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Final Report

Life Cycle Assessment of Biodiesel: Update and New Aspects

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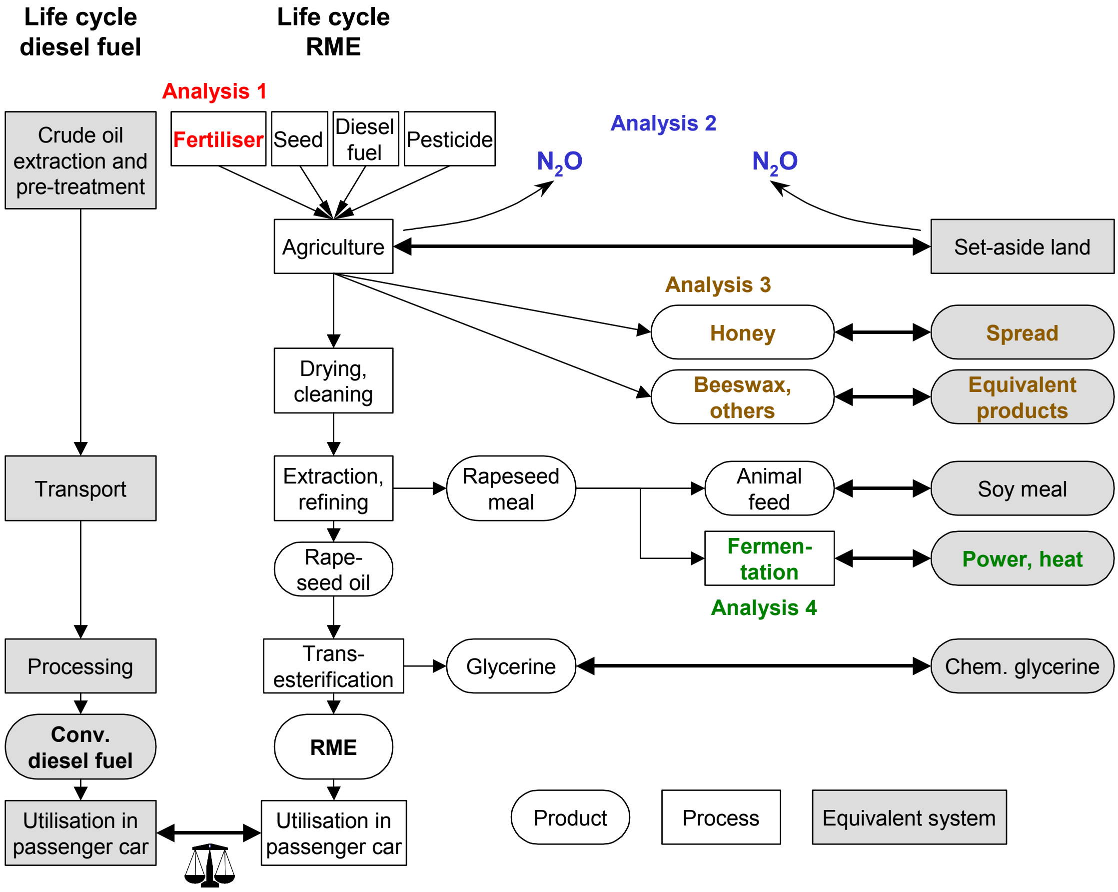
Content

1 Background and objective

In recent years the popularity of biodiesel (rapeseed oil methyl ester, RME) has increased dramatically in Germany. Since the beginning of the 1990s extensive research has compared the environmental impact of RME with conventional diesel fuel. The Institute for Energy and Environmental Research (IFEU) has provided detailed environmental analysis on this subject since 1991 and continues to update and advance these assessments. The IFEU's analysis has resulted in a number of important conclusions, which have been confirmed by other institutions both in Germany and abroad: on balance, RME offers more positive outcomes relative to diesel fuel if the goal is to conserve fossil energy and reduce the greenhouse effect. However, if it is more important to reduce acidification, lower the nutrient input into soils and surface water, and to decrease ozone depletion, conventional diesel fuel offers more favourable outcomes. With this general result the discussion of the advantages and disadvantages of RME compared to diesel fuel has apparently reached an end and the system seems to be reliably assessable.

In recent years, further progress has been made in areas of agricultural research, such as the emission of greenhouse gases from agriculture or the preceding crop effect of rapeseed on the yields of the subsequent crop. Furthermore, the recent increase in rapeseed production has led to a rise in the availability of co-products (for example, rapeseed honey) and innovative new uses for these co-products (such as the fermentation of rapeseed meal to generate biogas) that may be economically viable. The analysis of these effects was the objective of a study conducted by the IFEU on behalf of the Union for the Promotion of Oil and Protein Plants at the beginning of 2003. Starting with the overall comparison between RME and conventional diesel fuel, the investigation examined four key aspects. These are listed on the following page.

Contributions to the basic generation and coordination of scientific data have been made by: E. Härtl, Department of Agriculture Deggendorf; U. Keymer and A. Schilcher, Bavarian State Research Center for Agriculture, Munich; H. Krämer, Bio-System, Konstanz; and Dr. W. von der Ohe, Institute of Bee Research of Lower Saxony, Celle. Supplementary contributions regarding specific questions have been made by: Dr. B. Ball, SAC, Penicuik (Scotland); B. Gabrielle, INRA, Thiverval-Grignon (France); Prof. Dr. H. Goldbach, University of Bonn; Dr. O. Heinemeyer, FAL, Braunschweig; Prof. Dr. H. J. Hellebrand, ATB Potsdam; Prof. Dr. B. Honermeier, Justus Liebig University Gießen; Dr. P. Rosenkranz, University of Hohenheim, Stuttgart; Dr. R.-R. Schulz, Research Centre for Agriculture and Fishery Mecklenburg-Western-Pomerania, Gülzow, and Dr. U. Skiba, CEH, Penicuik (Scotland). The authors cordially wish to thank you all for your time and effort.



1 Preceding crop effect

On the basis of its characteristics, rapeseed positively affects the yield potential of subsequent crops. Recent research results are considered.

2 Nitrous oxide emissions

The release of nitrous oxide (N_2O) from soils is caused by microbial activity. Since the emission depends on various factors, recent corresponding research results are considered.

3 Honey production

The production of honey and its co-products – beeswax and pollen – are incorporated in the RME balance. This involves crediting equivalent products, which are substituted by rapeseed honey and its co-products.

4 Biogas generation from rapeseed meal

Instead of using rapeseed meal as animal feed (which is currently the most common use), it can also be fermented in a biogas plant and subsequently used in energy generation. This application is considered in the current study.

For RME as well as for fossil diesel fuel the entire life cycles 'from cradle to grave' are being taken into account.

2 Approach and predefinitions

Methodical approach

The balances of the life cycle comparisons considered in the current study have been calculated according to the life cycle assessment standard /ISO 14040/43/. The system boundaries, boundary conditions, and procedures are documented in /BORKEN ET AL. 1999/ as well as in /REINHARDT ET AL. 1999/. Some of the most important parameters and system boundaries are:

- Reference area for the production and use of rapeseed and RME is Germany. For all raw materials, auxiliary materials, transports etc. the actual mixes for Germany have been balanced including the actual import and export mixes. Reference period: 2000-2005.
- All extensions necessary for the calculations to be conducted have been adjusted to the procedures and system boundaries of the above-mentioned sources.

Database used

The majority of basic data is taken from /BORKEN ET AL. 1999/, /REINHARDT ET AL. 1999/ as well as /GÄRTNER AND REINHARDT 2001/. For additional calculations the following data were used:

- For the basic scenario:

  Update of the N fertiliser supply coming from /PATYK AND REINHARDT 1997/ based on /EFMA 1995/ and /EFMA 2000/: 12 g N_2O per kg of N fertiliser. N_2O emissions in soy production: 2 kg N_2O per ha and year /IFEU 2003/.
- For the preceding crop effect of rapeseed:

  Conversion of the surplus of the subsequent crop according to /KALTSCHMITT AND REINHARDT 1997/.
- For the honey production (selection of the most important data):

  Yield: 80 kg rapeseed honey, 2 kg beeswax, 2 kg propolis. Input: sugar solution 60 kg, sulphur 0.2 g, chemical agents 50 g, electrical energy 0.35 kWh (all data per ha and year, /IFEU 2003/ according to /HÄRTL 2003/ and /VON DER OHE 2003/). Overseas honey – mass equivalence, transport 10,000 km, use of cane sugar; strawberry jam – mass equivalence, 60 % sugar content, steam demand 1.3 MJ/kg; treacle – mass equivalence, steam demand 1.5 MJ/kg; chocolate hazelnut spread – mass equivalence, sugar 38 kg, vegetable oil 14 kg, hazelnuts and cocoa each 10 kg, transport hazelnuts 5,000 km, cocoa 8,000 km, steam demand 1.3 MJ/kg; pharmaceuticals 100 g per ha and year; carnauba wax – mass equivalence, transport 10,000 km, steam demand 1.3 MJ/kg (all data: /IFEU 2003/).
- For the rapeseed meal fermentation (selection of the most important data):

  Gas yield 350 l/kg rapeseed meal, efficiency of the combined heat and power (CHP) plant electrical energy 35 % and heat 55 %, energy demand of the system 10 % of energy output of the CHP plant, heat demand of the system 20 % of the heat output (/IFEU 2003/ based on /GEGNER 2003/, /KEYMER 2003/ and /KRÄMER 2003/), fraction of N in the residue available for plants corresponding to 100 % nutrient balance: 76 kg N per ha and year, upper and lower limit of the ammonia emission 0.3 resp. 0.12 g NH_3-N/g N (/IFEU 2003/ according to /EDELMANN ET AL. 2001/ and /KRÄMER 2003/), emission factors of the CHP plant based on /IFEU 2003/, remaining data based on /EDELMANN ET AL. 2001/.

Results presentation

In the basic scenario and the scenarios 'honey production' and 'rapeseed meal fermentation' the difference between RME and diesel fuel is presented in the diagrams. For the nitrous oxide scenario the relationship to the basic scenario is presented. In addition, the results are briefly discussed, presenting the most important findings. For the graphs various descriptive scale types were used.

For the description of the environmental impacts and the calculation results, articulate terms were preferred to the abstract scientific terms (for example, 'acidification' instead of 'potential acidification on the basis of SO_2 equivalents').

The environmental impacts analysed

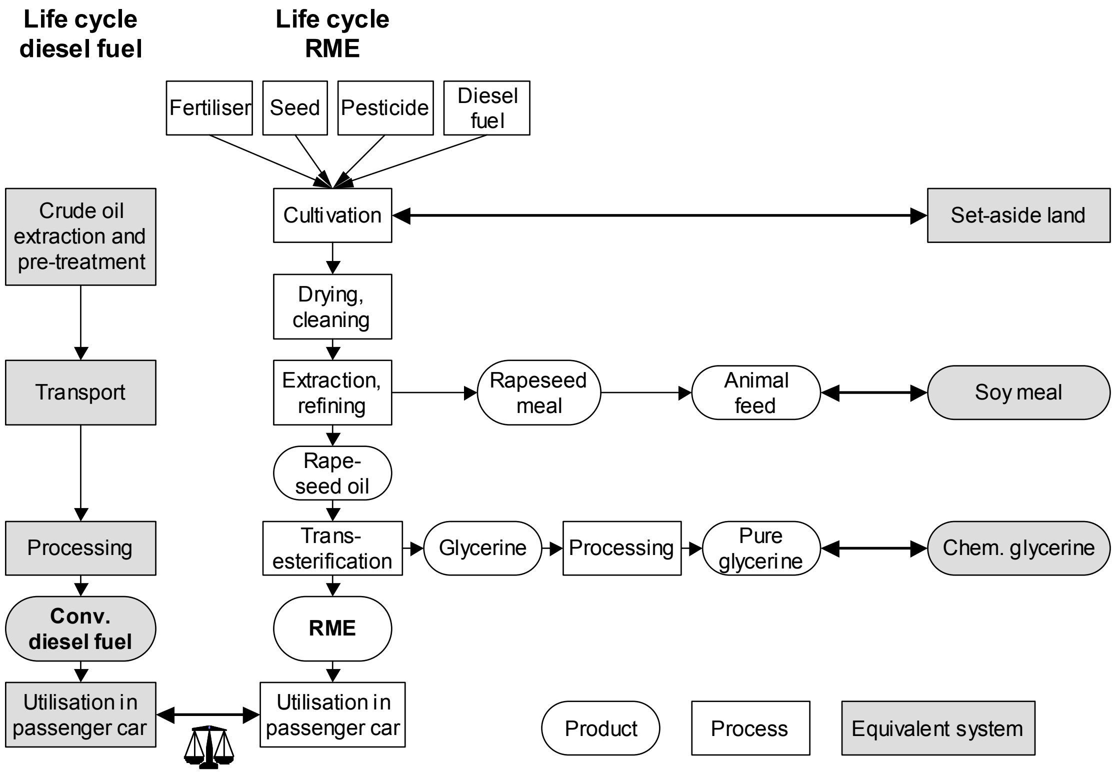
The environmental impacts analysed in this study are listed in the table below. Meaningful and advanced balances for the impact categories human toxicity and ecotoxicity are currently, in our opinion, impossible to calculate because the databases in the area of fuel combustion are insufficient. For the other two environmental impact categories of the DIN-NAGUS – noise and land use – a generally accepted balancing approach is currently still unavailable.

Environmental impact	Description
Energy saving	In this investigation the protection of the resources of non-renewable energy carriers is calculated, i.e. the non-renewable fossil fuels mineral oil, natural gas, and coal as well as uranium ore. In the following, based on the uniform tendency, the results of this impact category are termed 'energy saving'.
Greenhouse effect	Global warming as a consequence of the release of greenhouse gases by man. Most important greenhouse gas: carbon dioxide (CO_2) due to the combustion of fossil energy carriers. Here emissions of CO_2, methane, and nitrous oxide are recorded.
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.
Nutrient inputs	Input of nutrients into soils and water bodies (keyword 'algal bloom'). Nitrogen oxides and ammonia are recorded.
Photo smog (summer smog)	Formation of specific reactive substances e.g. ozone, in presence of solar radiation in the lower atmosphere (keyword 'ozone alert'). Hydrogen carbons are considered.
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases like CFCs or nitrous oxide (keyword 'ozone hole'). Here nitrous oxide is recorded.

3 Scenarios and results

Investigations conducted by IFEU over the last few years comparing the ecological impact of rapeseed-based biofuels and conventional diesel fuel form the basis of the current study. Based on these investigations the basic scenario is adapted to the reference area selected. This scenario forms the starting point of the analyses illustrated on page 3. The results of all subsequent analyses are discussed in relation to this scenario.

3.1 Basic scenario



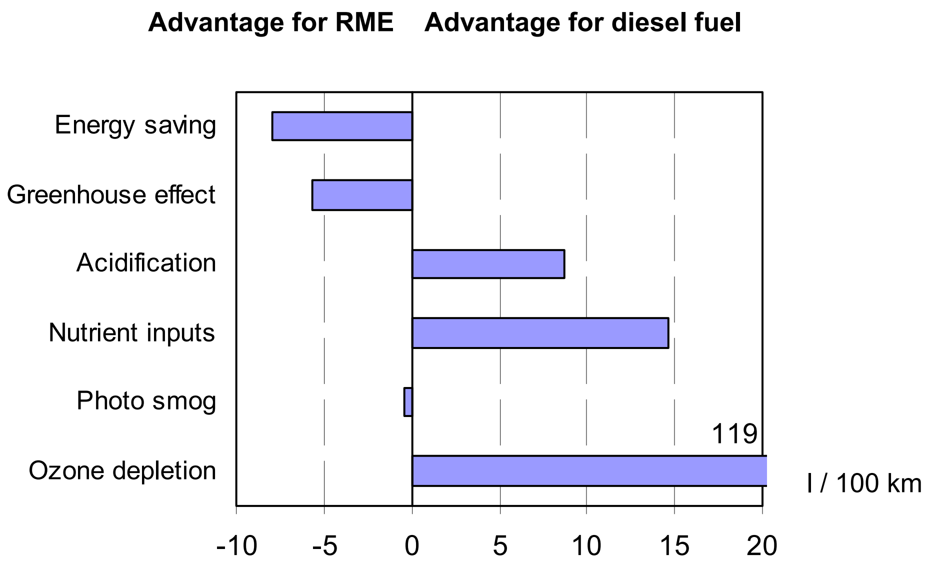
Agriculture: The production was calculated under average German conditions based on the guidelines of good professional practice in contrast to an annual actively re-vegetated set-aside land. The harvest is done by direct thrashing; rapeseed straw is incorporated into the soil. Rapeseed is dried, cleaned, and cooled.

Processing: Rapeseed is transported to a central oil mill, pressed, and rapeseed oil is extracted. The rapeseed meal accumulating as a co-product in this process is used as animal feed, substituting soy meal imported from North America. Rapeseed oil is then transformed into rapeseed oil methyl ester (RME) by means of a transesterification process. The resulting co-product glycerine is conditioned and used as a substitute for glycerine generated chemically.

Use: RME is used in diesel passenger cars and replaces conventional diesel fuel.

Differences between current and previous balances 'RME in comparison with diesel fuel'

During the specification of the basic scenario various updates of the preceding balances have been included (adjustments of the reference years for the preliminary chains, emissions caused by transports, etc.). In particular two of the adjustments resulted in remarkable alterations of the results – the update of the nitrogen fertiliser production and the integration of nitrous oxide emissions in soy production. Both updates result in significant advantages for RME in the categories greenhouse effect and ozone depletion.



Example how to interpret the top two bars in the diagram: The top two bars in this diagram indicate the results of energy saving and greenhouse effect for the comparison between RME and conventional diesel fuel for the basic scenario (see text). If RME is used instead of diesel fuel on a distance of 100 km the amount of energy saved equals the amount of energy required to produce 8 litres of diesel fuel and the amount of greenhouse gases saved equals the amount of greenhouse gases emitted due to the production and consumption of 6 litres of diesel fuel. Converted into a different unit approximately 2.2 kg CO_2 equivalents can be saved for each litre of RME used.

The use of RME instead of fossil diesel fuel produces environmental advantages as well as disadvantages. RME is beneficial with respect to the saving of fossil energy and to the greenhouse effect, but is detrimental regarding acidification, nutrient inputs and ozone depletion. No clear positive result for one or the other fuel is given within the impact category photo smog.

An objective, scientifically justified decision for one or the other fuel is therefore impossible. A comprehensive overall assessment can be achieved only if we draw on additional criteria. If for instance the protection of fossil energy resources and the greenhouse effect is given a higher priority than the other impact categories, a decision in favour of RME is justified. If other impact categories are valued higher the result may be different.

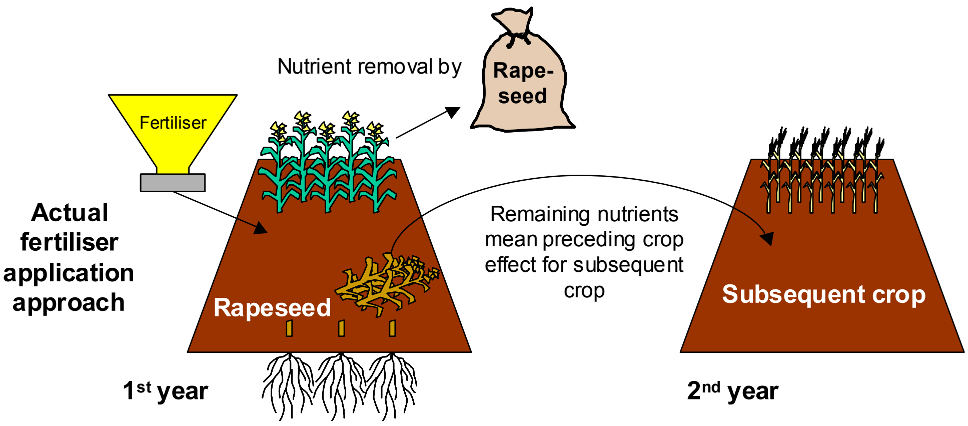
3.2 Preceding crop effect

In many life cycle assessments of agricultural products fertilisers often appear to be particularly relevant for the result. The same is true for the comparison between RME and diesel fuel. For that reason the derivation of the fertiliser balances, which have to be considered in the assessments, plays an exceedingly important role in the entire life cycle assessment. Two of the most common approaches used to determine the fertiliser quantities are:

- **Actual fertiliser application approach**:

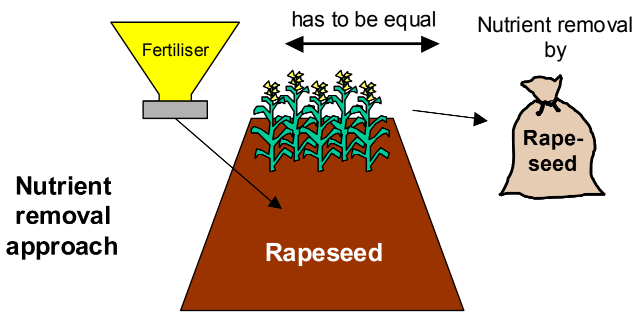
  In this approach the quantity of fertiliser actually applied in the production process is considered. From that quantity the preceding crop effect, if any, is deducted. The value of the preceding crop comprises the soil improving properties of the crop (e.g. the fertilising effect of the residues remaining on the field, serving as a nutrient source for the subsequent crop). As is generally known for rapeseed plants, this effect is very distinct.

  Using this approach, the IFEU considered rapeseed production in life cycle assessments of RME in the early 1990s /REINHARDT 1993/.



- **Nutrient removal approach** (across the entire crop rotation):

  According to this approach those quantities of nutrients removed from the field by the harvest of the crop are determined. By using this methodology the remaining plant residues are directly considered as the preceding crop effect and taken into account. Regarding the nutrient export of the entire crop rotation – including an annual fallow in contrast to one including the production of rapeseed – enables the consideration of crop rotation-specific nutrient conditions. This method of assessment has been used by IFEU since the middle of the 1990s as the standard approach for RME life cycle assessments.



Source	**Preceding crop effect** in kg N/ha
Literature values /REINHARDT 1993/	up to 60
Average value according to /REINHARDT 1993/	32.5
/HONERMEIER AND GAUDCHAU 2003/ calculated by /IFEU 2003/	15 – 30

Discussion

- **Preceding crop effect**. In the literature the preceding crop effect of rapeseed is reported to contribute up to 60 kg of nitrogen per hectare originating from the straw, roots, and empty pods. Results originating from single investigations, in which measurements have been conducted for a number of different soil types, also fit into this range. Latest studies published by /HONERMEIER AND GAUDCHAU 2003/ confirm these values. The preceding crop effect calculated in this study was equal to 15 to 30 kg of nitrogen taken up by the subsequent crop.

  Usually an average preceding crop effect is used in life cycle assessments. With respect to rapeseed a mean preceding crop effect of 32.5 kg N per ha was already estimated by IFEU in 1991 /REINHARDT 1993/. This estimate is still relevant to the current investigations. Briefly summarised, the new results, regarding the preceding crop effect, are not different from those already used in life cycle assessments of RME.

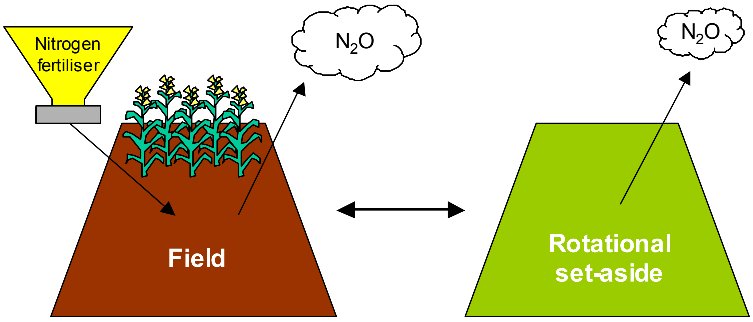
- **Comparison of the approaches**. As a matter of principle the nutrient removal approach underestimates the amount of fertiliser that has to be applied because the nutrients remaining on the field are not 100% available for the subsequent crop. Consequently the quantities of fertiliser calculated according to the nutrient removal approach tend to be lower than those calculated by the actual fertiliser application approach. On the other hand, for increased future rapeseed production for RME, a fertiliser regime optimised using good professional practices has to be assumed rather than the current average fertiliser practice. Comparing the data from both approaches, it becomes evident that the resulting differences of 10 to 20 kg N do not entail significantly different results. Therefore it can be concluded that the fertiliser quantities estimated in the calculations do not have to be altered.

Finally, it should be noted that nitrogen was quoted substitutionally for all other nutrients. For the other nutrients analogue approaches have been used with minor adjustments. Altogether the same conclusions can be drawn:

Conclusions

- Even recent publications about the preceding crop effect of rapeseed do not provide any new results regarding the life cycle assessment of RME.
- For a future-oriented life cycle assessment of RME the nutrient removal approach across the entire crop rotation is to be preferred to the actual fertiliser application approach.
- In this context for the current life cycle assessment of RME no changes have to be made in relation to the preceding life cycle assessments.

3.3 Nitrous oxide emissions

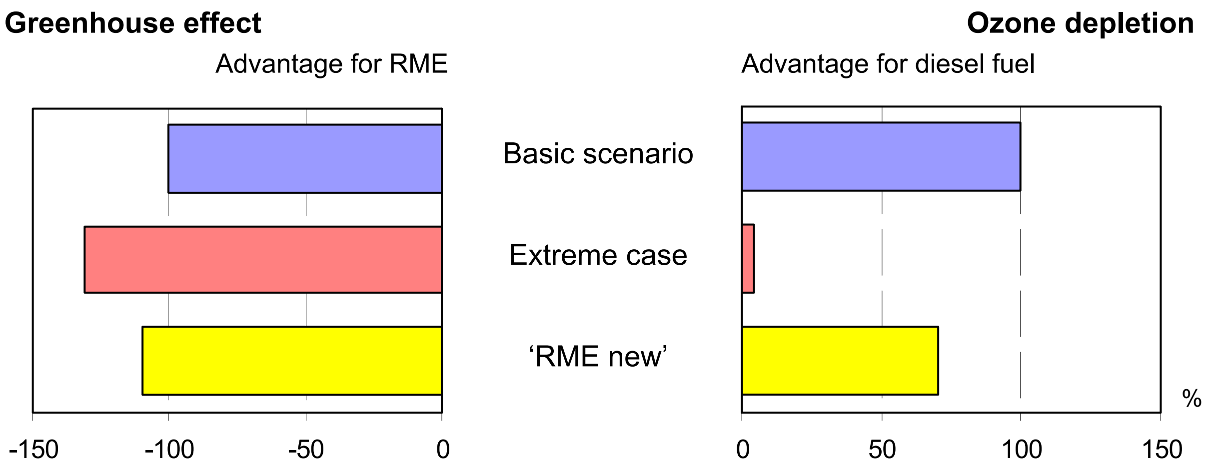


The release of nitrous oxide (N_2O) from nitrogen compounds present in the soil is caused by the activity of the soil microbial biomass. The rates of release depend on various factors such as soil type, nitrogen fertiliser use, tilling operations, and weather conditions. /IPCC 1996/ specifies both an average value and a range of the emissions due to a given nitrogen fertiliser rate as well as a background level for nitrous oxide emissions originating from the unfertilised soil or developing in addition to the fertiliser-induced emissions. The life cycle assessment of RME has a number of useful features in this respect, which will be addressed in the following.

Estimation of nitrous oxide emissions from set-aside land

Rotational set-aside land within a crop rotation is currently used as standard agricultural reference system for biodiesel rapeseed production. The data published by /IPCC 1996/, however, does not provide any information about the nitrous oxide emissions emanating from these fallow areas. To date nitrous oxide emissions have been set zero in most of the RME life cycle assessments (the background emission is already being taken into account by /IPCC 1996/). However, according to expert assessments, in particular cases nitrous oxide emissions from set-aside land can actually be as large as those from areas under agricultural use due to the pronounced nitrogen dynamic of agricultural soils. This fact is documented by /HEINEMEYER ET AL. 1998/. Comparable measurements on different soils, however, resulted in markedly lower values /HELLEBRAND ET AL. 2003/. In addition, according to expert judgements, nitrous oxide emissions are to a certain extent dependent on the nitrogen fertiliser rate.

As a consequence, it is safe to say that the previous way of assessing the nitrous oxide emissions (assuming zero emission) underestimates the actual emission rates. On the other hand, it is our opinion that assuming nitrous oxide emissions from set-aside land and from land under agricultural use are equal /SCHARMER 2001/ cannot be supported either. Therefore it is reasonable to assume that the true value lies somewhere in-between both extremes, depending on external factors. Since a scientifically reliable average value for Germany cannot be derived from the studies, we apply 50 % of the fertiliser-induced emissions according to IPCC (based on an average fertiliser rate of 180 kg N per ha annually for all crops in the rotation). In order to map the current situation of biodiesel rapeseed production as close to reality as possible, it was taken into account too that approximately 50 % of the current rapeseed is produced on so-called ‘basic areas’, which are thus unavailable for food production. As a consequence, continuous fallow is the most plausible agricultural reference system as that food would otherwise have to be produced somewhere else e.g. in foreign countries (for the systematic see /JUNGK AND REINHARDT 2000/), or in case of a reduction of the domestic surplus production, additional fallow areas would have to be established.



Example how to read the right hand diagram:

The category ozone depletion is represented for the comparison of RME with conventional diesel fuel.

Ozone depletion is reduced from 100 % (**basic scenario**) down to 5 % if it is assumed that the N_2O release of the rapeseed area is equal to that of the reference area (**extreme case**). If the current conditions are assumed (**'RME new'**) ozone depletion is reduced down to approx. 70 % of the basic scenario.

Result

The results presented in the **figure** illustrate that the difference between the highest and the lowest value (**basic scenario** = 'zero emission', **extreme case** = emission from set-aside land equals emission from the cropped area) is very large, but the previously derived main statements are unaffected: in contrast to diesel fuel, RME saves greenhouse gases but in turn causes increased nitrous oxide emissions. In contrast to the life cycle assessments published previously, the new approach derived by IFEU ('**RME new**' = 50 % of the fertiliser-induced emissions in addition to considering the production of rapeseed on basic areas, see above) results altogether in more favourable outcomes for rapeseed biodiesel.

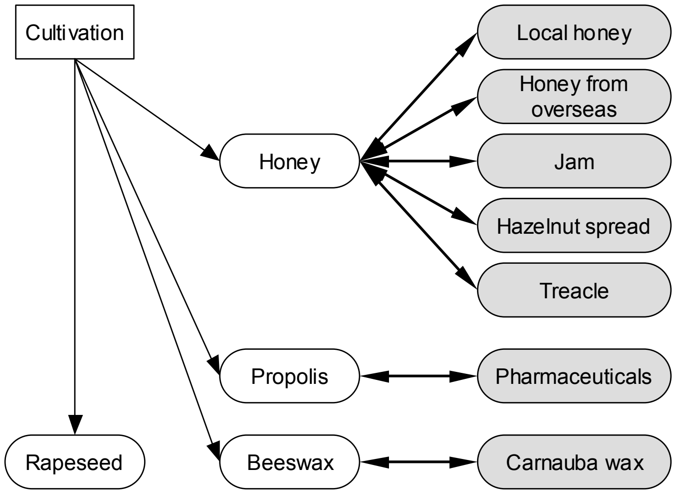
Conclusion

The interpretation of the latest results on nitrous oxide emissions from rapeseed fields as well as rotational set-aside land yields new basic data, which basically confirm the previous results but numerically turn out to be more favourable for RME:

- RME in contrast to diesel fuel continues to save greenhouse gases and to release more nitrous oxide.
- The greenhouse gas savings by RME are higher than previously assumed in most LCAs, while the additional nitrous oxide emission turns out to be smaller.

We recommend using the updated basic factors.

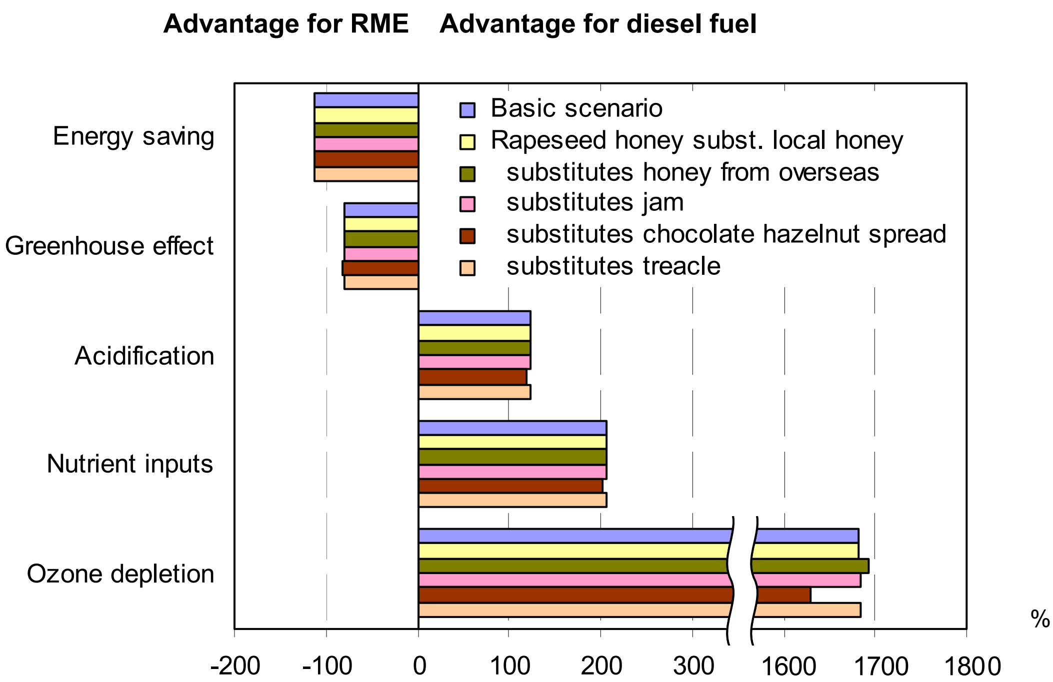
3.4 Honey production



Previous LCAs usually did not consider rapeseed to be a productive nectar source serving as a rich feedlot for bees. As a consequence of the extended rapeseed production in recent years, the supply of rapeseed honey on the German market has increased noticeably. Unfortunately statistics do not reveal which products will be adversely affected by the new supply and demand of German rapeseed honey. A number of scenarios exist in which these new products can substitute for honey. The following 5 possible surrogate products have been considered:

- Rapeseed honey can substitute other native honey varieties.
- Rapeseed honey may reduce the consumption of imported honey (e.g. from South America), which has got a market share of approximately 80 % in Germany.
- Rapeseed honey can be substituted for other spreads, such as:
  - strawberry jam as an example of the huge number of fruit spreads
  - chocolate hazelnut spread, present in many households
  - treacle, a spread with a sugar content and consistency similar to honey

In addition, honey production yields the co-products pollen, beeswax, propolis, and royal jelly. Beeswax is mainly used in the cosmetics and pharmaceutical industry and is able to substitute various substances. In the current study we assume that it can be used as a coating material for dragées substituting carnauba wax, a hard wax from the leaves of the carnauba palm native to Brazil. In contrast to wax production, which has certain significance in Germany, the use of the other products is negligible. As an example, propolis as a natural drug used to maintain human health is considered significant in preventing the application of chemical pharmaceuticals.



Example how to read the diagram (top bars):

The figure illustrates the energy balance between RME and conventional diesel fuel in the basic scenario.

If RME is used instead of diesel fuel the energy saving is equal to 1.1 times (110 % of) the energy demand for the production and use of diesel fuel.

Result

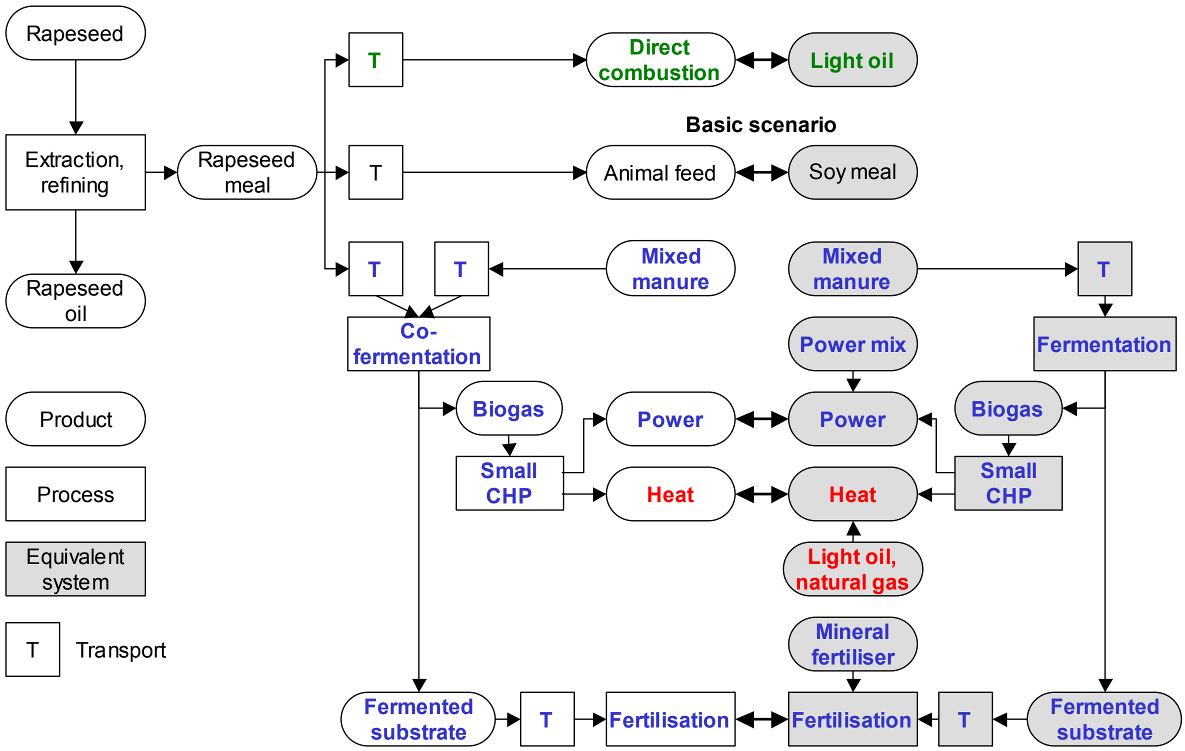
Honey production does not significantly alter the overall result of the LCA of RME, no matter which co-product is used in the calculation. This is basically due to the relatively small amounts of honey and its co-products. A detailed analysis (not shown) reveals that the co-products beeswax and propolis account for less than 20 % of expenses in all environmental impact categories. Therefore it is justified to trust the LCA conducted despite the fact that the substitutes of beeswax and propolis may be different depending on the respective application.

Conclusion

- The RME balance is completed by taking the production of honey and its co-products from rapeseed fields into account.
- However, even under extreme assumptions the co-product honey only marginally affects the overall assessment, which, depending on the scenario, may either have a positive or negative effect on the environmental impact of RME.

Nevertheless, for the sake of completeness we propose to include honey and its co-products from rapeseed fields in future life cycle assessments of RME.

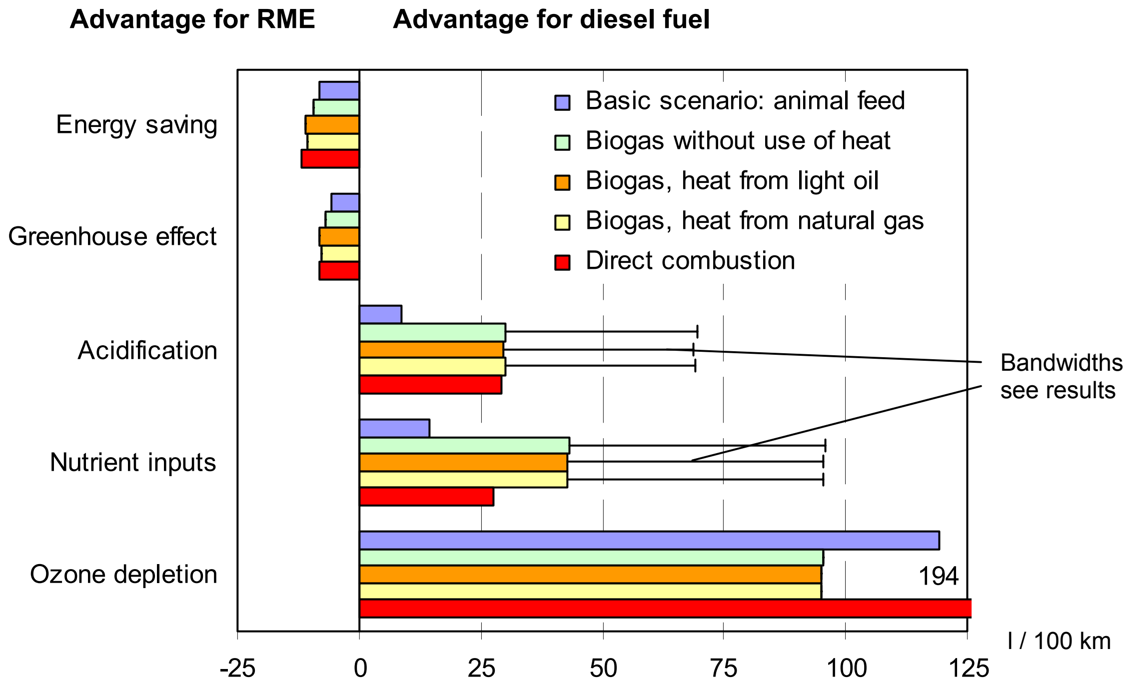
3.5 Biogas generation from rapeseed meal



Currently rapeseed meal is almost exclusively used as animal feed (basic scenario). However, the option of using rapeseed meal for energy generation is also under consideration for political reasons. In this respect a number of different scenarios are possible. Firstly, after extraction of the oil the resulting rapeseed meal can be fermented in a biogas plant. For that purpose a co-fermentation process with liquid manure is used, yielding biogas, which is converted into electrical energy and heat by a small combined heat and power plant. The process heat is used to heat the substrate and to compensate for heat losses, with a certain surplus of heat remaining. In this regard 3 options are calculated:

- **Biogas generation without heat utilisation**: surplus of heat is not used.
- **Biogas generation**, **heat from fuel oil** or **biogas generation**, **heat from natural gas,** respectively: the surplus of heat is used entirely for the supply of low-temperature heat e.g. on a pig breeding farm, which otherwise would have to be generated alternatively by either light fuel oil or natural gas.
- **Direct combustion**: in addition a sensitivity analysis was done for the direct combustion of rapeseed meal substituting light fuel oil (According to /GÄRTNER AND REINHARDT 2001/).

Comment on the figure above: since the liquid manure used would have to be utilised in either case, biogas generation from the same amount of liquid manure without rapeseed meal is considered as the reference system. As a consequence rapeseed meal is credited with the difference in electrical energy and heat generation as well as in the quantity of residue produced. The credit comprises electrical power from the public grid and mineral fertiliser.



Example how to read the diagram (second bar):

The top bars in this diagram represent the comparison of the entire energy balances between RME and conventional diesel fuel for the options animal feed, fermentation, and combustion of rapeseed meal.

If rapeseed meal is fermented and the resulting biogas used to generate electrical energy the energy saving is equal to the production and use of 8 litres diesel fuel on a distance of 100 km.

Results and conclusions

The interpretation of the data and results can be summarised as follows:

- **Comparison: biogas generation versus animal feed**. Both environmental advantages as well as disadvantages result from the different use of rapeseed meal. For that reason a scientifically justifiable, objective assessment is impossible. However, it is remarkable that the advantages and disadvantages are almost the same as for the comparison of RME with diesel fuel – advantages in energy saving and greenhouse effect, disadvantages in acidification and nutrient inputs. With regard to ozone depletion biogas generation has an additional advantage in comparison with the option animal feed. Therefore the following conclusion can be drawn: if a decision is made in favour of RME instead of diesel fuel based on ones own measure of value, then (as a consequence of the very same measure of value) biogas generation from rapeseed meal has clearly to be preferred to its use as animal feed.
- **Comparisons: 'animal feed versus combustion' and 'biogas generation versus combustion'**. By comparison, similar conclusions can be drawn if rapeseed meal is combusted directly instead of using it as animal feed or in a biogas plant. For the comparison 'animal feed versus combustion' a preference for RME entails opting for combustion (see /GÄRTNER AND REINHARDT 2001/). For the comparison 'biogas generation versus combustion' the combustion holds a single disadvantage only in the category

ozone depletion. Based on the same measure of value as above the combustion is therefore clearly more favourable than the fermentation of rapeseed meal.

- **General rating**. For the comparison ‘animal feed, biogas generation, or direct combustion of rapeseed meal’ the following conclusion can be drawn: based on a measure of value that favours RME instead of diesel fuel because of the benefits regarding energy saving and greenhouse effect, the options can be classified as follows: the direct combustion of rapeseed meal is more favourable than fermentation to yield biogas, which in turn is more favourable than the use of rapeseed meal as animal feed.

- **Significance**. The current assessment of the biogas generation has been conducted for average circumstances and specific basic conditions. It appears that the impact categories acidification and nutrient inputs are mainly determined by ammonia emissions, which arise from the storage and application of the residues after fermentation. In that respect certain determining factors are quite variable like, for instance, fermenting conditions and application technique. In the diagram the effects of these factors on the results are indicated in the form of bandwidth bars. Despite the magnitude of the bandwidths of the results, the conclusions regarding the assessment of biogas generation in comparison with the options animal feed and direct combustion do not change. In that respect the results can be regarded scientifically significant.

  In addition, the analysis revealed only small differences between the different options of fermentation. Consequently the overall result becomes only marginally more favourable if the surplus heat is utilised in contrast to not utilising it whereas the balances are slightly better if fuel oil is substituted instead of natural gas. The life cycle assessment on the other hand is determined by a multitude of factors like gas yield, fertilising effect of the residue, or system-specific differences (transport distances, plant dimensioning, etc.). Those factors may substantially alter the results.

  In a nutshell, the results derived for the options animal feed, fermentation or combustion of rapeseed meal in this study can be regarded reliable. However, for the analysis of a specific system or the comparison of different applications after fermentation of rapeseed meal to generate biogas has occurred, specific assessments are required.

4 Result summary

In contrast to previous life cycle assessments of RME the current analysis features a number of modifications. In addition to the adjustments concerning the basic scenario, which had been incorporated in the course of this project and which improve the outcome of RME, the updated basic data regarding the nitrous oxide emissions trigger numerically more favourable results in the categories ozone depletion and greenhouse effect. On the contrary, the supplementary consideration of the production of honey and its co-products from the rapeseed fields as well as the latest results on the preceding crop effect of rapeseed does not entail any significant changes of the LCA results. The potential fermentation of rapeseed meal however would markedly enhance the life cycle assessment of RME.

In detail the results are:

Considering the preceding crop effect of rapeseed

- With regard to the preceding crop effect, even recent publications do not provide any new findings for the life cycle assessments of RME.
- In that respect there are no significant changes in the current RME assessment compared to previous assessments.

Nitrous oxide emissions

The interpretation of the latest results on nitrous oxide emissions from rapeseed fields as well as rotational set-aside land provides new basic data, which in fact confirm the fundamental results, but numerically improve the current RME assessment:

- RME, in contrast to diesel fuel, continues to save greenhouse gases and to release more nitrous oxide.
- In the current study the saving of greenhouses gases by RME turns out to be larger than in previous studies, whereas the surplus of nitrous oxide emissions is smaller.

We recommend using the newly derived basic data in subsequent life cycle assessments.

Honey production

- Considering the production of honey and its co-products (beeswax, propolis, pollen, and royal jelly) from rapeseed fields was a part of the RME assessment.
- However, even under extreme assumptions the consideration of the production of honey and its co-products only marginally affects the overall assessment, which may be altered either to the advantage or to the disadvantage of RME depending on the respective scenario.
- The co-products beeswax and propolis, and the resulting variety of corresponding alternative products, play a minor role only.

Nevertheless, for the sake of completeness we propose to include honey and its co-products from rapeseed fields in future life cycle assessments of RME.

Biogas generation from rapeseed meal

- **Comparison: biogas generation versus animal feed.** Both environmental advantages and disadvantages result from the different use of rapeseed meal. For that reason a scientifically justifiable, objective assessment is impossible. However, it is remarkable that the advantages and disadvantages are almost the same as for the comparison of RME with diesel fuel: advantages in the categories energy saving and greenhouse effect, disadvantages in the categories acidification and nutrient inputs. With regard to ozone depletion biogas generation has an additional advantage in comparison with the animal feed option. Therefore the following conclusion can be drawn: if a decision is made in favour of RME instead of diesel fuel based on ones own measure of value, then – as a consequence of the very same measure of value – biogas generation of rapeseed meal has clearly to be preferred to the use as animal feed.
- **Comparisons: 'animal feed versus combustion' and 'biogas generation versus combustion'.** In analogy similar conclusions can be drawn if rapeseed meal is combusted directly instead of using it as animal feed or in a biogas plant. For the comparison 'animal feed versus combustion' a preference for RME entails opting for the combustion (see /GÄRTNER AND REINHARDT 2001/). For the comparison 'biogas generation versus combustion' the combustion holds a single disadvantage only in the category ozone depletion. Based on the same measure of value as above the combustion is therefore clearly more favourable than the fermentation of rapeseed meal.
- **General rating.** For the comparison 'animal feed, biogas generation, or direct combustion of rapeseed meal' the following conclusion can be drawn: based on a measure of value that favours RME instead of diesel fuel because of the benefits regarding energy saving and greenhouse effect, the options can be classified as follows: the direct combustion of rapeseed meal is more favourable than fermentation to yield biogas, which in turn is more favourable than the use of rapeseed meal as animal feed.
- **Significance.** The current assessment of the biogas generation has been conducted for average circumstances and specific basic conditions. In a nutshell, the results derived for the options animal feed, fermentation or combustion of rapeseed meal in this study can be regarded reliable. However, for the analysis of a specific system or the comparison of different applications after fermentation of rapeseed meal to generate biogas specific assessments are required.

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