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Screening Life Cycle Assessment of Jatropha Biodiesel

Final Report

Commissioned by

Daimler AG, Stuttgart

Heidelberg, 11 December, 2007

This report refers to both the screening life cycle assessment of Jatropha biodiesel, purchase order nos. 3965006118-F03 (‘Jatropha biodiesel compared to conventional diesel fuel: Energy and greenhouse gas balances’) and 3965006106-F03 (‘Environmental impacts of biodiesel from Jatropha’).

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Dr. Guido Reinhardt

Dipl.-Phys. Ing. Sven Gärtner

Dipl.-Geoökol. Nils Rettenmaier

Dipl.-Geoökol. Julia Münch

Dipl.-Ing. Eva von Falkenstein

IFEU – Institute for Energy and Environmental Research Heidelberg GmbH
Wilckensstraße 3
D-69120 Heidelberg
Tel.: +49 (0)6221 47 67-0; Fax: -19
www.ifeu.de, guido.reinhardt@ifeu.de

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Table of Contents

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Heidelberg, December 2007

Eva von Falkenstein
Sven O. Gärtner
Julia Münch
Guido Reinhardt
Nils Rettenmaier

1 Introduction

Background

In recent years, great hopes have been pinned on Jatropha as a source of bioenergy which can be grown in sub-humid to semi-arid climates. In 2003, Daimler AG, Stuttgart, Germany, and its project partners, the Central Salt & Marine Chemicals Research Institute, Bhavnagar, India, and the Institute of Animal Production in the Tropics and Subtropics, University of Hohenheim, Germany, started a public-private partnership project on Jatropha in India. This joint project ‘Biofuels from eroded soils in India’ is being co-financed by the Deutsche Investitions- und Entwicklungsgesellschaft, Cologne, Germany, and Daimler AG and is designed to demonstrate the feasibility of sustainable *Jatropha curcas* cultivation and biodiesel production from Jatropha oil.

In order to evaluate the environmental implications associated with the production and utilisation of biodiesel from Jatropha, Daimler commissioned the IFEU Institute for Energy and Environmental Research Heidelberg, Germany, to conduct a screening life cycle assessment of Jatropha biodiesel.

Goal and scope

The goal of this screening life cycle assessment is to evaluate the environmental advantages and disadvantages of Jatropha biodiesel compared to conventional diesel fuel.

For this screening life cycle assessment of Jatropha biodiesel, the environmental impact categories ‘Energy resources’ and ‘Greenhouse effect’ as well as ‘Acidification’, ‘Eutrophication’, ‘Summer smog’ and ‘Nitrous oxide’ (Ozone depletion) are examined. Other environmental impacts which are discussed in connection with Jatropha are outside the scope of this study. Some examples are the occupation of natural land areas with its effects on land quality including biodiversity and soil-ecological functions as well as the consumption of water for irrigation, a resource which is usually limited in sub-humid to semi-arid environments.

Besides the decentralised Jatropha biodiesel production concept implemented in a pilot plant in Bhavnagar, India, a number of other scenarios, options and variants are analysed. These include several cultivation scenarios, decentralised and centralised conversion technologies and different utilisations of main products and by-products, e.g. the utilisation of both Jatropha biodiesel and pure Jatropha oil. The influence of each step of the life cycle on the overall results is identified by means of sensitivity analyses; the most important parameters are highlighted in the presentation of the results. Ultimately, this analysis not only reflects the system characteristics but also leads to results which can be transferred from the pilot plant to India and other geographical regions.

Furthermore, the study points at environmental optimisation potentials, derives recommendations and addresses the need for further research.

General approach

The goal of this study, an evaluation of environmental advantages and disadvantages of Jatropha biodiesel compared to conventional diesel fuel, is best achieved by means of a life cycle assessment (LCA). Therefore, this analysis is carried out according to LCA methodology, i.e. regarding the complete life cycle of Jatropha biodiesel – from Jatropha cultivation through biodiesel production to its utilisation in a passenger car – compared to that of conventional diesel fuel (Fig. 1-1).

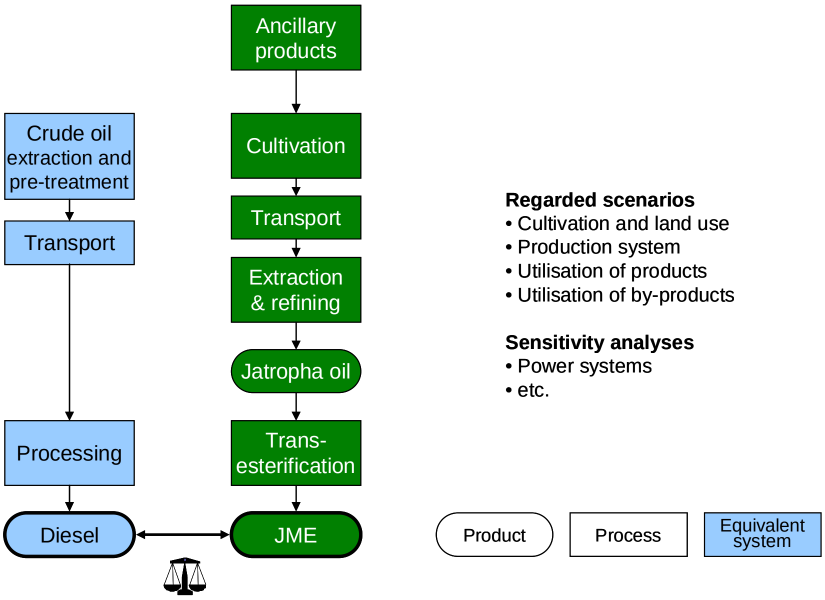

Fig. 1-1 Basic principle of the life cycle comparison between Jatropha biodiesel (JME) and fossil diesel fuel featuring the production steps ‘from well to wheel’

Based upon this methodology, a number of variations and sensitivity analyses are calculated for all life cycle stages and unit processes, respectively, such as Jatropha cultivation or by-product utilisation. This serves the purpose of identifying those parameters which have the greatest influence on the overall outcome and of analysing their specific impacts on the results under different boundary conditions. Through these investigations, it is possible to understand the fundamental interrelations as well as to identify optimisation potentials.

Further details regarding the approach of the study can be found in chapter 2, including sections on the LCA methodology, system boundaries and the analysed environmental impacts.

Chapter 3 describes all Jatropha systems investigated within the framework of this study and the respective criteria for their selection. The most important results are presented and discussed in depth in chapter 4. The final chapter (chapter 5) summarises the main results from which conclusions regarding optimisation potentials and the need for further research are derived as well as recommendations.

2 Methodology and data origin

This chapter describes the methodological framework as well as specifications which are applied in this study. Subsequently, the origin of the basic data used for the analyses is documented.

2.1 Methodology and specifications

As described in the introduction, the goal of this study is best achieved by means of a life cycle assessment (LCA). Therefore, this analysis is carried out following the internationally standardised LCA methodology /ISO 14040&14044/. Due to the background of this study, however, there is no need to conduct a full LCA according to the ISO standards which require, for example, an external critical review process. Nonetheless, this screening LCA very closely follows the standards' requirements and guidelines, thus leading to very reliable results.

In the following, some fundamental elements of the LCA methodology are presented, as well as the system boundaries and analysed environmental impacts. For further details, the reader is referred to the cited literature.

2.1.1 Life cycle assessment of products at a glance

The principles of life cycle assessments of products are regulated by international standards /ISO 14040&14044/. In particular, the following aspects are covered:

- Inputs and outputs (biomass resource and other materials, energy or waste materials, waste water, emissions, etc.)
- Potential environmental impacts (e.g. greenhouse effect, acidification)

This applies to the product's entire life cycle from raw material acquisition through production to the utilisation of the product, i.e. a 'well-to-wheels' approach in case of a (bio)fuel.

For these reasons, LCAs of products provide comprehensive information on environmental impacts of both single production stages and of the entire life cycle of products and services. By means of sensitivity analyses, optimisation potentials can be identified. Finally, information relevant for decision makers can be derived from the life cycle interpretation.

2.1.2 General specifications for this study

This screening LCA closely follows the international standards /ISO 14040&14044/. The scope definition required by these guidelines includes the following main items:

- Functional unit: Depending on the questions to be answered, different functional units might be necessary. As most questions relate to land use efficiency, the potential use of

Jatropha fruit from 1 ha of land in one year is assessed and most results are referred to this unit.

- Geographic and time-related coverage: The production and use of Jatropha biofuels is related to current Indian conditions, with the exception of some sensitivity analyses, in which the transferability to other regions is investigated. For processes taking place in other parts of the world, the geographic scope is enlarged accordingly.
- System boundaries: Generally, allocation is avoided by expanding the system boundaries (see /Borken et al. 1999/ for details). In case of bioenergy generation from Jatropha by-products, for example, credits are given for the avoided energy generation from conventional fuels. In accordance with LCA methodology alternative land use issues are included as described in /Jungk & Reinhardt 2000/.
- Depth of balances: All system inputs and outputs are taken into account, except for the manufacturing of processing equipment, vehicles and infrastructure.

2.1.3 Environmental impacts

A description of the six environmental impact categories analysed in this study can be found in Table 2-1. This selection follows the environmental impacts usually regarded in LCA practice. Further details such as indicators, life cycle inventory parameters and characterisation factors are listed in Table 2-2.

Table 2-1 Environmental impacts evaluated in this study

Environmental impact	Description
Energy resources	Demand for non-renewable energy carriers, i.e. fossil fuels such as mineral oil, natural gas and different types of coal as well as uranium ore. In the following, this impact category is neutrally termed ‘Energy’; it covers energy demand as well as energy savings.
Greenhouse effect	Global warming as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide originating from the combustion of fossil energy carriers, a number of other trace gases – among them methane and nitrous oxide – are included. In the following, this impact category is neutrally termed ‘Greenhouse effect’ as it covers both greenhouse gas emissions and savings.
Acidification	Shift of the acid/base equilibrium in soils and water bodies by acid-forming gases (keyword ‘acid rain’). Emissions of sulphur dioxide, nitrogen oxides, ammonia and hydrogen chloride are recorded.
Eutrophication	Input of nutrients into soils and water bodies (keyword ‘algal bloom’). Nitrogen oxides and ammonia are recorded.
Summer smog	Formation of specific reactive substances, e.g. ozone, in presence of solar radiation in the lower atmosphere (keyword ‘ozone alert’). Two category indicators are available: POCP (Photochemical Ozone Creation Potential) and NcPOCP (Nitrogen-corrected POCP). Hydrocarbons are recorded for both POCP and NcPOCP, whereas nitrogen oxides are only recorded for NcPOCP.
Nitrous oxide (Ozone depletion)	Loss of the protective ozone layer in the stratosphere through certain gases such as chlorofluorocarbons (CFCs) or nitrous oxide (keyword ‘ozone hole’). As only nitrous oxide is recorded in this study, this impact category is termed ‘Nitrous oxide’ instead of ‘Ozone depletion’.

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Most impact categories are generally regarded in life cycle assessments and described in the relevant literature. For ‘Summer smog’, however, the suggested models aggregating the potentially ozone-creating substances are still disputed among experts.

Due to the complex chemical reactions involved in the tropospheric ozone formation, modelling the interrelations between emissions of unsaturated hydrocarbons and nitrogen oxides is extremely difficult. As yet, the photochemical ozone creation potential (POCP), expressed in ethylene equivalents, is applied in impact assessments. However, this method is disputed in expert circles for two reasons: (1) it is based on changes of existing ozone concentrations and (2) it was developed for the calculation of regional long-range pollutant dispersion models. It relies on the ozone creation potential of the hydrocarbons and completely neglects the contribution of the nitrogen oxides to this process. In the context of a research project of the German Federal Environment Agency (Umweltbundesamt) which sought to develop an improved calculation model, a linear consideration of the nitrogen oxides was suggested /Stern 1997/. This translates to the following procedure: based on the POCP model (in ethylene equivalents), the emitted nitrogen oxides are multiplied by the calculated POCP value. With this, a new category indicator is gained which allows for a precise linear consideration of the nitrogen oxides; it was named the nitrogen-corrected photochemical ozone creation potential (NcPOCP).

Table 2-2 Indicators, life cycle inventory parameters and characterisation factors for the regarded impact categories

Environmental impact	Category indicator	Life cycle inventory parameter	Formula	Character. factor
Energy resources	Cumulative energy demand from non-renewable sources	Crude oil Natural gas Hard coal Lignite Uranium ore	—	—
Greenhouse effect	CO_2 equivalent (carbon dioxide equivalent)	Carbon dioxide fossil	CO_2	1
		Nitrous oxide	N_2O	298
		Methane	CH_4	25
Acidification	SO_2 equivalents (sulphur dioxide equivalent)	Sulphur dioxide	SO_2	1
		Nitrogen oxides	NO_X	0.7
		Ammonia	NH_3	1.88
		Hydrochloric acid	HCl	0.88
Eutrophication	PO_4 equivalents (phosphate equivalent)	Nitrogen oxides	NO_X	0.13
		Ammonia	NH_3	0.346
Summer smog (POCP)	C_2H_4 equivalents (ethylene equivalents)	Non-methane hydrocarbons	NMHC	0.416
		Methane	CH_4	0.007
Summer smog (NcPOCP)	Nitrogen-corrected C_2H_4 equivalents (ethylene equivalents)	Non-methane hydrocarbons	NMHC	—
		Methane	CH_4	—
		Nitrogen oxides	NO_X	—
Ozone depletion	—	Nitrous oxide (Dinitrogen oxide)	N_2O	—

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2.2 Data origin and quality

Concerning the origin of the basic data used in this study, two main categories are distinguished:

- Data on the upstream processes of ancillary products such as mineral fertilisers and conventional fuels as well as on the provision of electric power
- Data on the cultivation of *Jatropha curcas* and the conversion of its fruit to Jatropha oil and biodiesel as well as the biofuel's utilisation in a car engine

The former data originates from IFEU's internal database /IFEU 2007/. This data has been compiled and validated by IFEU throughout numerous studies and is generally acknowledged. Where necessary, it was adapted to Indian state-of-the-art conditions.

All Jatropha-specific data including inputs to and outputs from each life cycle stage from cultivation through conversion to utilisation has been compiled and published in a joint report /Reinhardt et al. 2007/. Most of this data originates from Daimler and its project partners, the Central Salt & Marine Chemicals Research Institute (CSMCRI) and the University of Hohenheim. The data consists of field and laboratory measurements as well as of expert judgements and has been continuously harmonised and agreed upon during the term of this project. In case of lacking data, IFEU's internal database was consulted /IFEU 2007/.

In the following, some important aspects of the basic data are addressed, divided into the main life cycle stages:

- Cultivation: Data on yield and carbon content of Jatropha plants, mass distribution between different parts of the Jatropha fruit (husk-to-seed ratio, oil content) and their respective nutrient, energy and water content is taken from /Reinhardt et al. 2007/. However, cultivation inputs such as mineral fertiliser are calculated on the basis of the nutrient removal and may differ from the actual application.
- Conversion: Data on transport and processing in the pilot plant are taken from /Reinhardt et al. 2007/. For centralised processing in a larger plant, data from IFEU's internal database /IFEU 2007/ are taken and conformed to Indian state-of-the-art conditions.
- Utilisation: Only little data is available regarding the utilisation of Jatropha biofuels (main products) and by-products. Emission measurements for Jatropha biodiesel have been performed by Daimler /Degen 2007/. However, no data exists regarding the emissions from by-product combustion for bioenergy generation. To close this gap, IFEU made expert judgements on the basis of /ecoinvent 2006/, /GEMIS 2005/, /ProBas 2007/ and its internal database /IFEU 2007/.

To conclude, the basic data used in this study is relatively inhomogeneous. Its quality can be regarded as quite fair: On one hand, data on conversion is reliable, whereas on the other, emission factors for by-product combustion are quite uncertain. In cases such as the latter, the influence of the respective parameters is investigated by means of sensitivity analyses. Nonetheless, the data quality is sufficiently sound to evaluate the Jatropha system.

3 System descriptions and basic scenarios

As already described in chapter 1, the environmental advantages and disadvantages of Jatropha biodiesel compared to conventional diesel fuel are evaluated by means of so-called ‘life cycle comparisons’. All Jatropha products and by-products are offset against the conventional products they substitute for.

This chapter describes the detailed setup of the life cycle comparisons conducted in this study. After a short characterisation of the Jatropha plant including a definition of terms for all parts of its fruit (chapter 3.1), the basic life cycle comparison is presented in chapter 3.2. Due to a large number of possible scenarios, options and variants, the main life cycle stages cultivation (chapter 3.3), conversion (chapter 3.4) and utilisation of products and by-products (chapter 3.5) are described separately before being merged in a synthesis (chapter 3.6). The last section (chapter 3.7) gives an overview of all sensitivity analyses conducted in this study.

3.1 Jatropha: short characterisation

The following list gives a short characterisation of the plant which is at the centre of attention in this study (after /Duke 1983/, /Degen & Maly 2003/ and /IPK & IPGRI 1996/):

- scientific name: *Jatropha curcas* L.; common names include physic nut and purgic or purging nut (English), pourghère and pignon d’Inde (French), purgueira (Portuguese), Purgi-Nuss and Purgiernuss (German), kanananaeranda, parvataranda (Sanskrit), bagbherenda, jangliarandi, safed arand (Hindi)
- family: Euphorbiaceae
- geographic distribution: native to the Americas; today pan-tropical occurrence in tropics and subtropics; dry to wet climates
- physical characteristics: shrub or tree to 6 m height; milky/yellowish sap from branches; deciduous leaves; yellowish, bell-shaped flowers; grows readily from seeds or cuttings; oil-containing fruit
- Uses include fly repellent for livestock (leaves); fish poison (bark); linen marking (sap); purgative and contraceptive use (fruit); illumination, lubrication, soap and energy (oil from fruit). All plant parts are toxic.
- energy value: One tonne of Jatropha fruit yield about 270 kg of oil with a lower heating value (LHV) of 39.5 MJ/kg. According to /Reinhardt et al. 2007/, the oil content of the capsules currently ranges from 17.7 to 25.1% (depending on the cultivation scenario).

The fruit of the plant, also referred to as the capsule, is made up of different parts: husks, seeds, shells and finally the actual oil-containing kernels; Fig. 3-1 shows these fruit parts.

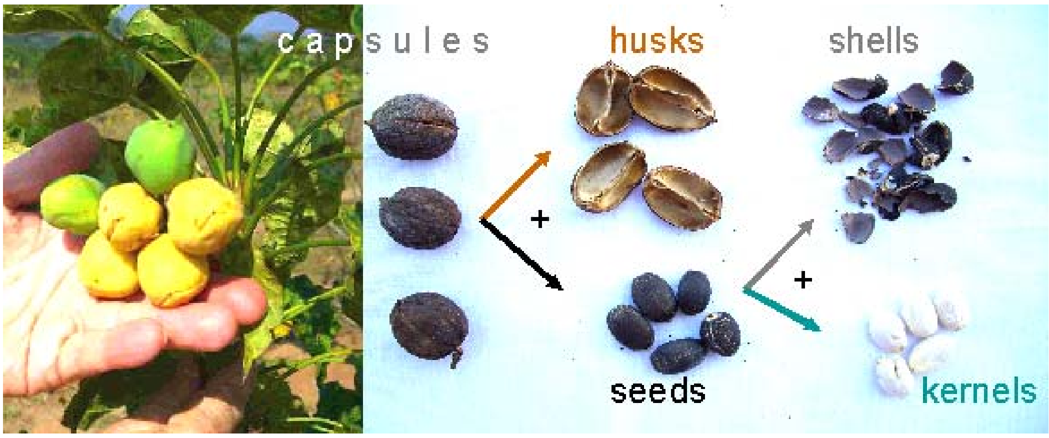

Fig. 3-1 The parts of the Jatropha fruit (or capsule): husks, seeds, shells and kernels

Table 3-1 lists and describes the parts of the Jatropha fruit which play a role in the JME production process as well as the by-products which consist entirely of processed fruit fractions.

Table 3-1 Parts of the Jatropha fruit including processed states

Terminology used in this report	Composed of sub-fractions	Description
Capsule	Husk + seeds	Entire fruit
Husk		Outer core of fruit, surrounding seeds; green and 'fleshy' in fresh state, later brown and dry
Seed	Shell + kernel	Compact unit inside fruit, consists of shell and kernel, usually 2-3 per capsule
Shell		Brown or black shell surrounding the kernel
Kernel		White compact nucleus of seed, actual oil-containing part of the fruit
Oily cake	Seeds (processed)	Leftovers from mechanical oil extraction from seeds (incl. shells), contains residual oils
De-oiled cake	Seeds (processed)	Leftovers from mechanical and solvent-aided oil extraction from seeds
Meal	Kernels (processed)	Leftovers from mechanical and solvent-aided oil extraction from kernels

Reinhardt et al. 2007

3.2 Basic life cycle comparison

For the evaluation of the environmental advantages and disadvantages of Jatropha biodiesel compared to conventional diesel, a simplified schematic life cycle comparison has already been established in chapter 1 (Fig. 1-1). For simplification, the various by-products which emerge from the cultivation of Jatropha plants, the extraction and refining of their fruit and the transesterification were not depicted.

Fig. 3-2 illustrates the basic life cycle comparison more elaborately along the lines of the actual Jatropha cultivation in India, the conversion of the fruit in a pilot plant in Bhavnagar and the utilisation of JME in a passenger car. Regarding the utilisation of by-products, the following configuration applies for the basic life cycle comparison:

- Cultivation of Jatropha. Apiary products such as honey substitute for equivalent products, e.g. jam (for details see e.g. /Gärtner & Reinhardt 2003/).
- Extraction and refining. The husks and oily cake are brought back to the field and used as organic fertiliser, thus replacing mineral fertiliser. Fatty acids are used in soap production and substitute for tensides.
- Transesterification. Glycerine is purified in order to substitute for chemicals in the pharmaceutical sector. Potassium (K) fertiliser replaces mineral fertiliser.

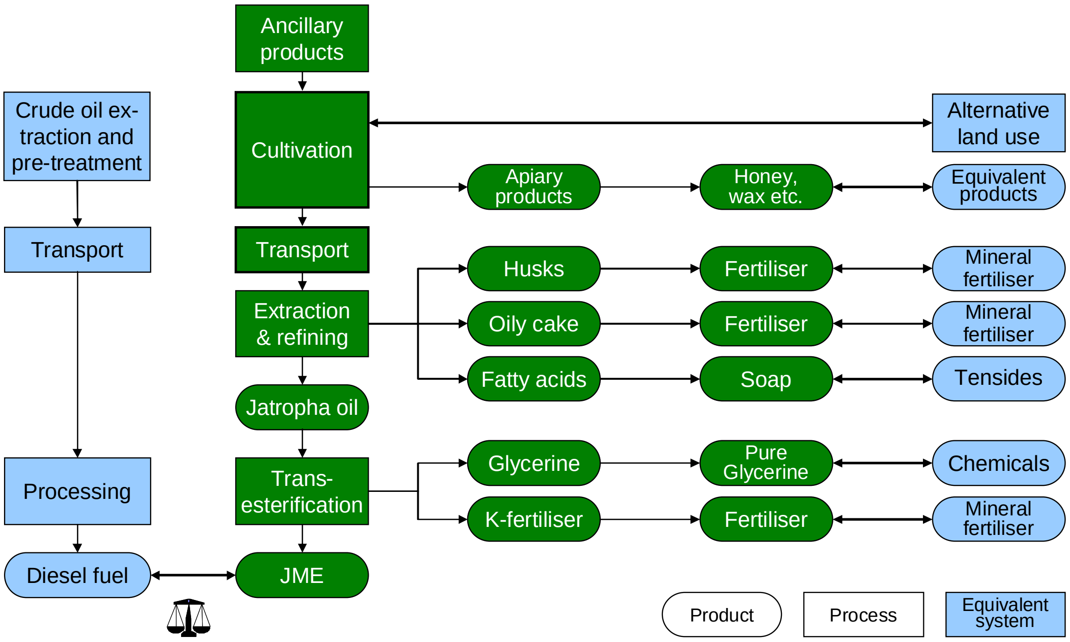

Fig. 3-2 Basic comparison between the life cycles of conventional diesel fuel and Jatropha biodiesel (JME) from the pilot plant scenario

The scheme depicted in Fig. 3-2 only represents one possible configuration of cultivation, conversion and (by-)product utilisation. The large number of other scenarios, options and variations is presented in the following chapters (3.3 – 3.5).

3.3 Cultivation and alternative land use

Large-scale cultivation of Jatropha is still in an early stage. This chapter addresses two important aspects of Jatropha cultivation, namely inputs and outputs (chapter 3.3.1) as well as alternative land uses (chapter 3.3.2), also referred to as the agricultural reference system. The latter defines what the cultivated land area would be used for if the investigated product were not to be produced; this is an essential part of an LCA.

3.3.1 Cultivation inputs and outputs

Within the Daimler / DEG project in India, for example, *Jatropha curcas* is being grown on some 30 hectares of land /Degen 2004/. Despite considerable cultivation efforts in the past, the yield is still quite variable even today. Moreover, the full potential of Jatropha is believed to be much higher than current yields suggest; improved agronomic practices and better plant breeds could possibly lead to increased yields.

The average yields of fruit, seeds and oil for three different scenarios of Jatropha cultivation on poor soils are presented in Table 3-2. The first scenario, named ‘Today’, reflects the current yields of Jatropha. The second scenario assumes higher yields due to future optimisations of agronomic practice and is therefore named ‘Optimised’. The third scenario, referred to as ‘Best’, is even more optimistic: It postulates a yet increased yield based on further agronomic improvements and in addition breeds with a higher seed-to-husk ratio. The numbers given refer to poor soils. Generally, yields might be considerably higher on agricultural soils or under more favourable climatic conditions; permanent irrigation could of course have a similar effect.

To which extent the results are influenced by the yield is being investigated by means of a sensitivity analysis (see chapter 4.7.1).

Table 3-2 Average yields of fruit, seeds and oil for Jatropha plantations on poor soils

Cultivation scenario	Yield fruit [kg / (ha*yr)]	Yield seeds [kg / (ha*yr)]	Yield oil [kg / (ha*yr)]
Today	2,270	1,418	402
Optimised	3,811	2,382	676
Best	6,572	4,436	1,381
			Reinhardt et al. 2007

Cultivating Jatropha requires a number of inputs such as seedlings, irrigation water (first three years only), diesel fuel (for tractor and irrigation pump) and mineral fertiliser. The respective inputs – at least for the scenario ‘Today’ – originate from CSMCRI’s experimental sites and can be found in /Reinhardt et al. 2007/. The amount of fertiliser, for example, is determined by fertilisation experiments. However, the actual nutrient input might differ from the nutrient removal which is the relevant parameter for agricultural systems. Therefore, the amount of required fertiliser is calculated on the basis of nutrient removal, which in turn is determined based on the nutrient contents of all single parts of the Jatropha fruit. The corresponding results are presented in Table 3-3.

Table 3-3 Fertiliser requirements based on nutrient removal

Type of fertiliser	N [kg / (ha*yr)]	P_2O_5 [kg / (ha*yr)]	K_2O [kg / (ha*yr)]
Today	48	19	53
Optimised	81	31	89
Best	141	56	139

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3.3.2 Alternative land uses

In comparison to the provision of fossil fuels, the production of agriculture or forestry biomass for energy requires relatively large areas of land. Therefore, when a comparison is being made between a bioenergy and a fossil energy carrier, it is always necessary to define an alternative way in which the required land might be used if not for the production of bioenergy. Any environmental assessment of a bioenergy production system must take into account such alternative land uses, which are also referred to as the (agricultural) reference systems /Jungk & Reinhardt 2000/.

As the Jatropha plant is well adapted to marginal growing conditions, many development cooperation projects opt for Jatropha cultivation on degraded or marginal land which otherwise would not be used for agriculture. In this way, both further land degradation and competition with food production would be avoided. Therefore, the reference systems defined in this study exclude all agricultural uses.

Nevertheless, any land use change, even from degraded land to Jatropha cultivation, influences the area’s biodiversity and above all its carbon stock, i.e. the carbon content of both soil and vegetation. Three possible developments can take place: a net carbon loss, no change in the carbon stock or, presumably, a net carbon gain. Irrespective of loss or gain, any difference in carbon stock before and after Jatropha cultivation is reflected in the greenhouse gas balances and must be depreciated (‘written off’) over a certain period of time, which is referred to as the depreciation period. In this study, a depreciation period of 20 years was selected which corresponds to a Jatropha plantation’s productive life span.

Transferred to the Jatropha plantation sites in the Indian states of Gujarat (Chorvadla site) and Orissa (Gopalpur and Humma site), these three carbon stock changes translate as follows: At Gopalpur (Orissa), a desert-like area (‘no vegetation’), Jatropha cultivation results in a net carbon gain, whereas at Humma (Orissa), the prevailing ‘medium vegetation’ (a kind of shrubland) is replaced by a Jatropha plantation of lower carbon stock, thus leading to a net carbon loss. With this, these two sites roughly represent the two “extreme values” carbon loss and carbon gain. The Chorvadla (Gujarat) site can be classed somewhere between these extremes. It can not be said with certainty here if it reflects precisely the approach chosen in this study, namely “no difference in carbon stock between Jatropha cultivation and pre-plantation state”, however, this is irrelevant for this study which analyses carbon stock changes qualitatively. These three qualitative carbon stock changes are depicted in Fig. 3-3.

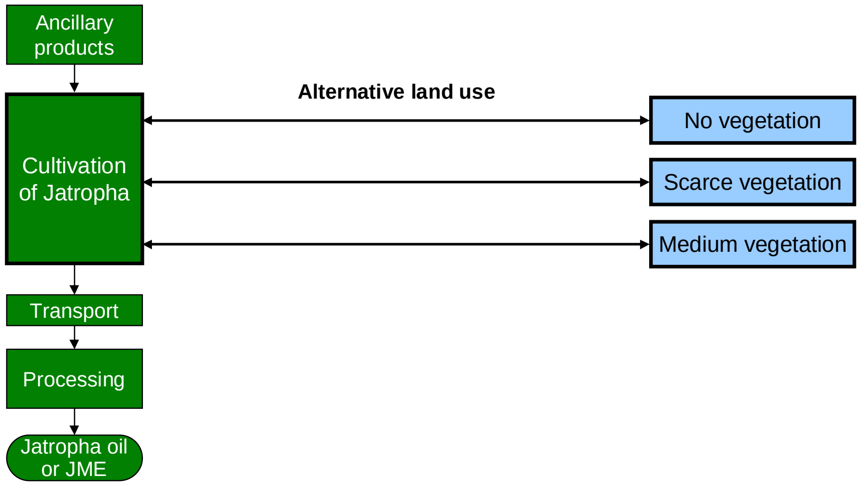


Fig. 3-3 Alternative land uses regarded for Jatropha cultivation in India

In order to include these carbon stock changes in the greenhouse gas balance, CSMCRI has determined the carbon content of their 3.5 year-old Jatropha plants to be 2.8 kg per plant. Multiplied by 1,667 plants per hectare, this amounts to roughly 5 t C / ha for a Jatropha plantation. Although fully-grown Jatropha plants presumably have a higher carbon content, the value of 5 t C / ha is used in this analysis. In Table 3-4**,** the carbon content of the alternative land uses is displayed. The carbon stock of ‘scarce vegetation’ was derived from /IPCC 2006/ (tropical semi-arid grassland), the one of ‘medium vegetation’ was defined on the basis of /Lasco et al. 1999/ (for details see /Reinhardt et al. 2007/). Even if the values on site should differ slightly from the ones chosen here, it does not matter for the qualitative evaluation of the question of carbon stock change.

For both qualitative and quantitative reasons, ‘scarce vegetation’ was chosen for the basic life cycle comparison, thus not leading to any carbon stock change and consequently not influencing the greenhouse gas balances.

Table 3-4 Carbon stock changes for different land use scenarios

Alternative land use	Carbon stock of natural vegetation [t C / ha]	Carbon stock of Jatropha plantation [t C / ha]	Carbon stock change [t C / ha]
No vegetation	0	5	+ 5
Scarce vegetation	5	5	± 0
Medium vegetation	25	5	- 20

Reinhardt et al. 2007

3.4 Production systems

Jatropha biodiesel is currently being produced in a small-scale pilot plant in Bhavnagar, India, following a decentralised concept, i.e. local production for local consumption. Alternatively, future production could also take place in large-scale centralised conversion plants. In this chapter, the differences between these two general production systems as well as a specific variant of centralised production are described.

3.4.1 Decentralised production

Fig. 3-4 depicts decentralised production as it takes place in the pilot plant involving the direct (mechanical) pressing of the entire seeds after removal of the husks. The crude oil is refined and can either be used directly or transesterified to Jatropha biodiesel (JME).

The by-products resulting from this decentralised processing option are the fruit husks, an oily cake (containing residual oil), fatty acids and – in the case of JME production – additionally glycerine and potassium (K) fertiliser.

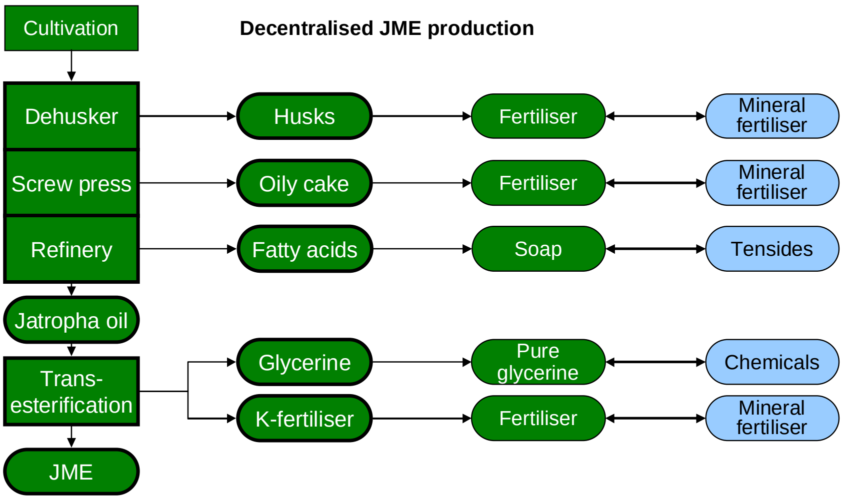


Fig. 3-4 Basic steps of decentralised JME production – Possible uses of the by-products and their equivalents (rightmost column) are exemplified for one option each.

3.4.2 Centralised production

Compared to small-scale decentralised production, a large-scale production in a centralised plant requires larger amounts of biomass and thus longer transport distances. On the other hand, the specific energy consumption is lower and the oil yield higher due to the fact that the mechanical pressing is followed by a solvent extraction. As shown in Fig. 3-5, this more sophisticated process involves the same basic process steps as the decentralised production but leads to fewer by-products (neither fatty acids nor K-fertiliser) and a de-oiled cake (no residual oil).

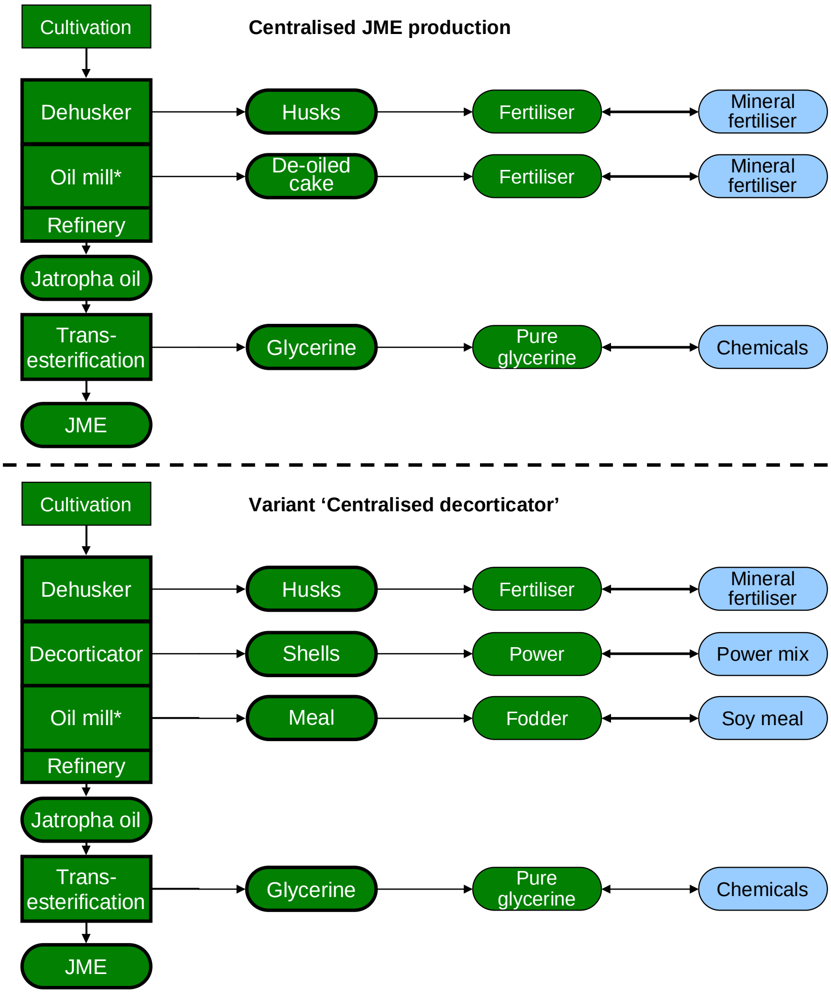


Fig. 3-5 Basic steps of centralised JME production and a variant – Possible uses of the by-products and their equivalents (rightmost column) are exemplified for one option each.

By-products for animal nutrition

Despite its high protein content, a direct utilisation of the cake as animal feed is unsuitable for two reasons: The cake contains both toxic substances and large amounts of seed shells which are rich in lignocellulose. If the by-products are nevertheless to be used for animal nutrition, there are two ways to deal with these problems: either a non-toxic protein concentrate can be extracted from the cake (see chapter 3.5.2) or the seeds can be decorticated (i.e. the seed shell removed) prior to the mechanical and solvent extraction. This latter variant, named 'Centralised decorticator' here, is also depicted in Fig. 3-5. After the oil extraction, a protein-rich meal is obtained which – after detoxification – could serve as animal feed. However, even if detoxification is not an option, decorticating the seeds may make sense if the biogas produced from the meal is economically valuable.

Otherwise, the 'Centralised decorticator' variant is identical to the centralised production process and also leads to the two by-products husks and glycerine.

3.5 Utilisation of products and by-products

Depending on the production system, different final products and by-products will be generated, each of which can be used in multiple ways. In this chapter, possible utilisations of both products and by-products are described.

3.5.1 Product utilisation

Like other vegetable oils, the inedible Jatropha oil can be used as a biofuel in both mobile and stationary applications. Pure plant oils (PPOs) are generally similar to conventional diesel fuel but differ in several important parameters (e.g. viscosity). As a consequence, PPOs are usually not suitable for use in conventional diesel engines. There are two possible solutions to this problem. Either the diesel engines are technically modified for the use of PPOs, or the vegetable oils are chemically converted into their methyl esters (biodiesel) resulting in a biofuel which is very similar to conventional diesel fuel.

The layouts of both the decentralised and centralised conversion processes are primarily aimed at the production of Jatropha biodiesel (JME) as this can be used in conventional diesel engines, e.g. car engines or power units. However, the intermediate product, pure Jatropha oil, could also be used as a liquid biofuel, e.g. for cooking stoves or adapted power units. This is especially interesting for decentralised production systems. Fig. 3-6 illustrates these utilisation options.

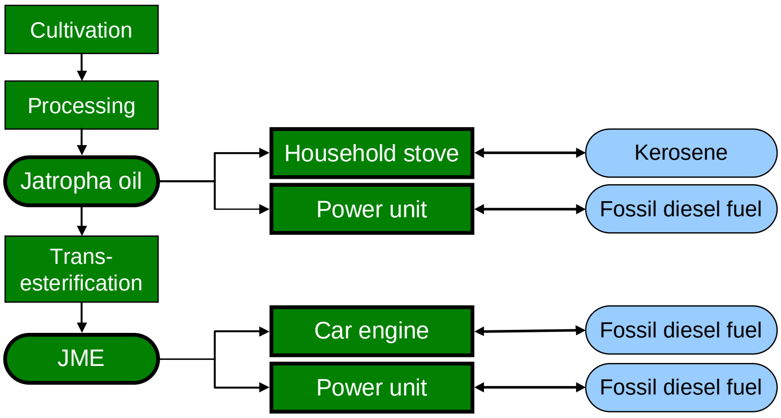
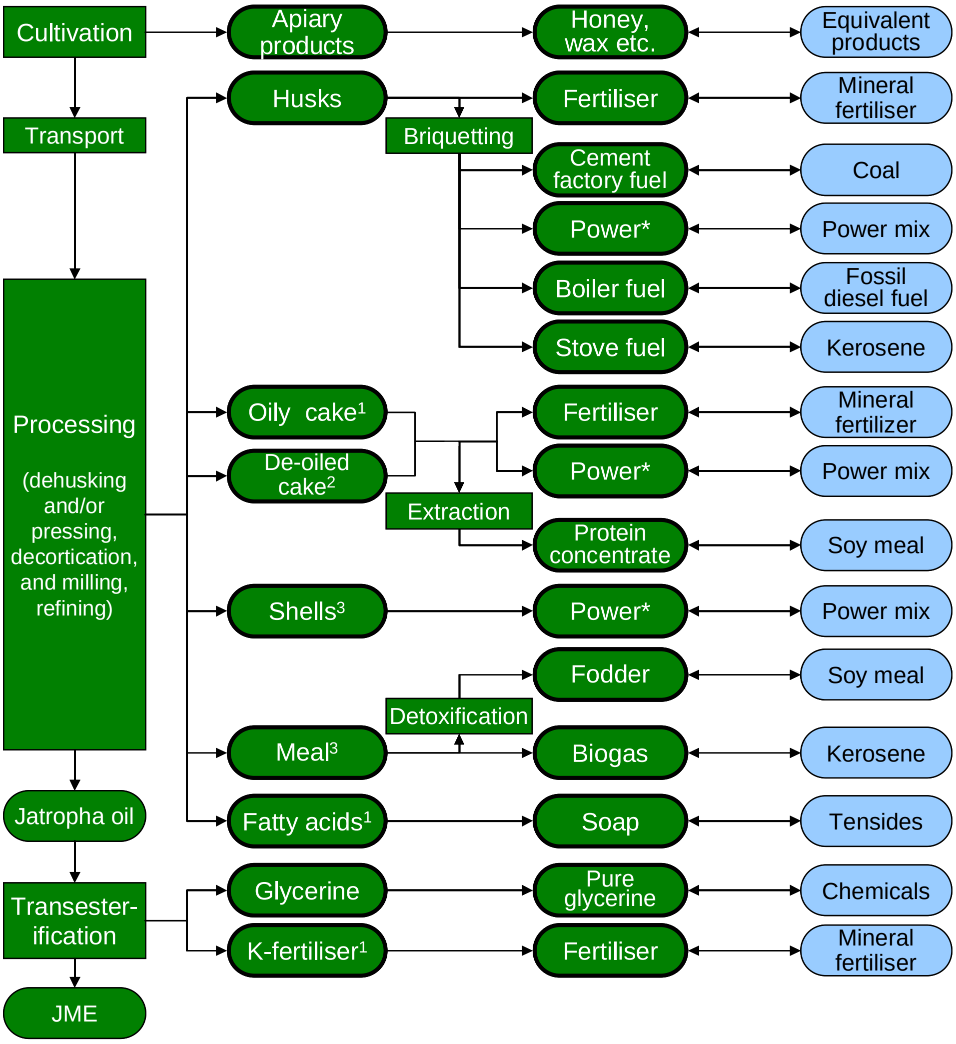


Fig. 3-6 Utilisation of Jatropha biofuels regarded in this study and their equivalents in terms of conventional products (rightmost column)

3.5.2 By-product utilisation

Along the life cycle of Jatropha oil and biodiesel, a number of by-products are generated. During the conversion to liquid biofuels, about 80% (by weight) of the Jatropha fruit emerge as residues, i.e. by-products. Fig. 3-7 gives an overview of these by-products and their respective uses regarded in this study.



^{1,2,3} production-specific by-products: ^{1} Decentralised, ^{2} Centralised, ^{3} Centralised decorticator

***** surplus power only

Fig. 3-7 Utilisation of by-products from Jatropha cultivation and processing regarded in this study and their equivalents in terms of conventional products (rightmost column)

Because most of the processing residues such as husks and cake are toxic, they are currently mainly used as fertilisers.

- Husks: This by-product can either be used as a fertiliser (basic scenario) or briquetted to form a solid biofuel. These briquettes could for example be used in cement factories, power stations, boilers and stoves and thus substitute for hard coal, power mix, diesel fuel and kerosene, respectively. Whether husks are also suitable for fuelling small-scale power units or co-generation units remains to be seen. At least, they could be used in a boiler to meet the process steam demand.

- Cake: Both oily and de-oiled cake can either be used as fertilisers (basic scenario) or as solid biofuels in power plants, thus substituting for power mix. Despite its high protein content, a direct utilisation as animal feed is unsuitable for two reasons: The cake contains both toxic substances and large amounts of lignocellulose (the former seed shell). In order to obtain a valuable product for animal nutrition, a non-toxic protein concentrate could be extracted from the cake. As this requires a relatively sophisticated process, which at the moment can only be realised at the lab scale, this option only applies to centralised production systems.
- Shells and meal: These two by-products result from the ‘Centralised decorticator’ variant instead of the cake. Here, the lignocellulosic shells and the protein-rich meal are obtained separately which facilitates their utilisation. The shells can be used as a solid biofuel in power plants, thus substituting for power mix. The meal, however, must be detoxified prior to utilisation as animal feed. Alternatively, it could be used as a biogas substrate.

In all cases, only the surplus power, i.e. the real output, is taken into consideration for the power production scenarios (marked with asterisks).

3.6 Synthesis of all main scenarios

For India-specific conditions, two main overall life cycle scenarios for Jatropha biodiesel are distinguished which are described in detail in chapter 3.4. Fig. 3-8 summarises the decentralised Jatropha biodiesel production – including the option of an alternative output of Jatropha oil – and Fig. 3-9 depicts the centralised Jatropha biodiesel (JME) production. Both schematic life cycle comparisons include all JME life cycle stages ‘from well to wheel’, that is to say from the cultivation of the Jatropha plant along Jatropha oil and biodiesel production all the way to their utilisation. Accordingly, they include the by-products generated from these production paths which can be used in different ways and represent added values.

Please note that the schematic life cycle comparisons in Fig. 3-8 and Fig. 3-9 represent India-specific conditions. Other or additional Jatropha oil and JME utilisation scenarios may apply in other regions in the world.

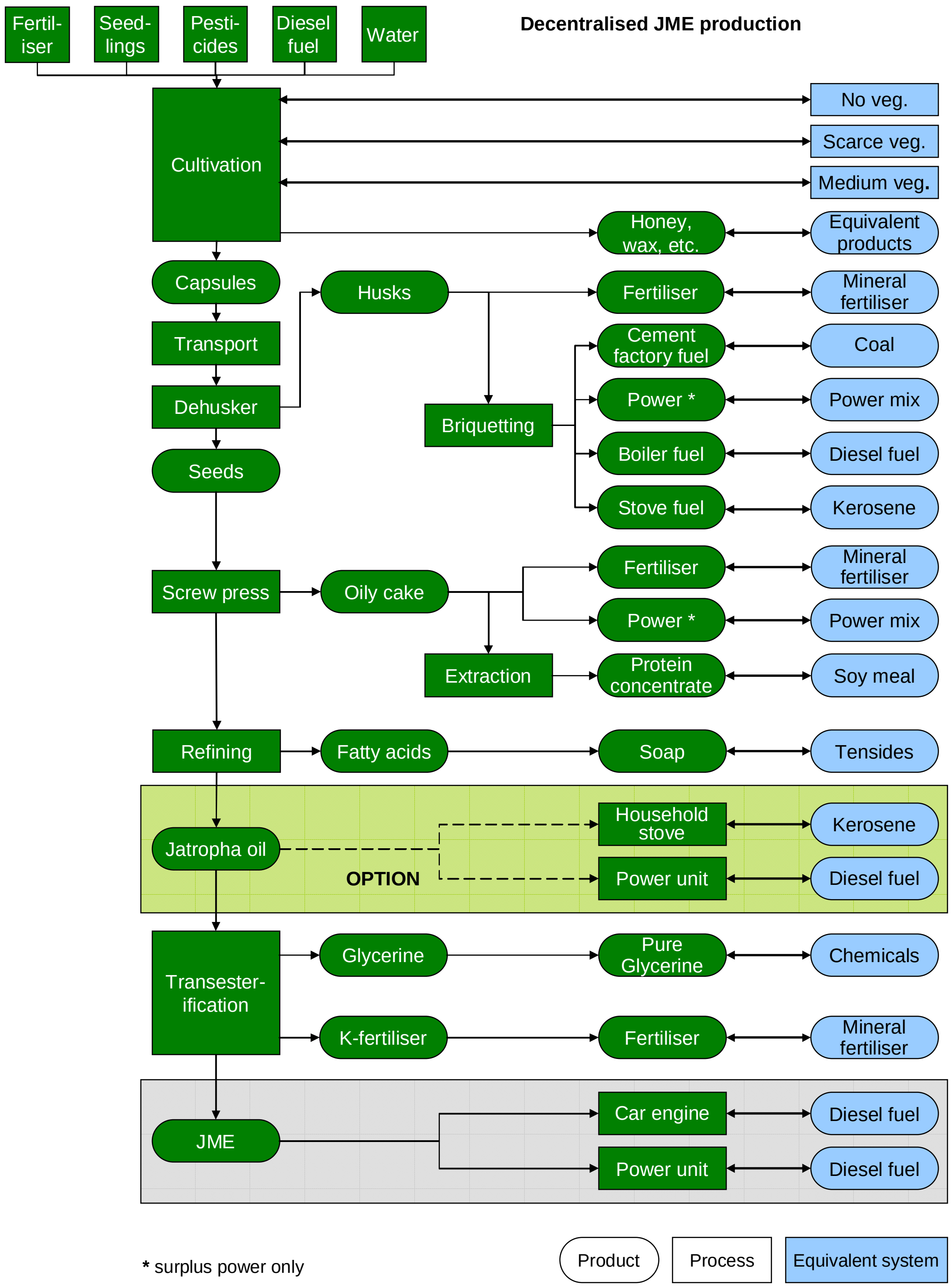


Fig. 3-8 Schematic life cycle comparison between Jatropha biodiesel (JME) and oil from decentralised production and conventional diesel fuel and kerosene, respectively, including different cultivation and scenarios as well as a number of alternative use scenarios concerning the utilisation of by-products (husks and meal). The (optional) transesterification step for the JME production is highlighted in the lower (lightly grey shaded) box.

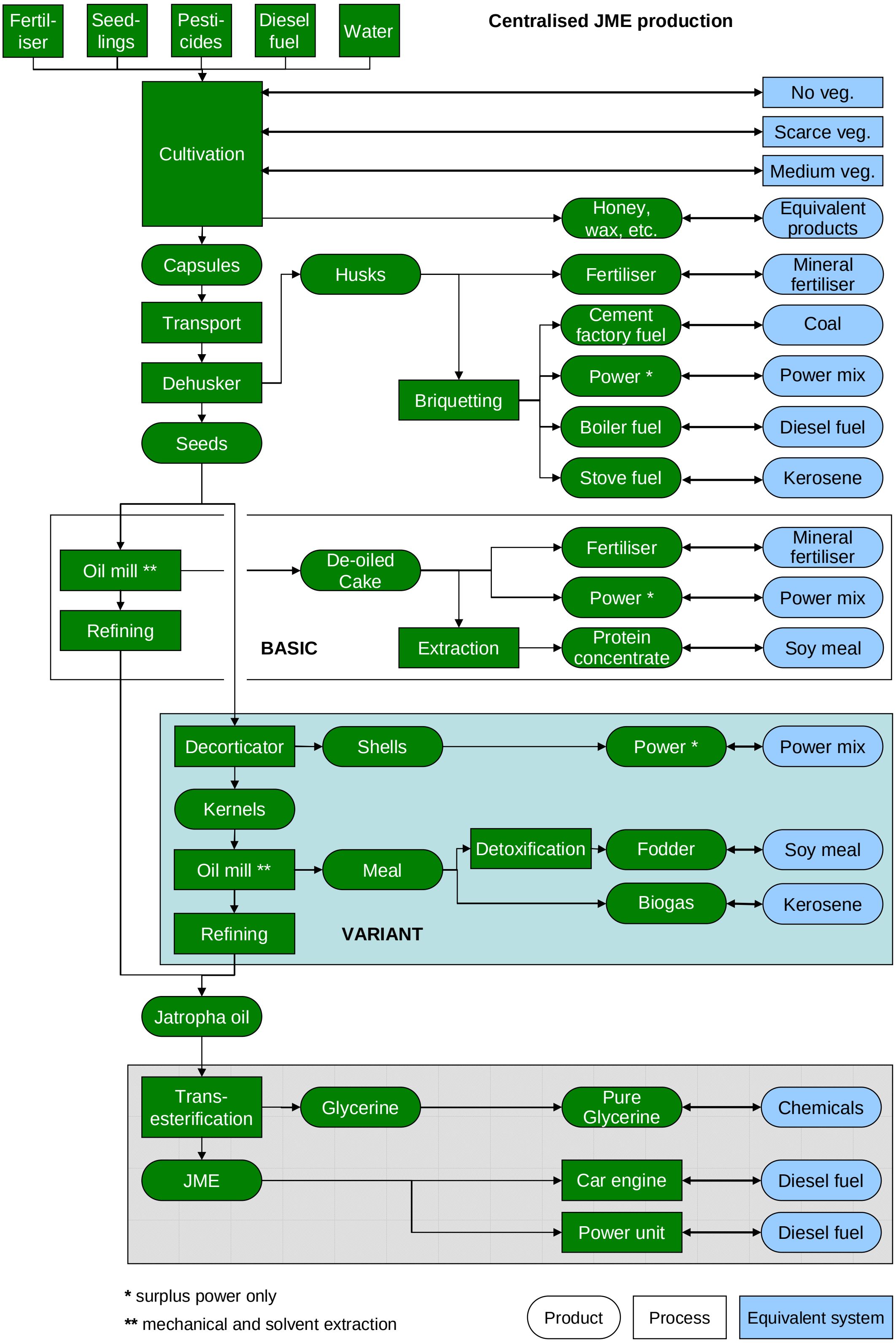


Fig. 3-9 Schematic life cycle comparison between Jatropha biodiesel from centralised production and conventional diesel fuel including different cultivation and scenarios as well as a number of alternative utilisation scenarios concerning the by-products (husks and meal). The variant including a decortication step is highlighted in the middle (blue) box.

3.7 Sensitivity analyses

In addition to the topics discussed so far, other parameters exist which may have a certain influence on the environmental impacts of Jatropha biodiesel – not only for the cultivation of Jatropha in India but also for Jatropha cultivation in other parts of the world. These parameters, for example transport distances and power systems, are presented in the following; the results of evaluations regarding their relevance for the balances are presented in the respective sensitivity analyses chapters.

3.7.1 Transport distance to centralised processing

The transports from the cultivation areas to the processing site are especially relevant in the case of a centralised oil production. The distances the fruit or seeds of the Jatropha plants must be transported depend on the capacity of the processing factories and on the yields of the cultivation sites – which on their part depend on the agricultural practices as well as on the land use intensity. These interrelations are described in further detail in the following. The underlying figures originate from /Reinhardt et al. 2007/.

Factory capacity:

- In this study, three factory capacity levels were distinguished based on the amount of JME produced per year: 20,000 tonnes per year (named ‘low’), 50,000 t / yr (‘medium’) and 100,000 t / yr (‘high’).

Land use intensity:

- To what extent the available land is used for the cultivation of Jatropha has a strong influence on the transport distances to the (nearest) processing site. In this study, two levels of land use intensity were regarded; they were defined as either 25% (‘realistic/medium’) or 50% (‘high’) Jatropha cultivation land within the factory’s catchment area. The lower the land use intensity, the greater the distance the fruit must be transported.

Yield from different cultivation regimes:

- Apart from the factory capacity and the land use intensity, another major determinant of the transport distances to the JME processing site is the actual yield from the Jatropha plantations. This amount depends largely on the agricultural practices applied, i.e. the plantation management is crucial. For this study, three cultivation scenarios were defined and named ‘Today’, ‘Optimised’ and ‘Best’ in accordance with increased harvests and/or oil content per fruit. They have already been described in more detail in the previous chapter (3.3.1).

Thus, the transport distances depend on these three parameters. The factory capacity determines how much biomass input can be processed. In order to calculate how far it must be transported to fulfil this demand to its optimum, the amounts produced in a certain area are identified by the land use intensity and the yield from the cultivation scenarios (‘Today’, ‘Optimised’ and ‘Best’). Fig. 3-10 illustrates the interrelation between these parameters and the resulting average transport distances; Table 3-5 lists the numerical outcome for the 18 settings regarded in this study.

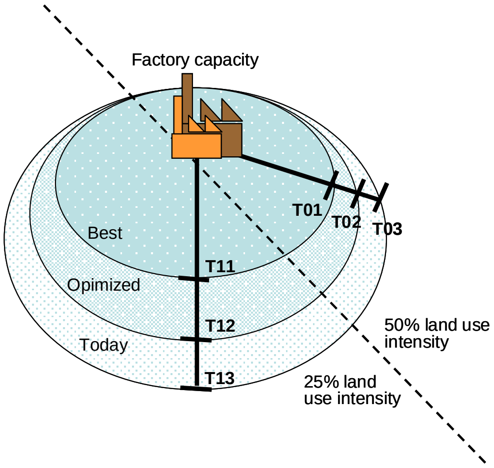


Fig. 3-10 Identification of average transport distances from Jatropha cultivation site to JME production facility, based on factory capacity, cultivation practice (i.e. yield) and land use intensity

Table 3-5 Average transport distances [in km] regarded in this study

Factory production capacity	Yield from Jatropha cultivation					
	Today		Optimised		Best	
	25% land use	50% land use	25% land use	50% land use	25% land use	50% land use
Low	17	12	13	9	9	7
Medium	27	19	21	15	15	10
High	38	27	29	21	21	15

Reinhardt et al. 2007

3.7.2 Emissions from product combustion

The combustion of Jatropha oil and biodiesel for energy generation leads to emissions which usually differ from those related to the combustion of conventional diesel fuel. On the other hand, biofuels help avoid emissions from conventional fuels. The credit for these avoided emissions depends on the conventional fuel's quality, e.g. its sulphur content. This sensitivity analysis investigates variations of both biofuel-related emissions and of avoided emissions.

Emissions due to Jatropha biodiesel combustion

Based on the measurements presented in Table 3-6, two scenarios for nitrogen oxides (NO_X) and hydrocarbons (HC) are derived. With the exception of a sensitivity analysis, specific biodiesel emission values are applied by default in the LCAs of JME in this study:

- 10% higher NO_X and 50% lower HC emissions (default)
- emissions equal to those of conventional diesel fuel (sensitivity analysis)

Table 3-6 Emissions of conventional diesel fuel and of Jatropha biodiesel (JME)

	Test	CO	HC	NO_X	Particul.	CO_2	Fuel cons.
Fossil diesel	Type approval	0.08	0.04	0.37	0.03	170	15.45
Biodiesel (JME)	Average	0.15	0.03	0.37	0.013	181	15.36
Change %		91%	-25%	-1%	-58%	7%	-1%

Degen 2007

Avoided emissions due to the substitution of diesel fuel

The outcome of the environmental impact assessment of JME may vary depending on the characteristics of the substituted conventional fuel, i.e. the fossil equivalent's environmental effects. One of these parameters – which differ greatly for the types of fossil diesel fuel used world-wide – is its sulphur content which can influence the acidifying effect of combustion.

Therefore, three levels of sulphur contents in fossil diesel fuels were taken into account. They reflect the range found in diesel fuels currently used world-wide /Degen 2007/:

- 10 ppm: maximum level in the European Union starting in 2009
- 500 ppm: common level in emerging countries, including India (default)
- 1000 ppm: common level in developing countries world-wide

3.7.3 Emissions from by-product combustion

The combustion of Jatropha by-products such as husks, cake or shells causes airborne emissions. IFEU has derived emission factors from its internal database; their influence on the overall outcome must be validated by means of a sensitivity analysis. The second part of this chapter deals with the emissions which can be avoided by substituting different types of conventional power.

Emissions due to by-product combustion

In order to validate the derived NO_X emission factors, two further scenarios are analysed with higher and lower NO_X emissions than in the default case:

- NO_X high: emissions from by-product combustion 50% higher than NO_X default value, from fossil fuel combustion (auxiliary energy demand and credits) 50% lower than NO_X default value
- NO_X low: emissions from by-product combustion 50% lower than NO_X default value, from fossil fuel combustion (auxiliary energy demand and credits) 50% higher than NO_X default value

Avoided emission due to substitution of power mix

Bioenergy generated from Jatropha husks, cake or shells substitutes for conventional energy which can be provided from different energy carriers. For India-specific cases, power is substituted for a so-called marginal mix by default. A marginal approach is based on the assumption that any future increase of conventional power generation will rely on either hard coal (80%) or natural gas (20%). In order to evaluate the corresponding range of results, two extreme cases are regarded: power from hard coal and natural gas, respectively (see Table 3-7). These energy carriers differ considerably regarding their emissions of carbon dioxide, sulphur dioxide and nitrogen oxides, thus leading to different credits for avoided emissions.

Table 3-7 Power systems regarded in this study for India and other geographic regions

Power mix	Description
Marginal mix ‘India’	Power from the public grid (80% hard coal : 20% natural gas)
Coal	Power exclusively from hard coal-fuelled power plants (100%)
Natural gas	Power exclusively from natural gas-fuelled power plants (100%)
	IFEU 2007

This generalisation also serves the purpose of allowing to transfer the results from India-specific conditions to other parts of the world where the power mix ranges somewhere between hard coal and natural gas.

3.7.4 By-product use for animal nutrition

If the cake or meal resulting from the JME production is used as animal feed, i.e. given that detoxification is possible, these substances’ nutritional values are relevant for the assessment of the environmental impact. Some research activities indicate that the composition of the proteins in the Jatropha cake is more nutritious than that of other animal feed, e.g. soy meal. In order to evaluate whether this has any impact on the environmental impacts, two scenarios of protein quality were defined: in the first scenario, Jatropha cake equals soy meal in its protein quality, in the second case, Jatropha cake has a protein quality twice as high as that of soy meal, so that less Jatropha protein than soy protein is needed in order to achieve the same nutritional effect. This aspect is thus evaluated in a sensitivity analysis (see chapter 4.7.5).

4 Results

In the following, the results of the life cycle comparison between Jatropha biofuels (pure oil and biodiesel) and conventional fuels are presented. The most decisive aspects along their life cycles are highlighted for different scenarios, options and variants and further investigated by means of sensitivity analyses.

4.1 Pilot plant scenario in detail

The life cycle comparison between Jatropha biodiesel (JME) and conventional diesel fuel is exemplified and briefly discussed for the pilot plant scenario which reflects the actual conditions of decentralised JME production in Bhavnagar, India. There, the husks and the oily cake are used as fertilisers and the fatty acids from the transesterification step are used for producing soaps (see chapters 3.4 and 3.5 for details).

Fig. 4-1 illustrates the results of the life cycle comparison between Jatropha biodiesel (JME) produced in the pilot plant and conventional diesel fuel for the impact categories Energy, Greenhouse effect, Acidification, Eutrophication, Summer smog and Nitrous oxide. A more detailed analysis of the greenhouse effect investigating (1) the relative contribution of each greenhouse gas and (2) the relative contribution of each life cycle stage can be found in the annex (chapter 6).

Results

- The energy balance for Jatropha biodiesel shows advantages, i.e. substituting JME for conventional diesel fuel saves fossil energy resources.
- The greenhouse gas (GHG) balances are also advantageous; however the savings stay within a small margin. This is mainly due to the nitrous oxide (N_2O) emissions from Jatropha cultivation and due to comparatively high energy inputs for the conversion from the raw materials to the biofuel product. In India for example, electric power is predominantly generated from hard coal which causes high CO_2 emissions.
- Acidification, eutrophication and nitrous oxide (a substance assumed to increase ozone depletion), however, increase if JME is used instead of conventional diesel fuel.
- Calculating summer smog balances with both methods described in chapter 2.1.3 yields clear advantages for POCP while for NcPOCP, the balance total is close to zero. Due to these significantly differing results, which point at a major influence of NO_X, no definitive statement can be made regarding the environmental impact category ‘Summer smog’.
- The various life cycle stages differ in their impact on the overall balances: Cultivation and processing are strong determinants, whereas transport has only a minor influence.
- The extent to which each life cycle stage contributes to the overall balance varies between the environmental impact categories: for example the greenhouse gas N_2O originating from fertiliser production and application influences strongly the GHG balance but has no influence on the energy balance.

Conclusions

The outcomes of the comparison between JME and conventional diesel fuel show both advantages and disadvantages for the biofuel. Based on these findings, an objective overall valuation is impossible. However, under consideration of subjective criteria, one might come to a (verbal-argumentative) conclusion. If, for example, saving energy and greenhouse gases is given the highest environmental priority, then Jatropha biodiesel can be judged superior to conventional diesel fuel.

Fig. 4-1 Results of the life cycle comparison between Jatropha biodiesel (JME) produced in the pilot plant and conventional diesel fuel. Upper part: detailed expenditures and credits. Lower part: resulting advantages and disadvantages for JME.

Reading the diagram (Exemplification)

The 1st bar shows expenditures of 15 GJ / (ha*yr) and credits of 7 GJ / (ha*yr) along the life cycle of JME. The 2nd bar shows the corresponding expenditures for the production of conventional diesel fuel, which amount to 16 GJ / (ha*yr). The 15th bar from the top depicts the energy balance total: By using JME instead of conventional diesel fuel in an average passenger car, about 8 GJ of primary energy can be saved yearly per hectare.

4.2 Comparison of environmental impacts

This chapter analyses the impact of different by-product utilisations on the overall results for six different environmental impact categories. It identifies general trends and patterns by contrasting the different environmental impact categories to each other in Fig. 4-2.

Results

- **Trends**: Energy and greenhouse gas balances generally show positive results, i.e. the use of Jatropha biodiesel instead of conventional diesel fuel usually leads to savings of fossil energy and greenhouse gas emissions. In contrast to this, the results for acidification, eutrophication and nitrous oxide are generally disadvantageous. The results for summer smog, however, mostly lead to advantages in terms of POCP but disadvantages in terms of NcPOCP. Therefore, this environmental impact category is excluded from further interpretation.
- **Patterns**: Most of the results follow a general pattern. Usually, an increase of energy and greenhouse gas savings leads to less favourable results for acidification, eutrophication and nitrous oxide.
- **Exceptions**: If results do not follow the above mentioned trends and patterns, they are displayed in the respective result chapters. Exceptions include, for example:
  - The generally advantageous trend regarding greenhouse gas balances can even be reversed if the carbon stock of the land converted into a Jatropha plantation is decreased (see chapter 4.6).
  - The general pattern is broken for by-product utilisations that involve a replacement of very polluting energy carriers, e.g. hard coal in a cement factory (in Fig. 4-2: 4th bar from top in each group = cement/fertiliser). In this case, a reduction of greenhouse gas emissions leads to a disproportionately great reduction of sulphur dioxide emissions thus resulting in a less unfavourable acidification balance.

Conclusions

The comparison of the outcomes concerning all environmental impacts regarded in this study shows that, generally, the qualitative results are the same for all scenarios under investigation. This reconfirms the overall pattern already known for other biofuels: advantages in terms of energy and greenhouse gas savings, but disadvantages regarding other environmental impact categories such as acidification, eutrophication and nitrous oxide. Therefore, the environmental impact categories acidification, eutrophication, summer smog and nitrous oxide will not be displayed in the following chapters (4.4 – 4.6). Instead, the results will primarily be exemplified for the greenhouse gas balances while specific cases in which the findings for the other impact categories are not in line with the general pattern will be discussed in sensitivity analyses (chapter 4.7.3).

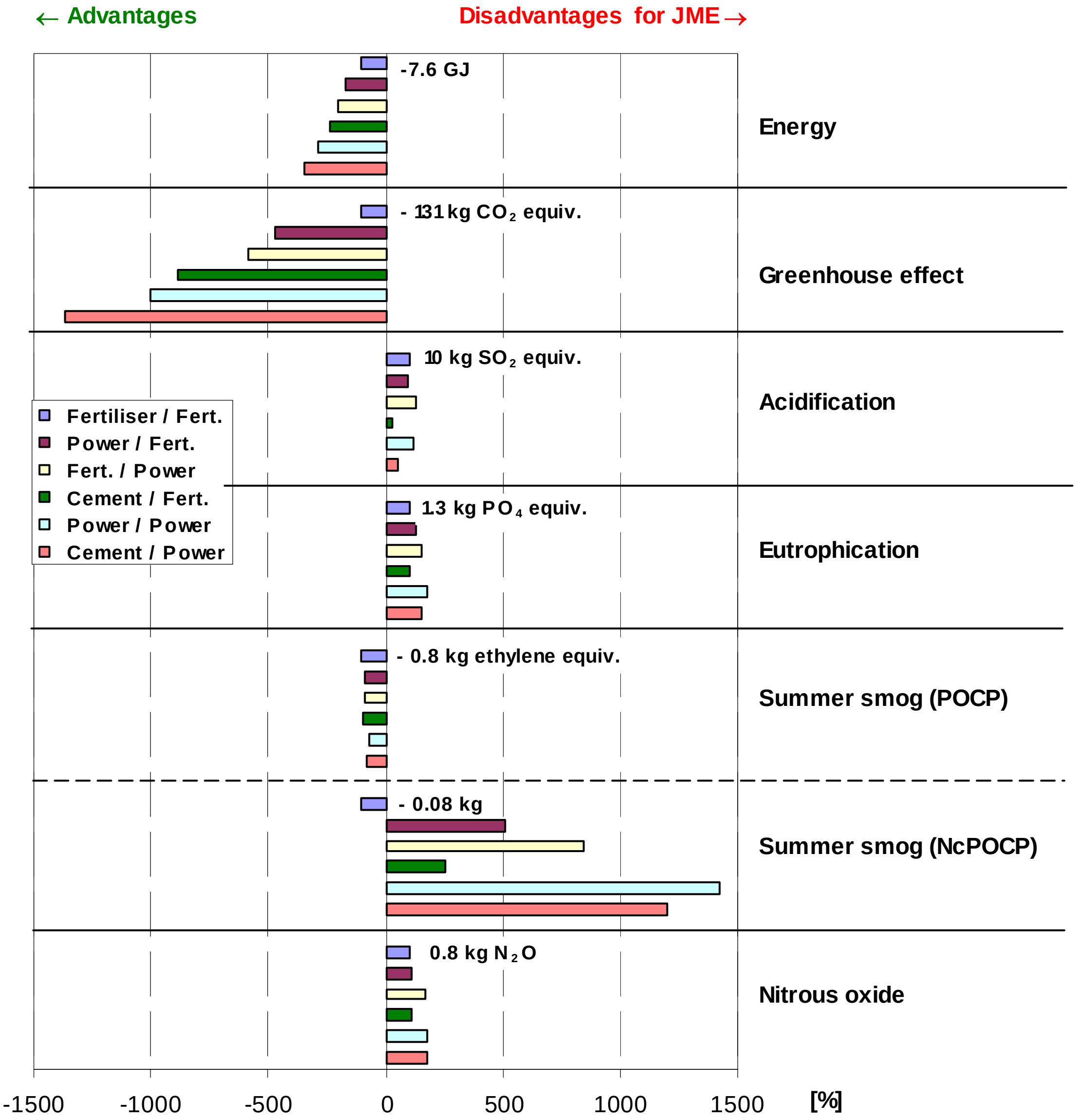


Fig. 4-2 Comparison of balance totals of Jatropha biofuels from different scenarios for six environmental impact categories – The top bar of each group represents the 'Pilot plant scenario', the corresponding value is listed to its right and defined as 100%. The other results (2nd -6th bar of each group) are depicted in relation to this.

Reading the diagram (Exemplification)

Using Jatropha biodiesel instead of conventional diesel fuel to run an average passenger car can lead to fossil energy savings. If the biofuel comes from decentralised production where the husks are used to fuel a cement factory and the cake is used as a fertiliser (4th bar from top), these savings can be twice as high as in the 'Pilot plant' scenario where both the husks and cake are used as fertilisers (top bar of each group).

4.3 Production plant scenarios

Biofuels from Jatropha oil can either be produced in small decentralised facilities such as the pilot plant in Bhavnagar or in larger centralised plants. These two options differ with regard to a number of parameters (see chapter 3.4 for details). This chapter first presents the results for optimisations of the decentralised production system, i.e. the pilot plant, as well as for selected centralised scenarios and then compares the two production systems with each other.

4.3.1 Decentralised production scenarios

Jatropha biodiesel (JME) is already being produced in pilot plants, for example in a small decentralised factory in Bhavnagar. The detailed results for this scenario, which are presented in chapter 4.1, point at a relatively low greenhouse gas saving potential. However, as such a pilot plant cannot be regarded as state-of-the-art commercial technology, various optimisation measures could be taken. These include reducing the external energy input, providing energy from by-products such as husks (steam self-sufficiency) or switching to different fossil energy carriers. Fig. 4-3 illustrates several of these possibilities for optimising the production process and compares them to the results for the pilot plant scenario.

Results and optimisation potential

- The utilisation of JME produced in the pilot plant instead of conventional diesel fuel leads to savings of 0.13 t CO_2 equivalents per hectare and year.
- Reducing the energy input for the production facility will improve the greenhouse gas balance of JME. A 50% reduction of the energy input into Jatropha conversion (as power and steam), for example, would triple greenhouse gas savings, i.e. 0.41 t CO_2 equivalents per hectare would be saved yearly.
- A second measure which could lead to an improved greenhouse gas balance is switching to (fossil) energy carriers in order to generate both the heat and power necessary for the JME production process. The required steam is currently generated from diesel fuel and power is taken from the Indian grid which relies primarily on hard coal. Both these fossil energy carriers could be substituted with a co-generation unit fuelled on natural gas. By opting for natural gas, twice as many (0.27 t) CO_2 equivalents could be saved yearly per hectare cultivation area.
- Another possibility to optimise the system is to strive for energy self-sufficiency, i.e. to provide as much – in the best case all – of the process energy using the occurring by-products. For example, the Jatropha fruit husks can be used entirely to produce all steam necessary for the conversion process. Also, a part of the Jatropha oil output could be recirculated inside the factory and used to fuel a co-generation unit. This concept would represent real energy self-sufficiency; the greenhouse gas balance of the JME resulting from such a production system (0.3 t of CO_2 equivalents) would lead to advantages similar to those of a natural gas-fuelled co-generation unit.

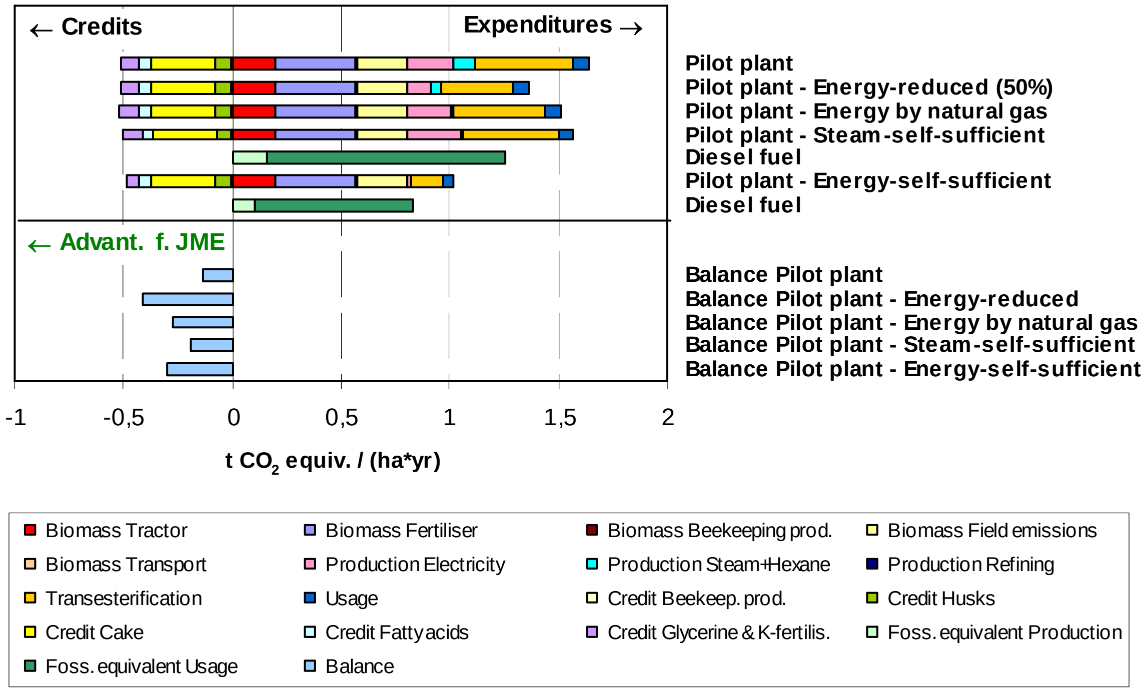


Fig. 4-3 Detailed greenhouse gas balance results for Jatropha biodiesel (JME) from different decentralised production scenarios, including the pilot plant scenario: optimisation potential regarding the energy-intensive processes of JME production

Reading the diagram (Exemplification for 2nd bar in the "Balance" group)

If Jatropha biodiesel is produced with a 50% lower energy input than in the 'Pilot plant' scenario and used instead of conventional diesel to fuel an average passenger car, 0.4 t of greenhouse gases can be saved yearly per ha cultivation area.

Conclusions

The outcome of the impact assessment for the pilot plant in Bhavnagar can be clearly upgraded by a number of optimisations. Possible measures include considerably reducing the process energy demand as well as generating the process energy on site through fossil fuels which account for less CO_2 emissions (e.g. natural gas) or, in the best case, by biofuels (e.g. husks for steam production or Jatropha oil for the total process energy). In case of a combined on-site power and steam production, an efficiency gain could be achieved versus the purchase of externally-produced power combined with own steam. A further reduction of the environmental implications could be realised by using the Jatropha oil internally, especially if this leads to the replacement of a power mix which accounts for high CO_2 emissions.

The proposed measures aim at reducing the process energy demand and at guaranteeing its on-site provision but have yet to be analysed regarding the technical viability. In particular, it must be found out which fossil fuels are available for the decentralised conversion plant in question and if these might be used in a small-scale CHP. Furthermore, it must be examined if such CHPs could also be fuelled on Jatropha oil instead of natural gas or diesel fuel.

4.3.2 Centralised production scenarios

Jatropha biodiesel (JME) production in larger centralised plants involves larger transportation distances (further analysed in chapter 4.7.2) but also an increase in oil yield per ton of input and a reduction of the specific energy demand. As described in chapter 3.4.2, a variant of centralised production involving the additional step of decorticating the seeds could be set up in order to obtain meal for animal feeding. Fig. 4-4 compares the two variants.

Results

- The greenhouse gas balance displays greater advantages for the 'Centralised decorticator' variant: 1.3 t of CO_2 equivalents could be saved per hectare and year compared to 0.8 t for the (standard) centralised production. The credit for shells and meal is largely dominated by the shells which are used for power generation. If this power credit was neglected, the two variants would lead to equal results regarding the greenhouse gas balance.

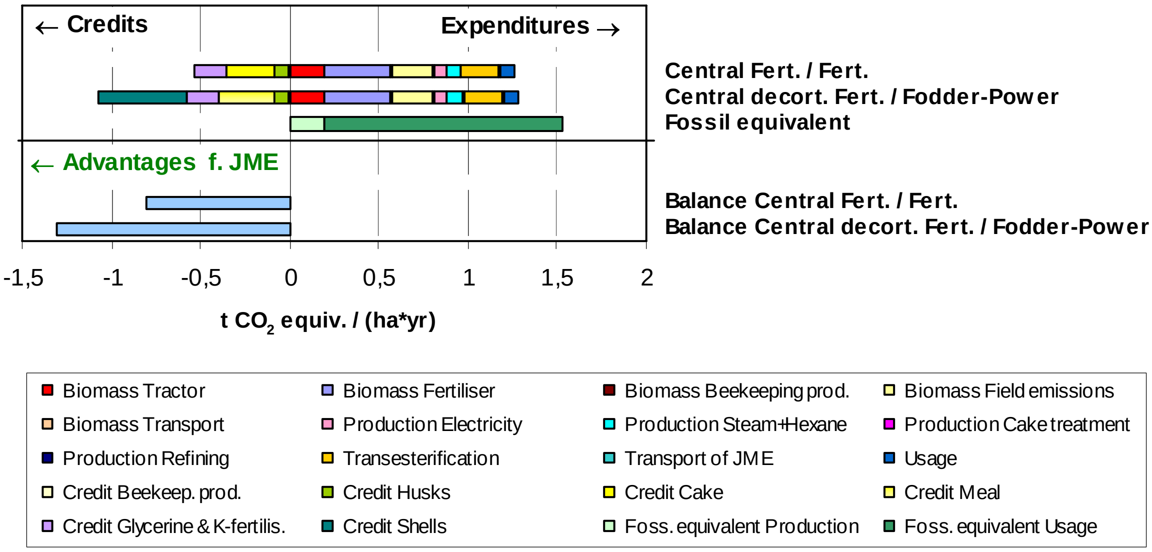


Fig. 4-4 Detailed greenhouse gas balance results for Jatropha biodiesel from different centralised production scenarios

Reading the diagram (Exemplification for 1st bar in the "Balance" group)

If Jatropha biodiesel originating from centralised production is used instead of conventional diesel, 0.8 t of greenhouse gases can be saved yearly per ha cultivation area.

Conclusions

The 'Centralised decorticator' variant is to be preferred from an environmental perspective because of the following side-effect: with the shells, a bioenergy carrier becomes available which is readily usable in power plants, thus leading to corresponding credits for saved conventional energy carriers.

4.3.3 Decentralised versus centralised production

In the following, the outcomes of a comparison between the decentralised and centralised JME production options are presented. Fig. 4-5 shows the detailed results for a selection of four such scenarios. It must be kept in mind that the results determined for the pilot plant technology (which is still quite far away from having commercial status) can not be considered generally valid for decentralised JME production.

Results

- Generally, the centralised production of JME shows greater advantages than the decentralised one. This is due to higher credits for the glycerine resulting from transesterification as well as due to lower expenditures for transesterification and power generation.

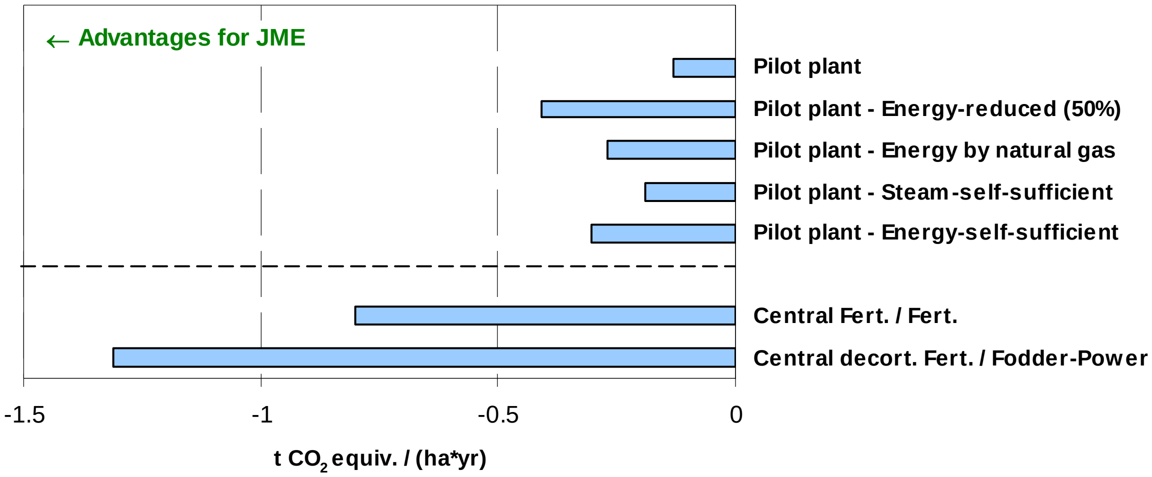


Fig. 4-5 Results of greenhouse gas balances for Jatropha biodiesel from different decentralised and centralised production scenarios in comparison

Reading the diagram (Exemplification for last bar)

By using Jatropha biodiesel originating from the centralised production variant which includes a decortication step and where the by-products are used as fertiliser (husks), for animal feed (meal) and for power production (shells) to fuel an average passenger car, 1.3 t of greenhouse gases can be saved yearly per ha cultivation area compared to conventional diesel fuel.

Conclusions

In the centralised production system, the greater expenditures for transport are overcompensated by a lower energy demand as well as by higher oil yields. Therefore, the comparison between the decentralised pilot plant and a centralised production system delivers clear environmental advantages for the latter, i.e. under environmental aspects centralised concepts should be preferred over decentralised ones. However, encouraging decentralised production – despite its slightly less favourable environmental performance – might well be beneficial to sustainable development if it leads to considerable socio-economic advantages.

4.4 Utilisation of Jatropha-based biofuels (products)

Different uses of pure Jatropha oil and biodiesel have been described in chapter 3.5.1. In the following, the corresponding results are presented. Fig. 4-6 allows the comparison between the use of Jatropha-based biofuels originating from both decentralised and centralised production as transport fuels and in stationary facilities.

Results

- For the decentralised production system, the use of the pure plant oil shows more favourable results in terms of energy and greenhouse gas savings. The relatively high energy demand of the transesterification process is not compensated by the clearly lower credit for the by-product glycerine.
- In centralised production systems no significant differences occur between the use of pure Jatropha oil and that of JME. The reason behind this is the relatively small expenditure for the transesterification in relation to the credit resulting from the by-product glycerine when it substitutes for chemicals. In analogy to /Reinhardt et al. 1999/ it might be said as follows: If the glycerine were to be used for energy, the use of the pure Jatropha oil would be more advantageous. If, on the other hand, it were to substitute technical glycerine, JME would be the better option.
- In general, no significant differences are to be found between the two options of using Jatropha biodiesel, either as a fuel for vehicles or for stationary facilities.

Conclusions

From an environmental perspective, the difference in results between the use of pure Jatropha oil and that of JME from centralised production is minimal. This is due to the fact that the additional expenditures for the transesterification and the credits for the chemically used glycerine practically counter-balance each other. When regarding the pilot plant scenario, however, a comparison between the use of oil and JME reveals clear advantages for the Jatropha oil, i.e. under current process management conditions, the transesterification should either be refrained from or all efforts should be made to optimise the conversion plant.

If for technical reasons process optimisation in the pilot plant is not possible, the following choice appears most reasonable from an environmental perspective: instead of processing the extracted Jatropha oil to biodiesel in an energy-demanding transesterification step, it should be used directly in stationary facilities. It can, for example, be used in household stoves instead of kerosene stoves or in a power unit where it replaces conventional diesel fuel.

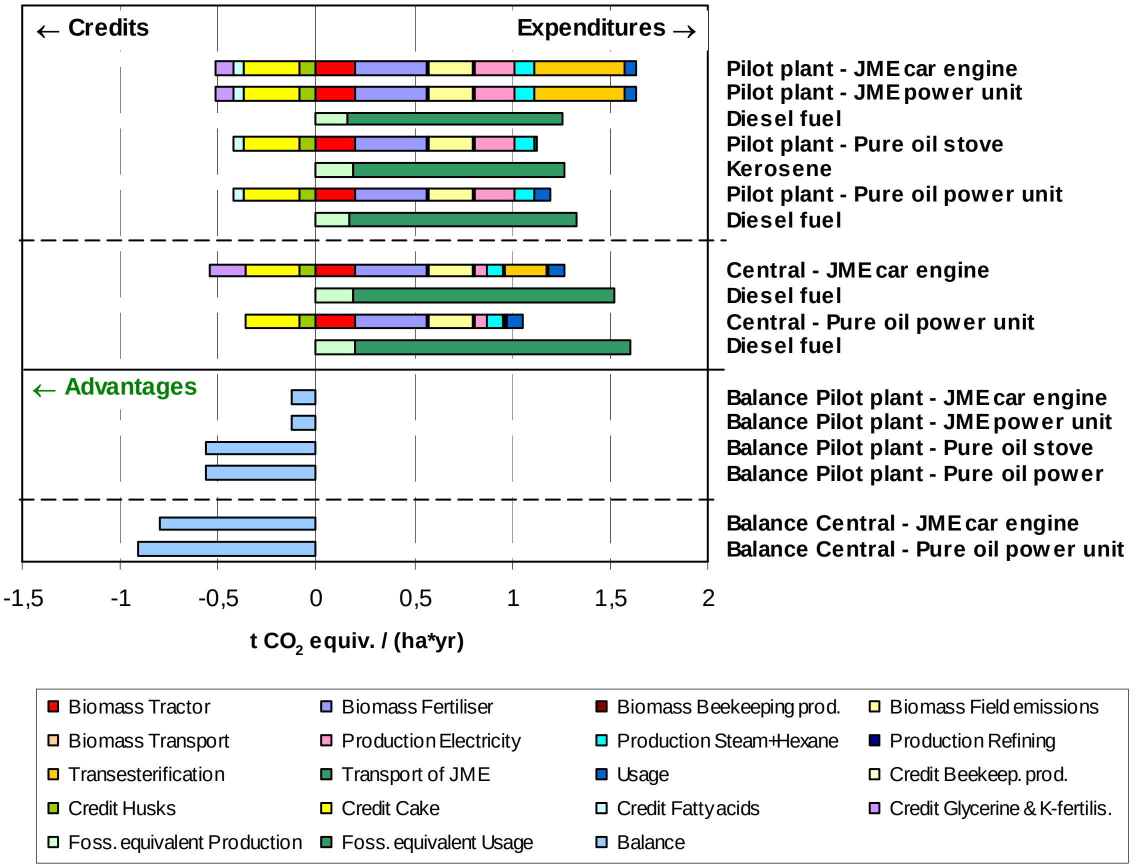


Fig. 4-6 Detailed greenhouse gas balance results for Jatropha biodiesel (JME) used as a transport fuel (car engine) and in stationary facilities (power unit) as well as for pure Jatropha oil used as a stove fuel and in stationary facilities (power unit), both originating from decentralised (pilot plant) and centralised production scenarios

Reading the diagram (Exemplification)

By fuelling an average passenger car with JME from the 'Pilot plant' production scenario (1st bar in the "Balance" group below the solid line) instead of conventional diesel fuel, 0.13 t of CO_2 equivalents can be saved yearly per ha cultivation area. If instead the pure plant oil from the same scenario is used as a stove fuel (3rd bar in the "Balance" group), these savings can amount to 0.57 t of CO_2 equivalents per ha.

4.5 Utilisation of by-products

As mentioned in the context of the production technology, the by-products which occur during the processing of Jatropha fruit to biofuel account for the greatest part of the credits and expenditures which are weighted against each other in the balances. This chapter highlights the most important environmental impacts of the by-products; Fig. 4-7 exemplifies them for different combinations and production scenarios.

Results

- The utilisations of the by-products which occur during the processing of Jatropha fruit to biofuels represent the most decisive parameters.
- Using the by-products as energy carriers leads to much better results than using them as fertiliser or for animal feed (incl. protein). For example, the credits given to the husks and oily cake are clearly higher when these fruit fractions are used to generate power (e.g. for cement factories) while using the husks as a fertiliser leads to practically no benefit. (Accordingly, the differences between the fossil energy savings of different production systems are greater when the by-products are used for energy than when they are used directly as biomaterials.)
- The potential of reducing the environmental impacts by using Jatropha biofuels is strongly determined by the utilisation of the by-products. Using these for energy production leads to greater savings of energy and greenhouse gases than the use of the main product, Jatropha biodiesel, itself and therefore is to be recommended. Using them directly as biomaterials (substances) should be avoided.
- A more detailed evaluation of this interrelation with respect to the power systems in other parts of the world was conducted by means of a sensitivity analysis; the corresponding results are presented in chapter 4.7.4.

Conclusions

The purposes the by-products are used for are of considerable importance for the outcomes of the life cycle impact assessments. If energy is produced from them, for example, this leads to greater environmental benefits in terms of energy savings and greenhouse effect than the use of the main product Jatropha biodiesel itself. Provided that it is technically possible to produce energy through the combustion of the husks and cake or, in centralised decorticator production, the husks, shells and meal, then – regarding the environmental impacts – this option is to be preferred over a utilisation as animal feed or fertiliser, both of which produce very similar results. This means that apart from using the Jatropha oil, greatest efforts should be made to push the development of concepts for facilitating the use of the by-products for energy-producing purposes.

Concerning the cake which might be difficult to handle in combustion facilities, it remains to be examined if and to what extent its use for generating energy is technically possible.

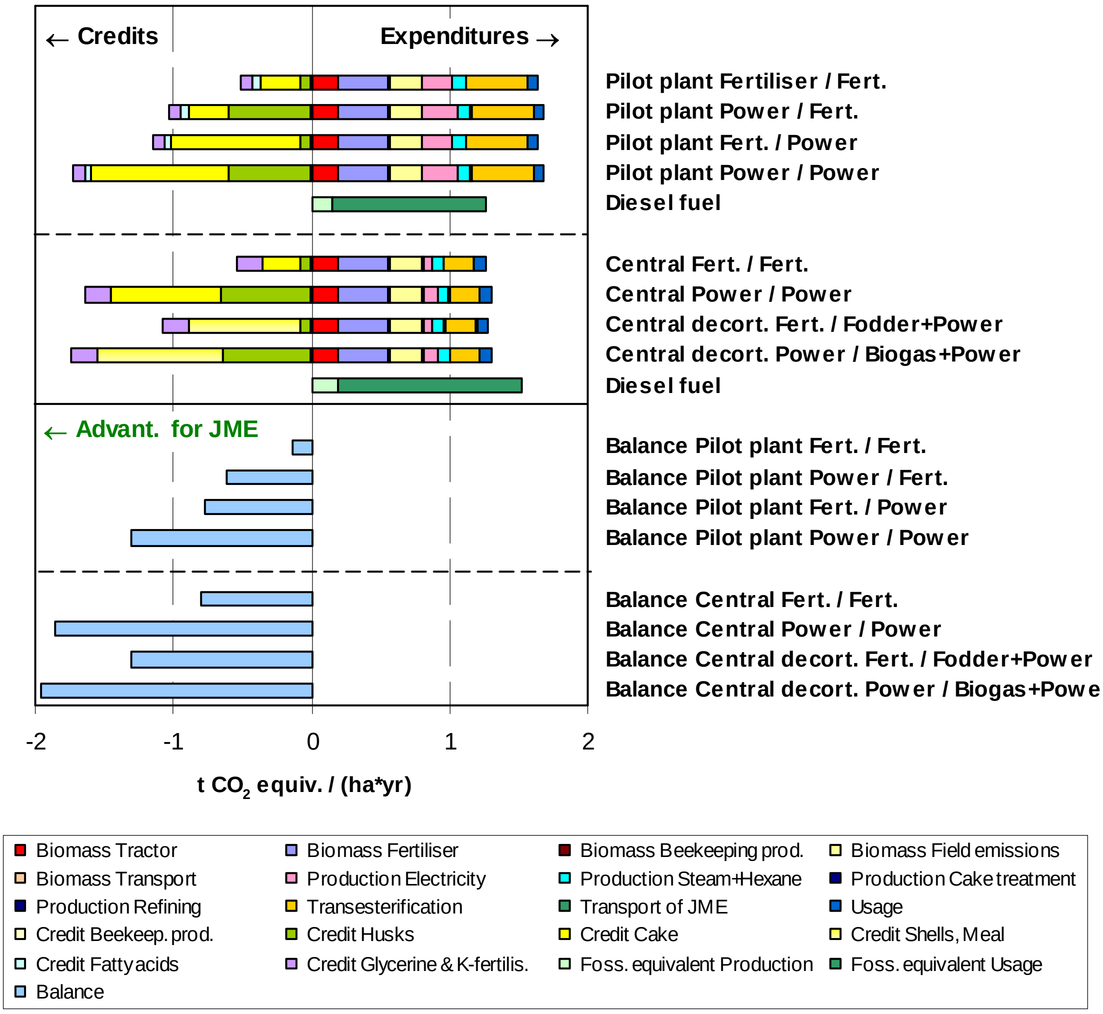


Fig. 4-7 Detailed greenhouse gas balance results for Jatropha biodiesel used as a transport fuel (JME) originating from decentralised or centralised production and different uses of the by-products

Reading the diagram (Exemplification)

By replacing conventional diesel fuel as a passenger car fuel with JME from centralised production and using the by-products husks and cake entirely to generate power (3^{rd} bar from bottom), 1.86 t of CO_2 equivalents can be saved yearly per ha cultivation area.

4.6 Carbon stock changes and depreciation period

As indicated in chapter 3.3.2, the carbon stock (in biomass and soil) of the land used for the establishment of Jatropha plantations may change. For example, if a desert-like area is chosen, its carbon stock can increase. The so-called alternative land uses can therefore greatly influence the outcome of the greenhouse gas balance.

Fig. 4-8 exemplifies the impact of the three alternative land uses regarded in this study on the ‘Pilot plant’ JME production scenario. The main results can be summarised as follows:

Results

- The alternative land use to Jatropha cultivation has a strong influence on the carbon balance of the area, i.e. on the greenhouse gas balance of JME. Considering a ‘no vegetation’ or ‘scarce vegetation’ situation leads to advantages in the balance (0.13 – 1.05 t CO_2 equivalents) while an alternative land use characterised as ‘medium vegetation’ delivers disadvantages (-3.53 t CO_2 equivalents).
- Viewing the carbon stock change over a longer period of time lessens its immediate impact on the greenhouse gas balance. However, no general agreement exists regarding the question which time span is to be considered in terms of scientific correctness and functionality. Generally, it can be said that the longer Jatropha is cultivated on a specific area, the less unfavourable the balance turns out in case of an actual carbon loss. If, on the other hand, the land use change leads to carbon sequestration, a shorter depreciation period results in a quantitatively even more advantageous balance total.

Conclusions

When land use changes are involved, the quantitative outcomes of the greenhouse gas balances depend largely on the carbon stocks of the above- and below-ground biomass as well as on the carbon stock of the soil. For the cases regarded here, only example values are known for this type of data; the carbon stocks must thus be explored in more depth within a system-analytical approach.

The establishment of a Jatropha plantation (on semi-natural land) influences the carbon stock of the area in question. Any accumulative or depleting change has an immediate and clear impact on the greenhouse gas balance. Generally, this impact is the stronger the shorter the regarded depreciation period is. Therefore, when a piece of land is developed for a Jatropha plantation, a reduction of the carbon stock of this area must absolutely be prevented.

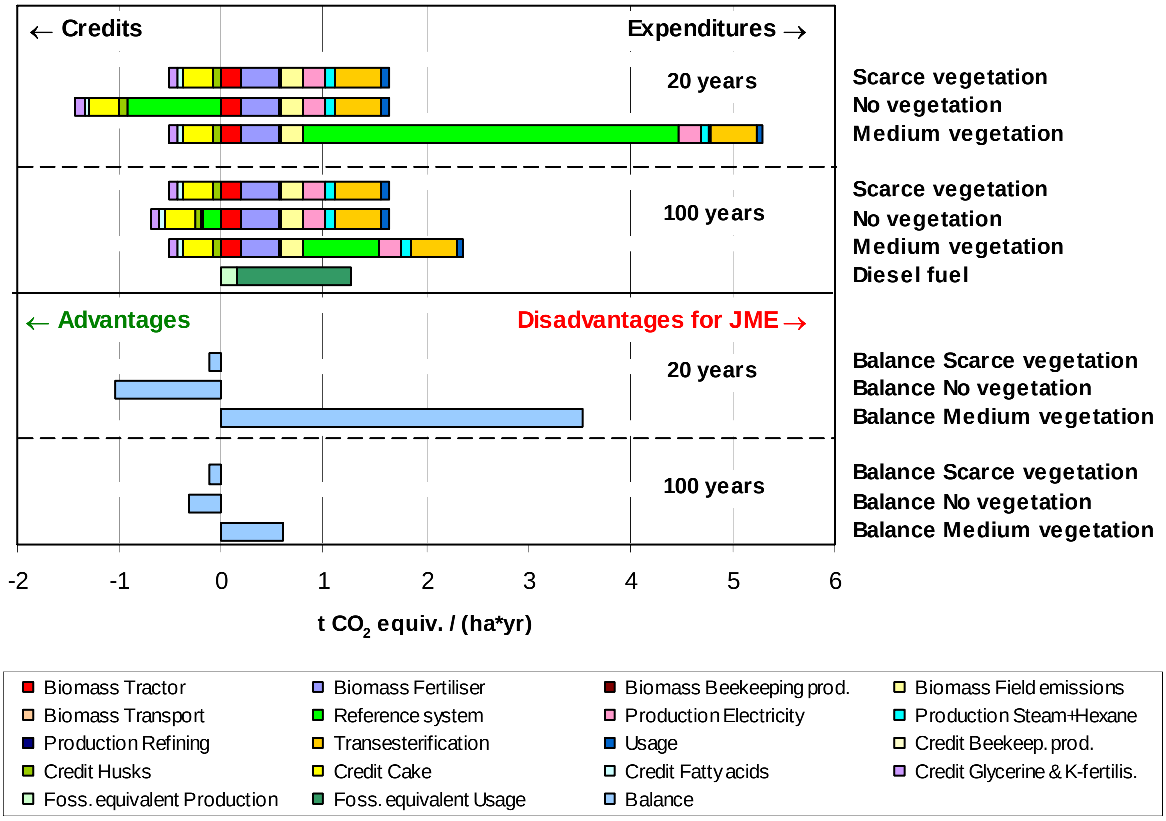


Fig. 4-8 Detailed greenhouse gas balance results for JME from the ‘Pilot plant’ production scenario under consideration of three different alternative land uses (‘no vegetation’, ‘scarce vegetation’ and ‘medium vegetation’) and two different depreciation periods (20 and 100 years)

Reading the diagram (Exemplification)

Replacing conventional diesel fuel as a passenger car fuel by JME from the ‘Pilot plant’ production scenario can lead to yearly savings of 1.05 t of CO_2 equivalents per ha cultivation area when the alternative land use is ‘no vegetation’, i.e. a desert situation, and the depreciation period chosen for the carbon stock change is 20 years.

4.7 Sensitivity analyses

Several parameters influence the LCA results of Jatropha biodiesel (JME). In the following, sensitivity analyses are presented in order to quantify the influence of specific parameters and to help interpret their meaning for the environmental effects of the use of Jatropha as a biofuel.

4.7.1 Cultivation scenarios

As already described in chapter 3.3.1, three cultivation scenarios are regarded in this study: Today, Optimised and Best.

Fig. 4-9 shows which effect these different cultivation scenarios have on the greenhouse gas balance of JME. The left and right parts of the figure differ in their reference. On the left side, the reference is ha*yr, on the right side it is t seeds.

Results

- The left graph shows that – granted the reference is the area under cultivation – agronomic optimisation leads to bigger savings of greenhouse gases compared to the current situation. Further optimisation and improved plant breeding (the 'Best' scenario) even result in greenhouse gas savings six times higher than currently possible.
- However, if the results are regarded for tonnes of seeds, agronomic optimisation has nearly no effect in terms of greenhouse gas savings while the effect of improved plant breeding is still positive – but to a far lesser extent.

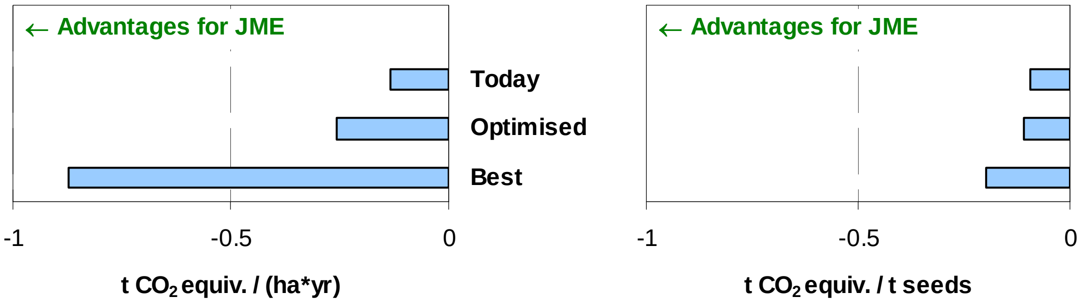


Fig. 4-9 Results of greenhouse gas balances for JME from the 'Pilot plant' production scenario under consideration of three different cultivation scenarios, i.e. biomass yield levels ('Today', 'Optimised' and 'Best') – Comparison for two different references: 'hectare and year' and 'tonnes of Jatropha seeds'

Reading the diagram (Exemplification for 3rd bar of left graph)

By fuelling average passenger cars with JME from the 'Pilot plant' production scenario instead of conventional diesel fuel, 0.8 t of CO_2 equivalents can be saved yearly per ha cultivation area if improved plant breeds are grown under optimised cultivation conditions.

Conclusions

The results are strongly determined by the reference which is chosen for the analysis so that an increase in production per cultivated area does not necessarily lead to a better outcome in terms of the environmental impact assessment. Against the background of a worldwide increase of land competition in the future, it is appropriate to regard one hectare of cultivation area – especially if spatial limitations are to be expected even for marginal areas. In this case the area efficiency will play the essential role and Jatropha might have to prevail against competing crops such as Pongamia or the castor oil plant, so that an increase of the yields through agronomic and especially breeding progresses is absolutely desirable.

4.7.2 Transport distance to centralised processing

If Jatropha biodiesel is produced in a large centralised factory, the fruit must be transported to this factory from some distance away. How far exactly depends on the three parameters described in chapter 3.7.1, namely the factory capacity, the cultivation scenario and the land use intensity. In Fig. 4-10, the outcomes of a corresponding comparison are presented, varying in terms of the reference. The left graph shows the influence of the transport distances on the greenhouse effect per hectare and year, the right graph per tonne of seeds.

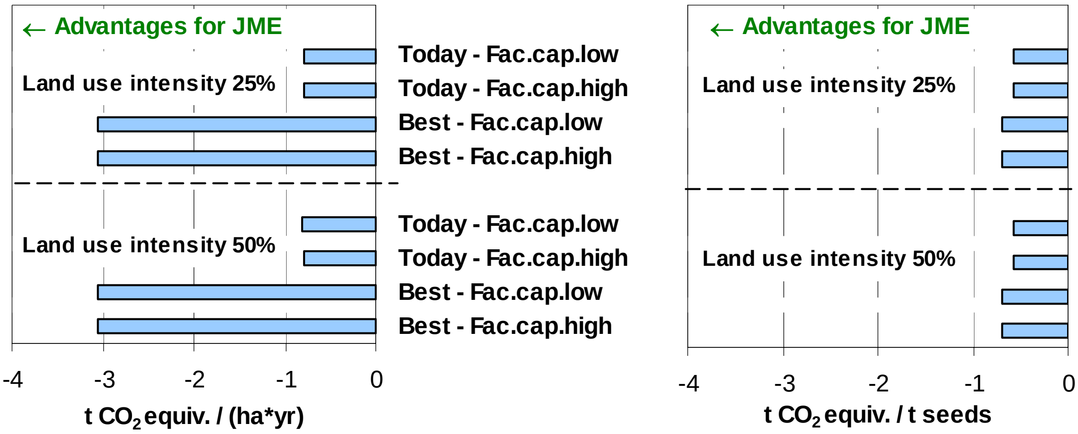


Fig. 4-10 Results of greenhouse gas balances for JME from centralised production under consideration of two different cultivation scenarios (‘Today’ and ‘Best’), two different factory capacities (‘low’ and ‘high’) and two different land use intensities (‘25%’ and ‘50%’) – Comparison for two different references: ‘hectare and year’ and ‘tonnes of Jatropha seeds’

Reading the diagram (Exemplification for 3rd bar of left graph)

By fuelling average passenger cars with JME from the centralised production scenario instead of conventional diesel fuel, 3.1 t of CO_2 equivalents can be saved yearly per ha cultivation area if ‘Best’ cultivation practices are combined with a 25% land use intensity and the factory capacity is ‘low’.

Results

- The land use intensity and factory capacity hardly influence the greenhouse gas balance. (If less fruit are processed, the greenhouse gas balance is slightly more favourable, just as it might be expected; this, however, practically plays no role.)
- This analysis examining the transport distances thus shows that the only significant parameter regarding the greenhouse gas balance is the cultivation (or yield). As shown in the previous chapter 4.7.1, however, its influence depends on the reference which is chosen for the illustration. If the reference is one hectare per year, agronomic optimisation and improved plant breeds can lead to four times higher greenhouse gas savings. When depicting the outcome for one tonne of seeds instead, this results in only a very slight improvement of the greenhouse gas balance of JME.

Conclusions

The results are again strongly determined by the reference chosen for the analysis (see chapter 4.7.1). In other words, differences are only significant when the outcomes are regarded per hectare of cultivation area. Compared to the cultivation scenario, the factory capacity and land use (or stock) intensity only play a minor role for the transport expenditures. An increase of these expenditures (i.e. longer transport distances) only has a minimal affect on the LCA results; above that it is overcompensated by the oil yield which is clearly greater than in the decentralised production.

4.7.3 Emissions from product combustion

This sensitivity analysis investigates variations of two parameters: (1) sulphur dioxide (SO_2) emissions which are avoided by substituting conventional sulphur-containing diesel fuel for sulphur-free JME and (2) biofuel-related nitrogen oxide (NO_X) emissions which usually differ from those related to the combustion of conventional diesel fuel (see chapter 3.7.2 for details). As these gaseous emissions influence acidification and eutrophication, the outcomes for these environmental impact categories are shown in Fig. 4-11.

Results

- Substituting JME for conventional diesel transport fuel with a high sulphur content leads to slightly reduced disadvantages regarding acidification.
- The variation of the JME emission factors has no significant relevance for acidification and eutrophication.

Conclusions

Both the sulphur content of the replaced conventional diesel fuel and the level of NO_X emissions from the combustion of JME only have a minor influence on the results of the acidification and eutrophication balances. However, substituting high-sulphur conventional diesel fuel, e.g. as it is commonly used in countries like India, Tanzania or Nicaragua, is more advantageous than a substitution of low-sulphur diesel as it is common in Europe, for example. For the regarded conditions, this means that Jatropha biodiesel should rather be used locally than exported to Europe.

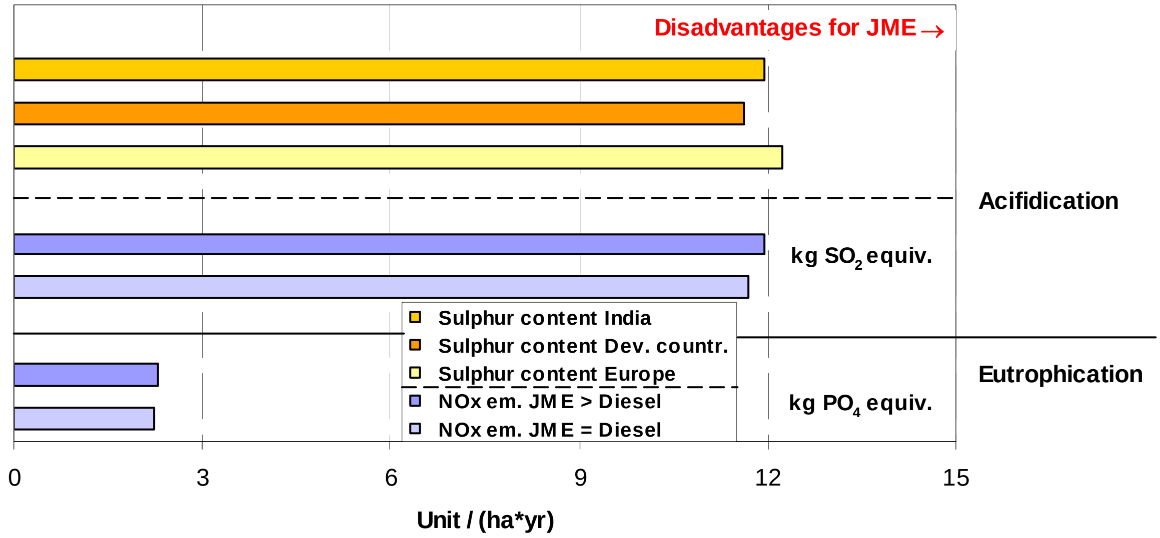


Fig. 4-11 Results of acidification and eutrophication balances for different variations of the substituted fuel's sulphur content (top three / orange bars) and variations of the NO_X emissions (em.) resulting from Jatropha biodiesel (JME) combustion in the pilot plant (lower four / blue bars)

Reading the diagram (Exemplification for 1st and 4th bar)

Substituting Jatropha biodiesel (JME) from the 'Pilot plant' scenario for conventional diesel fuel with a sulphur content of 500 ppm increases acidification by 11.9 kg per hectare and year if NO_X emissions from JME combustion are 10% higher than those from combustion of conventional diesel fuel.

4.7.4 Emissions from by-product combustion

As described in chapter 3.7.3, the combustion of by-products leads to both expenditures (emissions) and credits (avoided emissions). The blue bars in Fig. 4-12 illustrate the effect of the type of fossil energy carrier which Jatropha bioenergy substitutes for on the environmental impact categories greenhouse effect, acidification and eutrophication. The orange bars show the effect of the variation of NO_X emissions from the combustion of Jatropha by-products; they are only depicted for acidification and eutrophication.

Results

- Replacing power from hard coal by Jatropha-based bioenergy causes clearly more favourable results than replacing power from natural gas-fuelled power plants (blue bars). This is due to the differing carbon contents of the replaced fossil fuels.
- The results in terms of acidification and eutrophication are fairly sensitive to a variation of NO_X emissions (orange bars). If the NO_X emissions from by-products are 50% higher than in the standard case and at the same time the NO_X emissions from the fossil energy provision and credits are 50% lower or vice versa, a large range of outcomes (thin black 'error bars') results, which affects the eutrophication even more strongly than the substituted conventional fuel does.

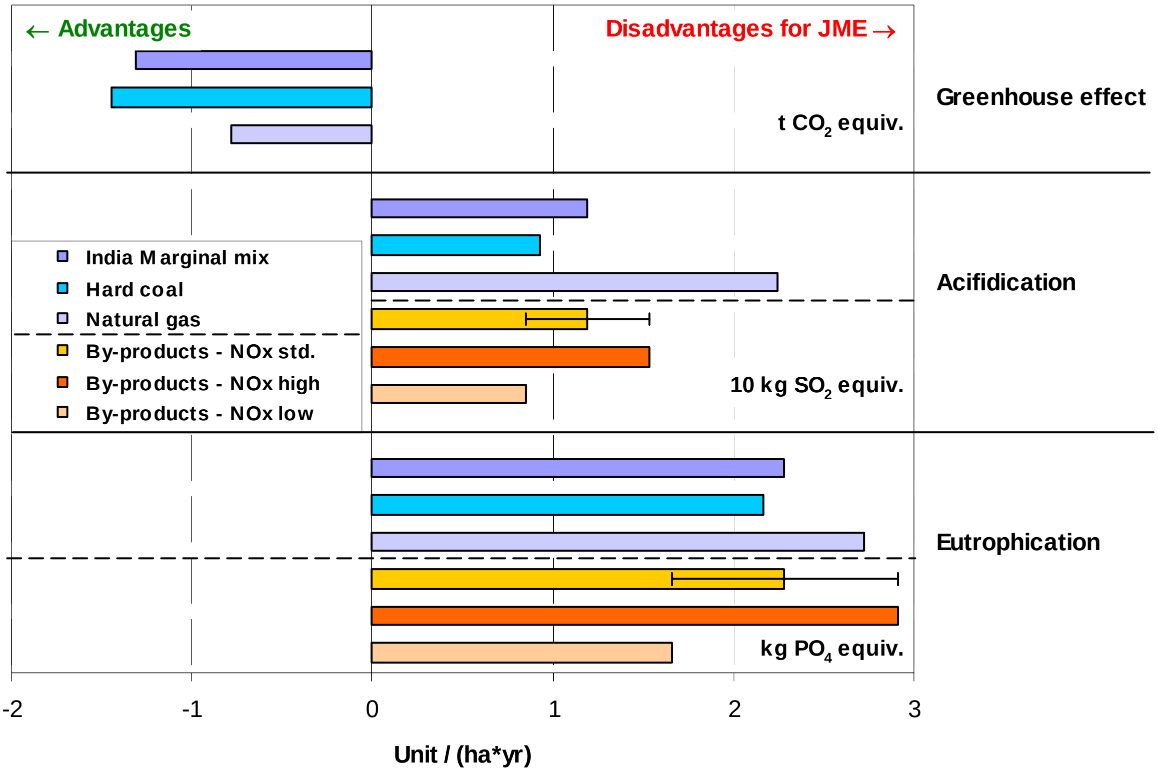


Fig. 4-12 Results of greenhouse gas, acidification and eutrophication balances for variations of the substituted fossil energy carrier (blue bars) and of NO_X emissions from by-product combustion

Reading the diagram (Exemplification for 2^{nd} bar from top)

By replacing conventional diesel fuel in a passenger car with JME from 'Pilot plant' production and ensuring that the by-products are used to generate power which replaces power from hard coal, 1.4 t of CO_2 equivalents can be saved yearly per ha cultivation area.

Conclusions

When the by-products are used as energy carriers, i.e. as biofuels, the amount of credits they 'earn' for JME depends especially on the substituted energy carrier or, if a power mix is, replaced, on the composition of the latter. In both cases, considerable differences in balance results can be found when comparing different countries or regions. Therefore, a main aim should always be to replace fossil energy carriers which account for high CO_2 and SO_2 emissions such as hard coal. This could be achieved by directly using Jatropha-based biofuels in (to date) coal-fuelled facilities such as power plants or cement factories.

When the aim is to produce energy through the combustion of the by-products, the amount of emissions (especially NO_X and NMHC) resulting from this combustion has a strong impact on the acidification and eutrophication balances. Since the emission factors for the by-products husks, shells and cake are largely unknown, however, respective measurements must be conducted.

4.7.5 By-product use for animal nutrition

When Jatropha biodiesel is produced, the cake or meal might be used as animal feed substitutes if these by-products can be detoxified. Since the nutritional value of this feed may exceed that of soy meal, two levels of protein quality were regarded (see chapter 3.7.4).

Fig. 4-13 presents results assessed for the centralised JME production concept – both the basic centralised production and the variant which involves a decorticating step – and for both levels of protein quality.

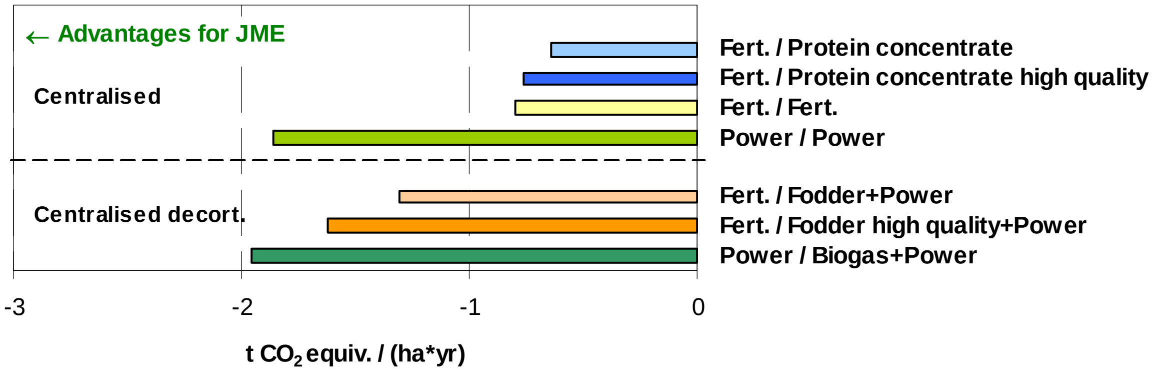


Fig. 4-13 Results of greenhouse gas balances for JME from different centralised production scenarios including the variant involving an additional decortication step and the utilisation of the by-products husks and cake as biomaterials, i.e. as fertiliser (fert.) and animal feed (protein concentrate) with two different protein qualities

Reading the diagram (Exemplification for 2nd bar)

Compared to conventional diesel fuel, the utilisation of JME from centralised production which involves the use of the by-product husks as fertiliser and the extraction and concentration of the cake's protein, saves 0.8 t of CO_2 equivalents yearly per ha cultivation area if the protein concentrate substitutes for the double amount of soy bean-based protein.

Results

- The effect of a variation in protein quality on the greenhouse gas balance is small. The additional savings of greenhouse gas emissions in the basic centralised production (top two / blue bars) are less than 20%.
- Extracting the protein from the cake leads to less greenhouse gas savings than using the cake as fertiliser. Even if a better protein composition is assumed for the cake which would substitute for the double amount of soy meal protein, its use as fertiliser (third / yellow bar) is still slightly more advantageous for the greenhouse gas balance than its use as animal feed. If, however, the cake is used for energy production (fourth / light green bar), the greenhouse gas savings are nearly tripled.

- The same holds true for the centralised variant: if – due to differing protein qualities – the cake substitutes for the double amount of soy meal protein, the greenhouse gas balance improves by about 20% (fifth and sixth / orange bars). However, the use of the by-products for energy production (last / dark green bar) would still exceed this variation. The smaller difference between the green bars and the other bars in both production scenarios is due to the fact that in the centralised decorticator variant there is no pure material use of the shells; these are used for energy production.

Conclusions

The by-products husks and cake (from the decentralised or centralised JME production) or husks, shells and meal (from the centralised decorticator production) should preferably be used for energy rather than as biomaterials. This general rule applies even if the Jatropha-based protein concentrate or the meal could both substitute for the double amount of protein from soybean. Nevertheless, it might be quite justified to process animal feed by extracting Jatropha protein from the cake or detoxifying the meal if on the whole this makes the Jatropha system more economically viable.

It remains to be seen if the protein extraction and meal detoxification can be realised in the near future at a large-scale level and with a reasonable energy input.

5 Summary and conclusions

In the following, the main findings from the environmental assessment of the oil crop *Jatropha curcas* regarding its cultivation as well as the conversion and utilisation of all parts of the fruit are summarised. Conclusions are derived and presented, among them possible optimisation measures and aspects which require further research. Furthermore, corresponding recommendations are made. In this context, the findings are described exclusively in a qualitative way; the respective quantitative results are to be found in the corresponding sections in chapter 4.

Main results

During the evaluation, a considerable number of specific results and interrelations could be derived from the life cycle impact assessments and sensitivity analyses. The results of this study are based on scenarios where the cultivation of Jatropha takes place on marginal or degraded land which can not serve any other agricultural uses, since this possibility to produce fuel on otherwise unproductive land is the plant's great strength. The main results apply to both the use of Jatropha oil as biodiesel and as pure plant oil. As a general rule, these findings do not apply exclusively to India but also to other regions of the world. When this is not the case, e.g. regarding the credits given to bioenergy production, this is explicitly pointed out.

General outcomes

- Along its entire life cycle, Jatropha biodiesel – under certain boundary conditions – holds considerable potential to help save fossil energy carriers and greenhouse gases. However, with respect to other environmental impacts such as acidification or eutrophication, it is disadvantageous. In order to be able to come to an overall rating, it is therefore necessary to weight each environmental impact category; this is not possible in an objective way but merely based on subjective value systems or decisions. If, for example, energy and greenhouse gas savings are given the highest environmental priority, then Jatropha biodiesel can be judged superior to conventional diesel fuel.

Detailed findings

- Certain life cycle steps prove to be especially relevant, among them the land use change due to the establishment of plantations, the conversion of the fruit to oil or JME and the use of the primary and by-products. The most important parameters are:
    - **Land use change.** The establishment of a Jatropha plantation on marginal or degraded land influences the carbon stock of the area in question. Any accumulative or depleting change has an immediate and clear impact on the greenhouse gas balance; generally, this impact is the stronger the shorter the regarded depreciation period is.
    - **By-products.** The purpose for which the by-products are used is of considerable importance for the outcomes of the life cycle impact assessments. If they are used for energy production, for example, this leads to greater savings of energy and greenhouse gases than the use of the main product, Jatropha biodiesel, itself. However, at the same time this causes greater disadvantages regarding the other environmental

  impact categories (except for acidification if Jatropha by-products substitute for coal in a cement factory), i.e. the results depend on which fossil energy carrier is replaced. Despite this fact, the overall rating would be still in favour of JME (versus conventional diesel fuel) if the same subjective value system as above was applied, i.e. if saving primary energy and greenhouse gases was given priority.

  Provided that it is technically possible to produce energy through the combustion of the husks and cake or, in centralised decorticator production, the husks, shells and meal, then – regarding the environmental impacts energy savings and greenhouse effect – this option is to be preferred over a utilisation as animal feed or fertiliser.

  - **Credits for bioenergy.** When the by-products are used as energy carriers, i.e. as biofuels, the amount of credits they 'earn' depends especially on the energy carrier that is replaced or the composition of the substituted power mix. Both of these can lead to considerable differences in the outcomes of the energy, greenhouse effect, acidification, eutrophication and nitrous oxide balances when comparing different countries or regions.
  - **Conversion.** In the centralised production system, the greater expenditures for transport are overcompensated by a lower energy demand as well as by higher oil yields compared to the decentralised production system. Therefore, the comparison between the decentralised pilot plant and a centralised production system delivers clear environmental advantages for the latter, i.e. under environmental aspects, centralised JME production concepts should be preferred over decentralised ones.
  - **Primary products.** From an environmental perspective, there is no big difference between the use of pure Jatropha oil and that of JME resulting from centralised production. This is due to the fact that the additional expenditures for the transesterification and the credits for the chemically used glycerine practically counter-balance each other. When regarding the pilot plant scenario, however, a comparison between the use of oil and JME reveals clear advantages for the Jatropha oil, i.e. under current process management conditions, the transesterification should either be refrained from or all efforts should be made to optimise the conversion plant.

- Transports, the provision of pesticides as well as of specific ancillary products used in Jatropha oil production, in its transesterification to biodiesel and during some sub-steps of by-product processing have a relatively small influence on the balance results.

From these findings, it is possible to derive a number of optimisation possibilities as well as to identify fields where further research is necessary.

Environmental optimisation potentials

During the environmental assessment, a number of areas have been identified in which optimisations can be implemented. These include both the Jatropha system in general and specifically the pilot plant in Bhavnagar.

General outcomes

- **Cultivation.** Against the background of a world-wide increase in land use competition, it should be strived to improve harvests through agronomic and breeding progress since higher yields lead to clearly better results of the life cycle impact assessments.

- **Energy input and output.** The results of the life cycle impact assessments depend on two parameters: (1) the type of energy carrier used for the conversion and – additionally and much more importantly – (2) the substituted energy carrier if the by-products are used as biofuels. Therefore, 'clean' fuels are to be preferred for the conversion and – regarding the by-product use – a main aim should be to replace fossil energy carriers which cause high CO_2 and SO_2 combustion emissions, such as coal. This could be achieved, for example, by the direct use of Jatropha-based biofuels in (to date) coal-fuelled facilities such as cement factories, thus reducing both the greenhouse effect and acidification.

Pilot plant

- **Conversion.** The pilot plant in Bhavnagar can be greatly optimised regarding its relatively high energy demand. Possible measures include considerably reducing the process energy input as well as switching to a less polluting fossil fuel (e.g. natural gas) or – in the best case – to biofuels such as husks or even Jatropha oil. Concerning the energy demand of the conversion process it must be reviewed if measures can be taken to reduce it; within the currently applied concepts this energy demand makes up an exceedingly large part of the environmental impact balances. An adaptation of the conversion plant could be achieved by generating part of the process energy (e.g. the steam) from combustion of the husks, for example; or by fuelling the total process on Jatropha oil.
- **Main products.** If for technical reasons a process optimisation is not possible in the pilot plant scenario, the following choice appears most reasonable from an environmental perspective: instead of processing the extracted Jatropha oil to biodiesel in an energy-demanding transesterification step it should be used directly in stationary facilities. It can, for example, be used in household stoves instead of kerosene or in a power unit where it replaces conventional diesel fuel.

Need for further research

During the calculation of the life cycle impact assessments, the database proved sound enough for the qualitative discussion but insufficient for the derivation of quantitatively reliable statements regarding two topics. Further research is thus necessary .

- **Carbon stocks.** When land use changes are involved, the quantitative outcomes of the greenhouse gas balances depend largely on the carbon stocks of the above- and below-ground biomass as well as the carbon stock of the soil. For the cases regarded here, only examples of such figures are known; they must thus be explored in more depth within a system-analytical approach. This does not affect the qualitative findings of this study; however, the respective knowledge is especially essential for the future definition of more precise figures regarding the greenhouse gas savings which can be achieved by using Jatropha oil and JME for energy.
- **Emissions from combustion.** The amount of emissions resulting from the combustion of the by-products with the aim of energy generation (especially NO_X and NMHC) has a clear impact on the balances for acidification and eutrophication. Because the emission factors for the by-products husks, shells and cake are largely unknown, respective

measurements are to be conducted.

Concerning the cake whose combustion might be difficult to handle, it remains to be examined if and to what extent its use for generating energy can be technically realised.

Recommendations

The following recommendations can be derived from the findings described above:

- **Establishment of new plantations**: When a piece of land is developed for a Jatropha plantation, a reduction of the carbon stock of this area must be prevented. Consequently, poor or sparsely vegetated soils (marginal or degraded land) in sub-humid to semi-arid zones should preferably be used for Jatropha cultivation as this leads to a net carbon sequestration. For the same reasons, Jatropha should not be cultivated on fertile cropland which could be used for other crops with a higher yield and carbon sequestration potential. At the same time, Jatropha cultivation on marginal or degraded land would help to avoid land use competition with food production – one of the main advantages of Jatropha compared to other oil crops which are more demanding in terms of soil quality.
- **System optimisation**: The numerous optimisation possibilities listed above should be tapped to the full potential. Among other things, this means securing high yields, considerably improving the decentralised pilot plant and also making use of or further developing utilisation paths which allow generating energy from the by-products.
- **Conducting necessary further research**: Further research should focus on analyses regarding (1) sustainable development of degraded land areas in sub-humid to semi-arid zones, (2) carbon stocks of the above- and below-ground biomass and soils, including changes occurring in connection with land use changes and (3) emission factors for the combustion of biogenic by-products for generating energy.

Outlook

The utilisation of all parts of the Jatropha fruit as biomaterials or as biofuels instead of fossil energy carriers shows a remarkable environmental potential – as far as the saving of energy and greenhouse gases is concerned. This does not apply categorically, however, due to the fact that the system is considerably influenced especially by the by-product use which still holds a large improvement potential itself. On the one hand, the findings derived in this context are generally reliable concerning the “direction” of the results, i.e. whether the balance totals are advantageous or disadvantageous for Jatropha biofuels in comparison to their fossil equivalents. On the other hand, they are not sufficient for a precise judgment of concrete technologies or utilisation paths; for this purpose, case-specific analyses must be conducted.

Where it is deemed necessary and for individual cases, it must be clarified how other environmental impacts such as the occupation of natural space and the respective effects on the surface quality – including biodiversity and soil ecology – are to be judged. Another example of such a case-specific open issue is the consumption of water, a mostly limited resource in sub-humid to semi-arid zones.

Since this study focuses on the environmental assessment of Jatropha biodiesel, specific conclusions drawn here do not directly cover all sustainability aspects but must moreover be weighed against the economic and social background. In terms of sustainable regional development, for example, it might be quite reasonable to encourage the decentralised production, should this bear considerable socio-economic advantages – despite its slightly less favourable ranking regarding environmental impacts. Nevertheless, in this case as in all others, all efforts should be made to tap the entire range of optimisation possibilities to the full potential.

6 Annex

Greenhouse effect in detail

This chapter refers to the greenhouse gas (GHG) emissions and savings for the pilot plant scenario depicted in Fig. 4-1. Like in all other figures in chapter 4, the GHG emissions and savings are shown as CO_2 equivalents per hectare and year for each life cycle stage.

Fig. 6-1 displays deep insight information on this, differentiating the relative contribution of CO_2, CH_4 and N_2O (all as CO_2 equivalents per hectare and year) to the overall expenditures and credits for both Jatropha biodiesel (JME) from the pilot plant scenario and for conventional diesel fuel.

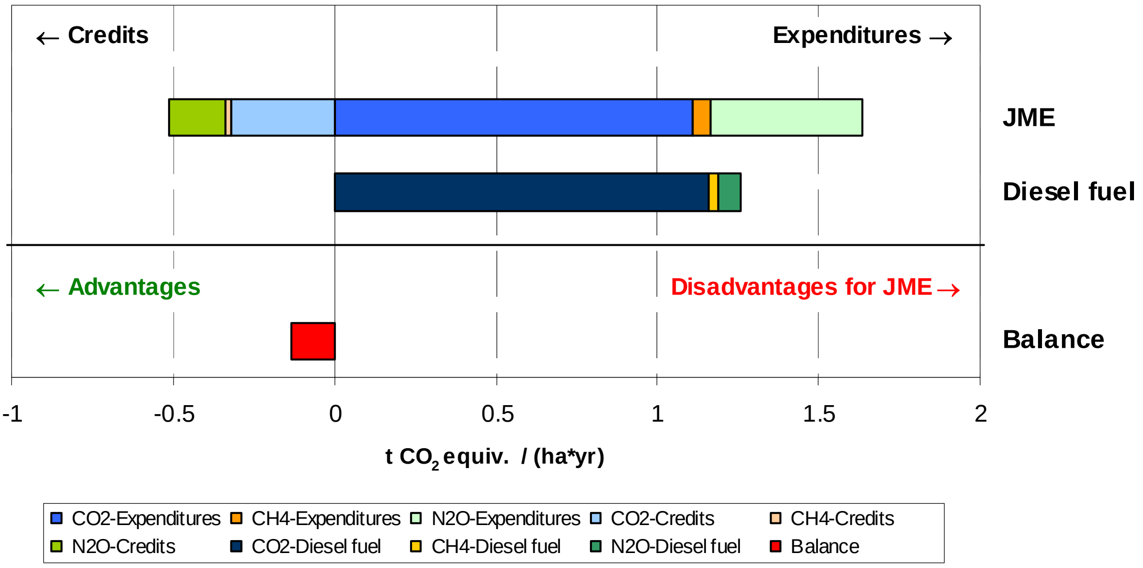


Fig. 6-1 Detailed greenhouse gas balance results for Jatropha biodiesel from the pilot plant scenario compared to conventional diesel fuel: relative contribution of each greenhouse gas (carbon dioxide = CO_2, methane = CH_4, nitrous oxide = N_2O)

Reading the diagram (Exemplification)

The 1st bar shows expenditures of 1.6 t CO_2 equivalents / (ha*yr) along the life cycle of JME: 68% of these originate from CO_2, 3% from CH_4 and 29% from N_2O. Credits amount to 0.5 t CO_2 equivalents / (ha*yr) showing a similar distribution between greenhouse gases: 63% from CO_2, 3% from CH_4 and 34% from N_2O.

Fig. 6-2 depicts the relative contribution of each life cycle stage to the expenditures and credits of CO_2, CH_4 and N_2O for Jatropha biodiesel (JME).

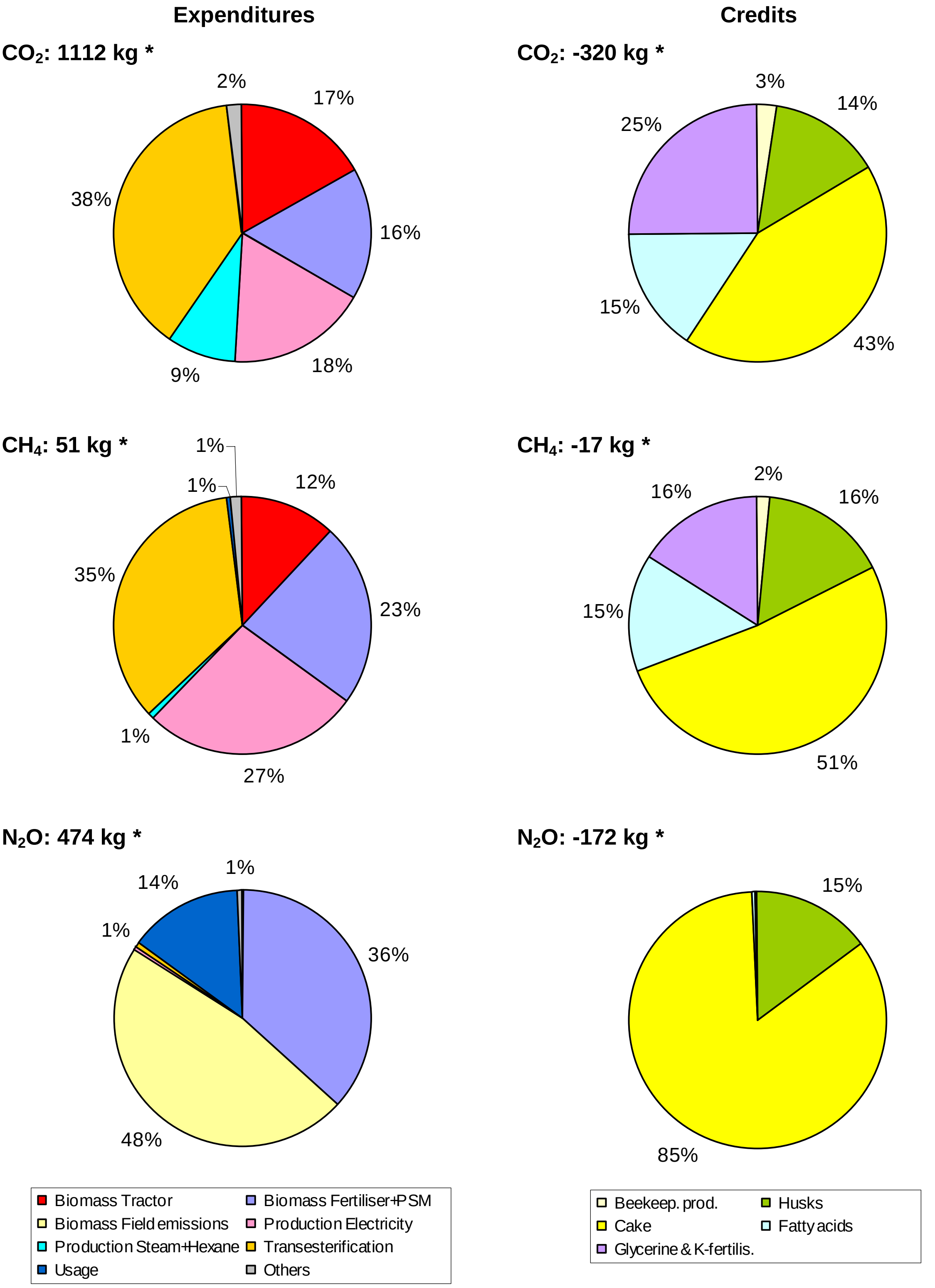


Fig. 6-2 Relative contribution of each life cycle stage to the emissions of each of the greenhouse gases CO_2, CH_4 and N_2O for the pilot plant scenario. The numbers marked with an asterisk (*) quantify the total expenditures (left side) and credits (right side) of each gas in kg of CO_2 equivalents per hectare and year.

Results

- Both greenhouse gas emissions (expenditures) and savings (credits) are dominated by CO_2 (roughly two thirds) and N_2O (about one third). CH_4 only plays a minor role in this system.
- CO_2 emissions mainly originate from conversion systems (provision of electricity and steam as well as transesterification) and to a lesser degree from cultivation (provision of tractor fuel and fertiliser).
- N_2O emissions predominantly stem from the provision of nitrogen fertilisers and field emissions due to the application of nitrogen fertilisers. A smaller part of the emissions comes from the usage stage.

Conclusions

As greenhouse gas emissions are generated from different life cycle stages, there are plenty of possibilities for optimisation measures aiming at a GHG reduction. CO_2 emissions from the production stage can be greatly reduced through various optimisations which have already been pointed out in chapter 4.3.1.

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