustion of biodiesel

Experimentally, it was found that combustion of 1 kg of biodiesel gave 41,238 kJ (0.04 GJ) of energy output. Thus, the total energy output from 3920 kg of biodiesel was estimated to be 161.65 GJ. And from calculation the total CO_2 emissions were found to be 11.21 Mton (11,213 kg).

6. Results and discussion

6.1. Net energy and CO_2 emissions result and full chain analysis

Fig. 1 shows the entire value chain of biodiesel production from Jatropha while Table 6 shows the stage wise energy input/output and CO_2 emissions per hectare during first 5 years of Jatropha life cycle. Total energy input during first 5 years of Jatropha plantation was found to be 93.51 GJ. The maximum energy input was during oil extraction and processing stage which is very clear from Fig. 2. The main factor resulting in excessive energy use during this stage was seed pressing, as the entire activity was done twice to extract the maximum oil from the seeds, yet could achieve only 80% extraction efficiency. It consumed almost 93% of the total energy input during oil extraction stage. The second energy intensive activity during this stage was oil processing in which transesterification alone consumed almost 50% of the total energy use followed by oil drying which consumed nearly 40% of the total energy input of the entire oil processing stage. During Jatropha cultivation stage the most energy intensive activity was the application of chemical fertilizers, as fertilizer production in itself is a very energy intensive process. Therefore, when reviewed in totality, the most energy intensive activity was seed processing followed by fertilizer application and oil processing, simultaneously.

It was estimated that end combustion of the entire biodiesel produced during first 5 years of Jatropha plantation, would release almost 161.65 GJ of energy, giving a net positive energy balance of 70 GJ, during that period and net energy ratio of 1.77.

Table 5
Energy use during various steps of oil processing for converting it into biodiesel.

Various steps in oil processing for converting it into biodiesel	Total energy input per unit kg in kJ	Total energy input for 4126.8 kg in GJ
Energy use for transesterification	2888	11.92
Energy use for washing	259	1.07
Energy use for drying	2256	9.31
Miscellaneous energy use for pumping unit	1.7	0.01
Total energy input		22

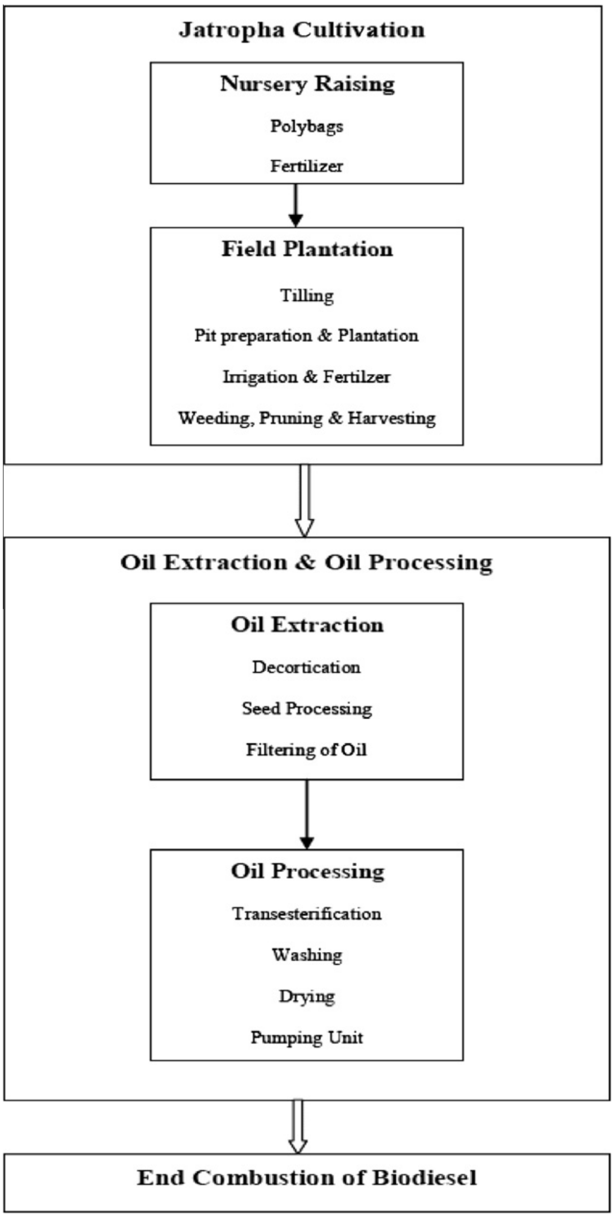

Fig. 1. Value chain of biodiesel production from Jatropha.

Fig. 3 shows that stage of oil extraction and oil processing emitted more CO_2 than Jatropha cultivation stage. It was so, because all the activities in this stage consumed a lot of electricity, which in India is produced from fossil fuels with a major share of coal in it. The major share of CO_2 emissions during Jatropha cultivation stage comes from the use of chemical fertilizers. Since fertilizer production is a very energy intensive stage so emissions should have been very high but it was not so, because the maximum amount of fertilizer produced in India is from natural gas, which is a clean fuel. The maximum CO_2 emission is from the end combustion of biodiesel.

The overall life cycle energy balance for first 5 years of biodiesel production from Jatropha was found to be positive, and will remain for the rest of Jatropha life. Our analysis showed that both NEB and NER will increase in the further years as the energy use during Jatropha cultivation stage will decrease because of lesser fertilizer and irrigation requirements.

6.2. Comparison with other studies

In a similar kind of case specific LCA of Jatropha biodiesel, a small scale, but low input Jatropha biodiesel system on wasteland in Allahabad, India was studied. This study evaluated life cycle energy balance for Jatropha biodiesel system over the rotation period of 20 years. It considered non-renewable energy requirement which included construction of all the machineries used in the Jatropha biodiesel production along with fertilizer, electricity and diesel production and use. The management practices included use of inorganic fertilizers only before the plantation establishment, while the biomass residues, produced during its life cycle, were brought back to the field. Irrigation was practiced only in extreme conditions when monsoon was late. The average yield was expected to be 1695 kg dry seeds per hectare, 275 kg crude Jatropha oil per 1000 kg seed with production of 97 kg of Jatropha biodiesel per hectare. Considering the energy content of only Jatropha biodiesel and excluding that of co-products, the net energy gain was 78.2 kJ per FU (release of 1 MJ in a car engine fueled by Jatropha biodiesel) and net energy ratio was 1.35 [23].

When this was compared with the current study, it was found that average yield per hectare of the current study was eight times to that of the literature study with low input system. Even if we include the non-renewable energy requirement given in this literature, the energy balance remains higher.

Another study was done on energy analysis for Jatropha plantation system for biodiesel production in Thailand. The management practices included use of fertilizer once every year with irrigation. Details of irrigation were not given in the literature. For one hectare perennial plantation over a period of 20 years, the total energy use was about 940 GJ. Total energy output, including all the co-products like crude glycerin, peel, seed cake and wood was 5660 GJ. While that from biodiesel alone was less than 1500 GJ [24]. The net energy ratio of this study was 1.42, which was found to be lesser than that of the current study.

As per our analysis, with the passage of time the NEB and NER will increase for the current study as the energy use during Jatropha cultivation stage will decrease because of lesser fertilizer and irrigation requirements in the ensuing years. Thus, widening the gap between the values of NEB and NER for the current study and the two studies mentioned above.

Table 6
Stage wise energy input/output and CO_2 emissions per hectare during first 5 years of Jatropha life cycle.

		Energy input/output (GJ)	CO_2 emissions (Mton)
Jatropha cultivation	Nursery raising including use of polybags and fertilizer	0.52	0.02
	Tilling,	0.45	0.03
	Fertilizer during field plantation	30	1.8
	Irrigation	4.11	0.3
Oil extraction and oil processing	Decortication	2.42	0.22
	Seed pressing	31.9	4.39
	Filtering of oil	0.11	0.01
	Oil processing	22	1.87
Total energy use/CO_2 emissions		91.51	8.64
Total energy output during end combustion of Biodiesel		161.65	11.21
NEB/total CO_2 emissions		70	20
NER		1.77	

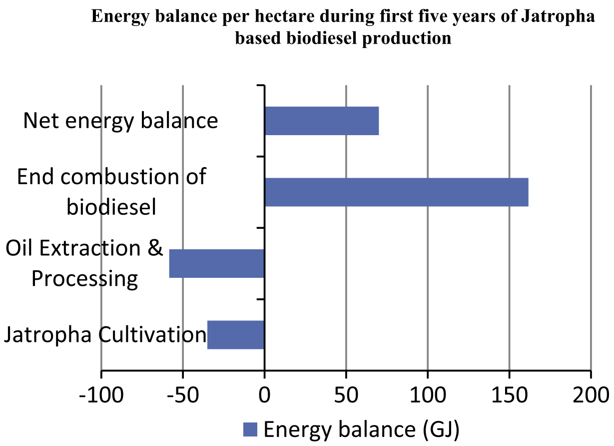

Fig. 2. Energy balance per hectare during first 5 years of Jatropha based biodiesel production.

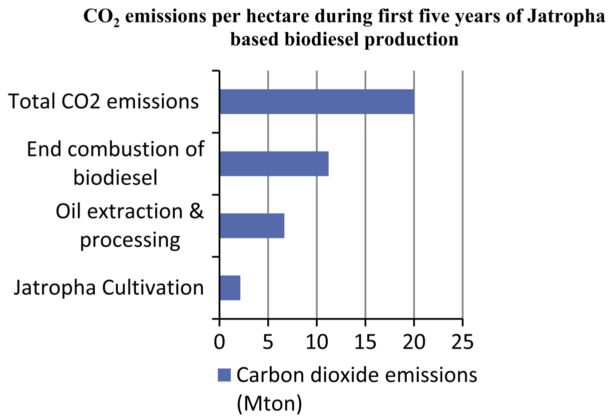

Fig. 3. CO_2 emissions per hectare during first 5 years of Jatropha based biodiesel production.

Studies of another full chain energy analysis of biodiesel production, but this time from Palm oil, clearly showed that even if the NEB and NER of biodiesel from Jatropha were lesser in comparison to those of Palm oil and Coconut oil, yet when energy content of the co-products were also considered, Jatropha had the highest value for both the indicators in comparison to the rest two [18].

Table 7 shows the NEB values for all the compared studies with the information of the year and country done.

7. Conclusions

During first 5 years, the balance energy available for useful work was found to be 70 GJ, which was 43% of the total energy produced by Jatropha based biodiesel during that period, while rest 57% of it was consumed during Jatropha based biodiesel production. If we also include the energy content of the byproducts, the energy balance, as well as energy ratio will increase further.

The net energy balance and net energy ratio can further be increased by manufacturing such a screw press which may provide almost 80% extraction efficiency at very first pressing or by using better and more efficient oil extraction methods. Further, if the plantation field is nearer the nursery, the polybags can totally be avoided. The decreased energy input will automatically take care of the greenhouse gas emissions.

Since, the production of chemical fertilizers is energy intensive, a further study is required to find out the effect on the productivity of Jatropha plants, if chemical fertilizers are totally or partially replaced with organic fertilizers. Even the seed cake, formed during the end of biodiesel production from Jatropha, can be used as organic fertilizer.

When the values for NEB and NER were compared with the values of other low input Jatropha biodiesel systems, these were found to be higher than those. It can be observed that these values will further increase on including the energy content of the co-products formed during the life cycle, which is very well supported by the study done on the Palm oil and Coconut oil. A few of the co-products include wood and seed cake. The wood content and seed cake can be increased by regular pruning as it gives rise to more branches and thus more seeds, which is further enhanced by proper fertilizer and irrigation practices. While our analysis also

Table 7
NEB values of the compared studies.

Year of study	Plant	Country	Crude oil yield (kg/ha)	NER (considering energy yield from biodiesel alone)	References
Current study	Jatropha	India	2052 (in the 5th year)	1.77 (for initial 5 years)	
2010	Jatropha	India	466 (mean yield over 20 years)	1.35 (for 20 years' lifetime)	[23]
2010	Jatropha	Thailand	1932 (in the 6th year)	1.42 (for 20 years' lifetime)	[24]
2009	Palm	Thailand	2800 (mean yield over 25 years)	2.42 (for 25 years' lifetime)	[18]

showed that both NEB and NER will increase in the further years, as the energy use during Jatropha cultivation stage will decrease because of lesser fertilizer and irrigation requirements.

It has been found that excessive use of Nitrogen fertilizers increase Nitrous oxide emissions, which have very high global warming potential [48]. But it can be reduced by better utilization of Nitrogen fertilizer and increased use of organic fertilizers. Appropriate crop management practices, which lead to increase in N use efficiency and yield, hold the key to N_2O mitigation. Application of nitrate (NO_3–N) fertilizers in crops with aerobic conditions and ammonium (NH_4–N) fertilizers in wetland crops, also helps reducing the N_2O emission. Another innovative technology is the use of nitrification inhibitor that curtails the nitrification process, thus reducing soil emissions [49].

There are many oil processing techniques available, like transesterification using base catalyst, acid catalyst, biocatalyst catalyst and catalyst-free supercritical alcohol method. The production of biodiesel, using a biocatalyst and catalyst-free supercritical alcohol method, eliminates the disadvantages of the alkali process by producing product of very high purity with less, or no downstream operations of washing and drying, which is a very energy intensive process. But the biocatalyst process has not yet been implemented in an industrial scale due to certain constraints, like enzyme inhibition by methanol, exhaustion of enzyme activity and high cost of enzymes. Super critical process takes place at very high temperatures, thus requiring more energy [50]. So, further research needs to be done to overcome such problems, and come up with a less energy intensive oil processing technique.

It can be concluded from the results that there is a huge potential for increasing the overall productivity of Jatropha biodiesel system by adopting high input practices with proper allocation of resources at right time and with proper care.

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