Comparative life cycle assessment of biodiesel from algae and jatropha: A case study of India

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HIGHLIGHTS

• Algae could be an alternative source for biodiesel due to Indian meteorological and geographical conditions.
• The environmental performance of algae and jatropha biodiesel could be superior to fossil diesel.
• Seed yields have a significant impact on the environmental performance of jatropha biodiesel production.
• Efficient utilization of co-products is essential for algae biodiesel production.

ABSTRACT

Algae and jatropha, two types of promising and unconventional biomass, are investigated in this study for large-scale production of biodiesel. The aim is to evaluate the potential advantages and the magnitude of closeness of life cycle balances between these two biodiesel pathways compared to fossil diesel, by taking into account possible uncertainties. The geographical location of this study is India with a prospect of utilizing available wastelands in southern regions. The results indicate that the environmental performance of algal biodiesel is comparable to that of jatropha biodiesel. Both show significant GHG emission and fossil energy depletion reductions which are in the range of 36–40 and 10–25% respectively compared to fossil diesel in the studied geographic context.

1. Introduction

As a developing country with high rate of economic expansion, India has been excessively relying on fossil fuels where petro-based fuels account for about 95% of India’s transportation energy demand (National Policy on Biofuels, 2009). India’s dependency on foreign crude oil has been increasing rapidly and domestic production can merely provide 24% of the total oil demand (US EIA, 2013). It has been estimated that with the current trend of development, the country will have a fleet of nearly 500 million vehicles by the next two decades, from the current 150 million (Sharma, 2011). This threefold increase would exacerbate India’s dependence on imported energy and it is likely to intensify the environmental adverse effects attributed to fossil fuels consumption such as greenhouse gas (GHG) emissions.

Among few available alternatives to substitute some parts of fossil fuels’ share in transportation sector, biofuels are considered to be a promising source of renewable energy because they can be easily blended with fossil fuel and used in conventional engines. As a legislative attempt to augment the share of biofuels in India, the ministry of new and renewable energy set up a national policy which defined an indicative target of 20% blending of biofuels – whether biodiesel or bioethanol – by 2017. Bioethanol mandate has been effective since October 2008 however blending levels for biodiesel are intended to be recommendatory for now, despite arrangements for research and development of new generations of biomass such as lignocellulosic, jatropha and algae (National Policy on Biofuels, 2009). Both jatropha and algae can be utilized for production of biodiesel and despite fundamental differences in cultivation and harvesting, there are many similarities in downstream stages. This similarity along with other mentioned reasons are justifying a comparative LCA study.

Few previous scientific attempts are available to evaluate production of transportation fuels from jatropha and algae. These studies have shown substantial uncertainties in analysis of energy and environmental performances. For instance and for the case of jatropha biodiesel (JBD), the reported net energy ratio (NER) values are in the range of 1.2–8.6 and the GHG emissions reduction compared to fossil diesel is ranging from 40% to 107%. Variations in values are mainly due to the influence of system boundaries considered in each LCA study, such as energy, mass and market
value allocation, without allocation, irrigated and rain fed, displace-ment of energy and fertilizer, variation in seed yield selected for the LCA (Achten et al., 2010; Kumar et al., 2012). Similarly for algal biodiesel (ABD), reported net energy ratios (NER) range from 0.1 to 4.2, while the GHG emissions for a functional unit of 1 MJ of produced biodiesel range from 35 to 140 gCO₂eq. Some studies claimed that energy and environmental performance of ABD could be sustainable and superior when compared to fossil diesel (Campbell et al., 2011; Sills et al., 2013). Some others indicated low differ-ences between ABD and fossil diesel (Lardon et al., 2009; Stephenson et al., 2010; Frank et al., 2011); while a few claimed poor performances with negligible advantages (Kho et al., 2011; Liang et al., 2013). It is essential to consider certain conditions for a case study of these types of biofuels, and then to perform uncertainty analyses in order to assess influences of each factor on the entire process. Gnansounou et al. (2009) previously have shown how important the wide range of system definitions, boundaries, functional units and reference systems could be for the final results. Furthermore, Sills et al. (2013) studied the effects of inconsistent system boundaries and uncertainties on the LCA studies of algal biofuels and illustrated the wide discrepancy between the results. The focus of this study is to compare the life cy-cle assessment of jatropha and algae production in India concerning some of these uncertainties.

2. Geographical context of India

Despite being relatively energy deprived, India has numerous potentials for development of renewable energies, particularly biofuels. Availability of vast areas of wastelands is one of these poten-tials. Ramakrishnaiah (2006) described Indian wastelands as any degraded land which “can be brought under vegetative cover with reasonable effort and which is currently underutilized” and esti-mated that there were up to 32 million hectares of waste land in India mainly in forms of covered with scrubs and saline, aban-doned and degraded forests. The objective of this study is to evaluate environmental performance of large-scale production of biodiesel from algae and jatropha based feedstock in India, with a focus on the southern region (Tamil Nadu) and by considering utilization of local potentials. This is due to the fact that, potential to grow jatropha and algae is high in this region due to waste land, coastal line, industry availability and favorable meteorological con-ditions suitable for jatropha or algae and its co-product utilization and also the region is well known for jatropha and algae cultivation (Chanakya et al., 2012).

Indian electricity network is connected locally and the energy matrices are different from one region to the other. Electricity authority in India is divided into five regions namely Northern, Southern, Eastern, Western and North-Eastern. Coal, hydropower, natural gas, nuclear, diesel, biomass and other renewables are the main sources of power generation in India. The energy mix of the southern region for electricity generation in 2011 is as follows: coal 44%, hydropower 21%, biomass and other renewables 22%, natural gas 9%, nuclear 2% and diesel 2% (Energy statistics, 2012). An average transmission and distribution loss of 18% in the southern region was also taken in account.

3. Process description

3.1. Jatropha cultivation and harvesting

Jatropha curcas L. is a perennial drought tolerant oil-bearing bush that is native to tropical regions and can be cultivated on semi-arid and marginal lands where it does not compete with food crops. Jatropha cultivation process involves land preparation, sow-

ing, irrigation, fertilizer and pesticides application, pruning and seed harvesting. Initial investigations indicated promising results on jatropha, as a source of biomass for bioenergy; however more recent studies have proved that actual yields could be much lower than theoretical yields depending on region, cultivation, irrigation and crop maintenance characteristics (Singh et al., 2013). Cultivation data (fertilizer, water, pesticides and diesel) used for modeling in this study were collected from literature and normalized for 1 kg biodiesel produced (Table 1). Minimal mecha-nization was considered for agricultural activities and all works were considered to be done manually unless it is stated. Cultiva-tion land was irrigated using diesel pump for which the energy consumption was taken into account. Leaves shed during plant growth were assumed to be left on the ground whereas, the twigs accumulated (410 kg/ha) after pruning were considered as a co-product with a lower heating value of 16 MJ/kg (Wani et al., 2012). Seeds were harvested manually. A yield of 2 t/ha and oil content of 35% (w/w) in dry seed were assumed for the base case scenario.

3.2. Microalgae cultivation and harvesting

Raceway ponds and closed bioreactors are the most studied methods of large-scale production of algal biomass. Higher produc-tivity with water, CO₂ and nutrient saving and protection from contaminants which provides the option of high-value added co-products are the advantages of closed bioreactors. However, high maintenance cost and technical difficulties have so far made this method un-economical (Stephenson et al., 2010). Raceway ponds on the other hand are relatively cheap with easier maintenance and the operation is more energy efficient which would suit for India. As a result only raceway ponds were considered in this paper. Depending on the strain, microalgae can be both cultivated in freshwater or seawater. Considering the capacity of a large scale biodiesel production and the scarcity of fresh water in India, only seawater algae strains were considered. During cultivation, micro-algae absorb CO₂ for photosynthesis. A feasible economic algae cultivation system requires a source of carbon with higher concentrations than the atmospheric CO₂ (FAO, 2009). Carbon capture from flue gas emissions, particularly from power plants that burn fossil fuels can be a promising option to provide high concentration of CO₂ (up to 20%) and postpone carbon emissions at the same time. For this study, it has been assumed that a readily available CO₂ stream can be utilized for the raceway ponds and has been previously cooled down and stripped from NOₓ and SOₓ emissions before entering the system boundary.

Few studies modeled cultivation of algae in raceway ponds. A well-established numerical method was used by Stephenson et al. (2010) where an energy input of 7.2 MJ was considered per kg of algal biodiesel. Lardon et al. (2009) also modeled a raceway pond system where the energy input was 20.8% lower compared to the latter. In this paper, the model described by Frank et al. (2011) was considered as a base to characterize the raceway ponds. Among algal species, Chlorella with an oil content of 25% of total dry biomass was assumed for the case study of India. Additionally recycle pumping and pumping from off-site were included by con-sidering similar pumping designs described in Davis et al. (2012). The total energy inputs were then normalized and the data are described in Table 2.

For further processing, the cultivated biomass should be separated from its growing medium.

There are various technical and conceptual technologies pro-posed for harvesting algal biomass (FAO, 2009). The harvesting stage of this study has been modeled based on three consecutive stages: settling tanks coupled with the cultivation ponds, a dis-solved air flotation (DAF) unit and centrifugation. Chitosan which
is an organic coagulant and has previously been shown to be effective by studies such as Chen et al. (1998) is considered to be used in the DAF unit. Apart from dewatering and homogenization, pumping of liquids was also included in the harvesting section.

### 3.3. Oil extraction and transesterification

Biodiesel or fatty acid methyl ester (FAME) is formed by transesterification of acylglycerols (glycerides) namely monoacylglycerols (MAG), diacylglycerols (DAG) and triacylglycerols (TAG), as well as free fatty acids (FFA) and phospholipids (PL). Triglycerides are considered as the most favorable type of lipids with the highest yield for production of biodiesel. Fatty acids are constituents of lipids and in general, a fatty acid molecule is comprised of a hydrocarbon chain attached to a carboxyl functional group. If the structure consists of at least one double bond, then it is an unsaturated fatty acid, thus it can bond with hydrogen otherwise it is saturated. Vegetable oils and animal fats mostly contain triglycerides which can be broken down by natural enzymes into other acylglycerols and free fatty acids. Various non-acylglycerols types of lipids may be present in the extracted bio-oil such as polar lipids, FFAs, ketones, pigments, etc. These would have an adverse impact on transesterification process and often need purification step before transesterification stage.

Oil extraction is defined as the process of separating triglyceride (TAG) lipids from the harvested and concentrated algal biomass and it could be done through a variety of mechanical or chemical manipulation techniques. Two variants of hexane oil extraction procedures have been considered in this paper because of the intrinsic differences between jatropha and algal biomass. For jatropha, hexane extraction model of Whitaker and Heath (2009) was considered where the seed cake is assumed to be recycled back to the cultivation field as fertilizer. For algae oil extraction, the stripper column model by Stephenson et al. (2010) was selected.

Current commercial transesterification of lipids is performed in the presence of alkaline (KOH/NaOH) catalysts. Methanol is generally used for large-scale production due to its availability and lower costs compared to other options. The main factors affecting transesterification are the biomass humidity, TGA content, and the amount of inhibitors. Transesterification of both oils is usually modeled based on industrial processes that are currently used for conversion of first-generation bio-oils such as rapeseed and soybean oils. Oil extracted from these biomass is considered to have low FFA content (often less than 1%) and high TGA lipids respectively. However for oil extracted from jatropha and algae, the percentage of FFA and other inhibitors is usually much higher (up to 14%) than the maximum allowable content. Consequently, the inhibitors should be purified and removed from the oil before transesterification in order to prevent soap formation due to saponification (reaction of FFA and NaOH) and biodiesel hydroslysis.

The quality of biodiesel produced from natural oil depends on saturated, unsaturated and free fatty acids composition of oil. The degree of unsaturation and FFA of oil determines the iodine value and acid value of biodiesel respectively. According to BIS (Bureau of Indian Standards) and EU standards the iodine and acid values should be less than 120 (g/100 g sample) and 0.5 (mg KOH/g) respectively. A high value of iodine value in biodiesel indicates a tendency to polymerization resulting in deposit formation. Study by Gouveia and Oliveira (2009) showed that the average degrees of unsaturation of jatropha and algae oil are in line with BIS and EU standards. In case of acid value it is related to FFA content of oil and biodiesel produced via transesterification depends on the FFA content of oil. For an alkali catalyst transesterification (familiar industrial process for biodiesel production) to be efficient, the FFA content of oil should be less than 2%. In order to avoid undesired reactions like saponification and hydroslysis, two-step transesterification has been suggested (Chen et al., 2012). Oil containing more than 2% FFA has to undergo a pre-treatment step (esterification) with methanol in the presence of sulphuric catalyst to reduce FFA content followed by transesterification with methanol and sodium hydroxide (Zhang et al., 2003). Thus more chemicals and energy are involved in the process. In literature, FFA content of jatropha and algae oil is in the range of (0–14%) (Chitra et al., 2005) and in this study an average value of 7% FFA content in jatropha and algae oil was assumed. Materials and energy required for processing oil with 7% FFA using a two-step process (acid esterification and alkali transesterification) modeled and reported in Zhang et al. (2003) were used in this LCA study. Data normalized per functional unit is given in Tables 1 and 2.

### 4. Co-products handling and fertilizers

There are various options for using the remaining biomass after extraction of oil such as combustion, fermentation, utilization as animal feed or fertilizer. The lipid extracted biomass is rich in carbohydrates and proteins and has a substantial heating value. Besides, recoverable amounts of used nutrients are available within the structure of the residues. Once recycled, the attained energy and nutrients can give a credit to the production cycle. For production of JBD, both harvesting and oil extraction stages have around 280 g residues/kg biodiesel (Wani et al., 2012; Whitaker and Heath, 2009). Among few available options for handling the jatropha waste (Chandra et al., 2012), recycling the residues back to the cultivation fields is considered based on recommendations of a previous study (Whitaker and Heath, 2009).

For production of biodiesel from microalgae, anaerobic digestion (AD) has been selected by various studies as an appropriate method to handle the lipid extracted algal waste (Sialve et al., 2009; Frank et al., 2011). Since algae-to-biodiesel production cycle is dependent on electricity; anaerobic digestion (AD) can offset some of the electricity requirements or according to some studies produces excessive heat and electricity. AD can contribute to the sustainability of an algal biofuel system in two ways: firstly by facilitating the nitrogen and phosphorus recycling which are present in algal waste and as a result improving environmental and economic impacts of the whole system, secondly by producing biogas.

Although it is possible to calculate theoretical methane yields of anaerobic digestion of algae by stoichiometric methods, some factors such as limitation for accessibility to intercellular components or enhancement of yield after lipids extraction due to cell disruption might affect the theoretical yield of anaerobic digestion (Sialve et al., 2009). For LCA studies it is essential to consider that these numerical methods do not take into account materials and further required energies, and as a result the outputs of studies with similar conditions were considered for modeling of algae process (Sialve et al., 2009). Both algae and jatropha require nitrogen and phosphorus fertilizers for cultivation. Fertilizer requirements of jatropha are considered to be one of the lowest among oil-rich biomass (Whitaker and Heath, 2009). Cultivation of fresh water algal species using wastewater could be a favorable option. However, despite densely populated areas in the studied region, this scenario is not followed in this study because of the lack of large wastewaster network in India. Industrial production of nitrogen fertilizers is vastly done by using Haber–Bosch process, through which natural gas provides energy and the reactant hydrogen in order to form ammonia from the air nitrogen (Pfromm et al., 2011).

The remaining digestate of the AD process is rich in nitrogen and phosphor and can be mineralized and used as a source to amend some of the nutrition requirements of algae cultivation, particularly Nitrogen. For electricity generation from the produced biogas, case-by-case issues such as power plant size, electricity...
generation efficiency, heat recovery, separation and recycling of stack emissions and the possibility of co-generation are all dominating. For the model, it is considered a combined heat and power (CHP) plant with the electrical efficiency of 34% and heat efficiency of 41% (Frank et al., 2011; Garofalo, 2009). Despite all the remaining energy content of biogas in converted into heat, only 62% of this heat could be recovered (Garofalo, 2009). It is further discussed how different scenarios regarding heat recovery can effectively modify the outcomes of LCAs studies.

5. LCA methodology and system boundaries

LCA methodology of a product or service quantifies environmental impacts of the whole process by considering the source of all inputs and the fate of all products and wastes. In order to assess sustainability burden of a process, LCA studies incorporate resource consumption, energy balance and emissions throughout various stages of the process within the system boundary. The methodology of this study was based on the “Environmental management– life cycle assessment – principles and framework of International Organization for Standardization (ISO). The domain of the study was: well-to-wheel (or cradle to grave) for three studied pathways.

In order to obtain the required data, a literature review has been performed, and the process requirements of the inventory were selected and then normalized for a functional unit of 1 kg to estimate the GHG emission and fossil energy for well to tank (WtT). For Well to wheel (WtW), the methodology developed by Gnansounou et al. (2009) was used to estimate the fuel efficiency and consequently the well-to-wheel GHG emissions of the biodiesel for 1 km traveled was calculated using Eqs. (1) and (2). Where, biofuel, fuel blend and fossil fuel represent biodiesel, biodiesel blend and fossil diesel per km service.

\[
\text{Fuel efficiency}_{\text{biofuel}} = \left( \frac{\text{biofuel blend factor} \times \text{fuel efficiency}_{\text{fuel blend}}}{1 - (1 - \text{biofuel blend factor})^2} \right) / \text{fuel efficiency}_{\text{fuel blend}} / \text{fuel efficiency}_{\text{fossil fuel}}
\]

\[
\text{GHG}_{\text{biofuel WtW}} = \text{GHG}_{\text{biofuel WtT}} \times \text{Fuel efficiency}_{\text{biofuel}}
\]

Data from the chosen system boundary were then modeled with Simapro 7.3.3 and later the impacts were assessed by Recipe midpoint (E) methodology, by considering the conditions of the case study that were described before. Figs. 1 and 2 show the system boundaries of this study.

Fig. 1. System boundary and process description of the studied jatropha biodiesel model.
Two challenging factors affecting LCA studies of algal biofuels are the lack of data for large-scale production cycles and the variety of options for different stages of the process.

Up until today, the sustainable and large-scale production of algal-based biofuels has not been commercialized and the environmental impacts, feasibility studies and economical assessment of such projects are subject of debate. As a result algal biofuel pathways are theoretical rather than mature. For this study, a hypothetical system based on extrapolation from lab studies was considered in order to simulate a hypothetical large-scale production of biodiesel with a capacity of 100,000 tons of biodiesel/year. The model for algae was defined to include five main stages namely: cultivation, harvesting, oil extraction, conversion and co-products handling. Since the functional unit of this study is 1 km. The model considered individual components for each step and later data required by the input of the model were assembled.

Tables 1 and 2 represent the numerical figures used for the base case study of both models. This data inventory is consisted of energy, mass flows and transportation within the defined system boundaries. Each of these stages is characterized by energy requirements which can be in the form of heat (expressed in MJ) or electricity (expressed as kWh). Energy data were always given as inputs to the system, except from the co-product handling stage of the algae cycle, where it was specified as energy credit.

6. Uncertainty analysis

As it was stated in the previous sections, there are many factors that would affect outcomes of an LCA study of biofuels. In order to provide more realistic results, scenarios were chosen for each biomass representing the range of figures that a similar study would render. In order to identify these boundaries three scenarios were defined namely base case, best case and worst case. For jatropha, previous feasibility studies have been considered for selecting the base-case scenario. Seed yield is considered to be the most important criterion for economic jatropha biodiesel production (Singh et al., 2013; Kumar et al., 2012); therefore the impact of
seed productivities in biodiesel production pathway for 2000 kg/ha, 2400 kg/ha, and 1600 kg/ha as base, best case worst case respectively were studied. It should be noted that in the current situation, seed yields reported in southern region is less than the considered figure which has led to the crop failure. Consequently, the seed yields figure assumed in this study are on the basis of prospective viewpoint.

Electricity and heat generation from biomass residue and their uses are important for algae biodiesel system (Frank et al., 2011). Electricity can be completely used due to its demand in the process but heat produced in CHP plant only has partial demand in algae biodiesel system and handling the heat in various ways would change the impact results. Therefore, three different scenarios were defined for handling the produced heat: in the base case, as the generated heat only was utilized for heat requirements of the process. In the worst case the generated heat was used for heat requirements of the process except for the transesterification unit – which was located elsewhere. Finally, in the best case all the recoverable heat was utilized for the process and the rest by other neighboring industries.

7. Impact assessment and discussion

Since the ultimate aim of this study was to assess potentials of algae and jatropha to replace fossil derived fuels, the results were expressed by considering the amount of non-renewable fossil energy that was utilized for the production cycle. For energy analysis, this study relies on fossil depletion ratio as an indicator of net energy balance. Greenhouse gas emission reduction was expressed as percentage of reduction compared to emissions of fossil diesel. GHG emission from well to wheel was estimated based on data inventory and the fuel efficiency of biodiesel blend. Fuel efficiency of B20 (20% biodiesel and 80% fossil-diesel in volume) at medium to full load is less by ∼1–3.3% (Lapuerta et al., 2008) compared to that of fossil diesel fuel economy (18.4 km/l or 0.0543 l/km) reported by Society of Indian Automobile Manufacturers (SIAM). Assuming an average of 2% lower efficiency, fuel economy of B20 would be 0.0554 l/km. Using Eq. (1) and assuming 0.832 kg/l and 0.88 kg/l as the density of diesel and biodiesel respectively, the fuel economy of biodiesel is 0.053 kg/km. CO₂ emissions of biodiesel per km using equation 2 for each study case for jatropha, algae and fossil diesel is given in Fig. 3. The individual process contribution of base case jatropha and algae biodiesel production to impact is shown in Figs. 4 and 5. In both cases higher emission and fossil depletion was seen in the cultivation stage followed by transesterification process. This is due to high energy and materials demand in these two stages. Similar life cycle energy and CO₂ emissions results were reported by Kumar et al. (2012), Liang et al. (2013) and Alvarado-Morales et al. (2013) for JBD and ABD respectively. On the other hand, Liang et al. 2013 reported high energy use and CO₂ emissions for ABD based on mixed-unit input–output life cycle assessment (MUIO-LCA). This could be due to ABD system boundary considered by Liang et al. (2013), in which the reuse of electricity and heat recovery from biomass residue through AD processing were not taken in account.

The majority of algae and jatropha biodiesel studies cited in the introduction section considered energy return on energy invested (EROI) or net energy ratio (NER) as indicators of energy balance. Both of these indicators are defined as a ratio of primary energy input over the energy content of the products. Variations of these two indicators consider different methodologies particularly in case of including or not including renewable and non-renewable energy sources in the ratios (Garofalo, 2009). In order to give extra attention to fossil energy inputs of these two processes, the fossil energy depletion for all the case is shown in Fig. 3 and the% reduction of GHG emissions and fossil depletion compared to the fossil depletion is shown in Table 3.
The results showed that 52% of the electricity requirements of the site can be compensated by conversion of the produced biogas of the co-products handling stage. The rest is imported into the system from the local grid. Energy and heat requirements of the process highlight the importance of energy generation within the co-product handling stage of ABD. Hence, choosing the suitable method of power generation from the produced biogas is critical. Considering the dependency of the algae production cycle on electricity, more efficient electric power generation would hugely affect the energy balance of the whole process. However before selecting a method the local infrastructure should be considered for a prospective biogas power plant. Since the southern regions do not rely on natural gas as a source of energy, the construction of a combined cycle gas power plant has not been considered.

### Table 2
Data inventory of micro-algae biodiesel production per kg.

<table>
<thead>
<tr>
<th>Stages</th>
<th>In/out</th>
<th>Utilities/materials</th>
<th>Unit</th>
<th>Base case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivation&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>Input</td>
<td>Water</td>
<td>kg</td>
<td>221.75</td>
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<tr>
<td></td>
<td></td>
<td>Urea</td>
<td>g</td>
<td>88.14</td>
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<tr>
<td></td>
<td></td>
<td>Diammonium phosphate</td>
<td>g</td>
<td>79.28</td>
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<tr>
<td></td>
<td></td>
<td>Concrete</td>
<td>g</td>
<td>2.2 x 10^-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel</td>
<td>g</td>
<td>7.5 x 10^-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plastic</td>
<td>g</td>
<td>5.08 x 10^-3</td>
</tr>
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<td></td>
<td></td>
<td>Cast Iron</td>
<td>g</td>
<td>1.8 x 10^-3</td>
</tr>
<tr>
<td></td>
<td>Output</td>
<td>Electricity</td>
<td>kW h</td>
<td>3.40</td>
</tr>
<tr>
<td>Harvest&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Input</td>
<td>Chitosan</td>
<td>g</td>
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<td></td>
<td></td>
<td>Electricity</td>
<td>kW h</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>Output</td>
<td>Algal broth</td>
<td>kg</td>
<td>2555.6</td>
</tr>
<tr>
<td>Extraction&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Input</td>
<td>Hexane</td>
<td>g</td>
<td>2.95</td>
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<td></td>
<td></td>
<td>Electricity</td>
<td>kW h</td>
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<tr>
<td></td>
<td></td>
<td>Heat</td>
<td>MJ</td>
<td>2.30</td>
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<tr>
<td></td>
<td>Output</td>
<td>Algal oil</td>
<td>g</td>
<td>4620</td>
</tr>
<tr>
<td>Anaerobic Digestion&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Input</td>
<td>Electricity</td>
<td>kW h</td>
<td>0.71</td>
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<td></td>
<td></td>
<td>Heat</td>
<td>MJ</td>
<td>3.30</td>
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<td></td>
<td>Output</td>
<td>Deoiled algae biomass</td>
<td>kg</td>
<td>3570</td>
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<td>Biodiesel production&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Input</td>
<td>Electricity</td>
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<td>Output</td>
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<td></td>
<td>Methanol</td>
<td>g</td>
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<td>Sodium hydroxide</td>
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<td>Sulphuric acid</td>
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<td>Electricity</td>
<td>kW h</td>
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<td></td>
<td>Heat</td>
<td>MJ</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water</td>
<td>kg</td>
<td>0.14</td>
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<tr>
<td></td>
<td>Output</td>
<td>Biodiesel</td>
<td>g</td>
<td>1000</td>
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<td></td>
<td></td>
<td>Glycerin</td>
<td>g</td>
<td>113.3</td>
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<td>Transport</td>
<td>From plant to biodiesel industry</td>
<td>km</td>
<td>100</td>
<td></td>
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<tr>
<td></td>
<td>From biodiesel industry to outlet</td>
<td>km</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Frank et al. (2011).
<sup>b</sup> Davis et al. (2012).
<sup>c</sup> Stephenson et al. (2010).
<sup>d</sup> Zhang et al. (2003).

The results showed that 52% of the electricity requirements of the site can be compensated by conversion of the produced biogas of the co-products handling stage. The rest is imported into the system from the local grid. Energy and heat requirements of the process highlight the importance of energy generation within the co-product handling stage of ABD. Hence, choosing the suitable method of power generation from the produced biogas is critical. Considering the dependency of the algae production cycle on electricity, more efficient electric power generation would hugely affect the energy balance of the whole process. However before selecting a method the local infrastructure should be considered for a prospective biogas power plant. Since the southern regions do not rely on natural gas as a source of energy, the construction of a combined cycle gas power plant has not been considered.

**Fig. 3.** Fig. 4: GHG emission (kg CO₂ eq./km) and fossil depletion (kg oil eq./km) of B20 biodiesel. ABD-Algae biodiesel, JBD-jatropha biodiesel, 1-base case, 2-best case, and 3-worst case.
Fossil depletion solutions enhance energy and environmental aspects of these fuels. The process may also be considered. Perspectives for improvement of energy and materials requirements of an industrial-scale cultivation system may also help better LCA studies, while technological advances are expected to be improving as well. Other downstream processing methods have been studied recently such as hydrothermal liquefaction or catalytic gasification (Delrue et al., 2013) and also emphasized that downstream processes (harvesting, oil extraction and transesterification) account for the majority of the energy requirements of the process. Recent LCA study by Udom et al. (2013) revealed that, choice of coagulants and pressing processes used in algae harvesting improve the environmental performance of ABD. Thus, it is essential to provide more efficient methods for these mentioned stages in order to make economic-scale production viable. Alternatively, other downstream processing methods have been studied recently such as hydrothermal liquefaction or catalytic gasification (Delrue et al., 2013) and proved to potentially reduce some of the energy requirements of the whole process.

8. Conclusion

Literature data show a significant variation in seed yield (0.5–12.5 t/ha/year) for jatropha biodiesel system in India. Concerning the variation, environmental feasibility of algae biodiesel as an alternative or additional source to jatropha biodiesel was compared in this LCA study. LCA impact results show that, GHG emission and fossil energy depletion of algal biodiesel are similar to those of jatropha biodiesel. Both biodiesel system show reductions of 36–40% GHG emission and 10–25% fossil energy depletion compared to fossil diesel in the studied geographic context. Thus algal biodiesel could be a prospective sustainable transport fuel in India in addition to jatropha biodiesel.

It should be noted that the energy and environmental analyses of jatropha and algae biofuels are in their early stages. It is expected that more realistic jatropha productivity figures would be available in the future. More precise field data from recent plantations and improvements of biomass and oil productivities are among the issues that would help better assessments of jatropha biodiesel. More precise models and demonstration plants of algae cultivation systems may also help better LCA studies, while technical and biological advances are expected to be improving as well. The adverse effect of non-triacylglycerol lipids on the conversion characteristics of bio oils was briefly discussed in this study. Since both algae and jatropha oil are characterized by relatively high FFA content, it is necessary to further study such effects on larger scales where energy and materials requirements of an industrial-scale process may also be considered. Perspectives for improvement of biodiesel production pathways from algae and jatropha have been presented by recent research trends. It is expected that innovative solutions enhance energy and environmental aspects of these fuels and respond to the shortcomings. Furthermore, the by-product handling stage of jatropha seemingly requires major technical improvement in order to help with the energy balance and nutrients recycling. Chandra et al. (2012) investigated anaerobic digestion of jatropha residues after harvesting and oil extraction. Modeling this technique to industrial scales is recommended to be included in future LCA studies. The algal biodiesel LCA results also emphasized that downstream processes (harvesting, oil extraction and transesterification) account for the majority of the energy requirements of the process. Recent LCA study by Udom et al. (2013) revealed that, choice of coagulants and pressing processes used in algae harvesting improve the environmental performance of ABD. Thus, it is essential to provide more efficient methods for these mentioned stages in order to make economic-scale production viable. Alternatively, other downstream processing methods have been studied recently such as hydrothermal liquefaction or catalytic gasification (Delrue et al., 2013) and proved to potentially reduce some of the energy requirements of the whole process.

References

Frank, E.D., Han, J., Palou-Rivera, I., Elgowainy, A., Wang, M.Q., 2011. Life-cycle analysis of algal lipid fuels with the GREET model, ANL/ESD/11-5, Argonne National Laboratory, Argonne, Ill., US.

Table 3

<table>
<thead>
<tr>
<th>Impact reduction (%)</th>
<th>ABD (base case)</th>
<th>ABD (best case)</th>
<th>ABD (worst case)</th>
<th>JBD (base case)</th>
<th>JBD (best case)</th>
<th>JBD (worst case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>36.4</td>
<td>37.3</td>
<td>24.7</td>
<td>39</td>
<td>42.6</td>
<td>33.2</td>
</tr>
<tr>
<td>Fossil depletion</td>
<td>20.6</td>
<td>21.7</td>
<td>6.9</td>
<td>10.1</td>
<td>15.8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 4. GHG emission (kg CO$_2$ eq.) and fossil depletion (kg oil eq.) per kg of jatropha biodiesel (base case).

Fig. 5. GHG emission (kg CO$_2$ eq.) and fossil depletion (kg oil eq.) per kg of algae biodiesel (base case).


