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Climate design of vegetable oil fuels for agricultural equipment

The use of biofuels in agricultural machinery is an option for complying with climate protection requirements that are presently discussed to be placed on manufacturers of mobile off-road machinery by the European Commission. A mathematical model has been developed that allows calculating greenhouse gas emissions (GHGE) of biofuels for complex production paths in a straightforward, transparent manner and in pattern with the EU's Fuel Quality Directive (FQD). Therewith it has been shown that both rape seed and camelina sativa oil fuels can save more than 60 % GHGE. Key parameters have been identified and rules for a climate design of vegetable oil fuels have been formulated.

Keywords
Vegetable oil fuel, green house gas emissions, climate protection, mixed cultivation

Abstract
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The use of bio-fuels in agricultural equipment is an option for responding to climate protection requirements which are presently discussed to be placed on manufacturers of mobile off-road machinery by the European Commission. Vegetable oils are interesting candidates among bio-fuels because the production can be done on the farm itself from the field into the tank. Rape seed oil however, which is predominantly used in Germany just falls short of the minimum GHGE saving of 60% that will be compulsory from 2018 on. If produced in the standard production pathway that is underlying the EU Fuel Quality Directive (FQR) [1] it allows only for greenhouse gas emission (GHGE) savings of 57% compared to diesel fuel. A solution are optimized cultivation and production methods for rape seed oil, but notably false flax (camelina sativa) oil that is produced in mixed cultivation and from which phosphorous, alkali metals and alkaline earth metals have been completely removed. The proof of suitability of such cleaned camelina sativa oil as fuel for advanced tractor engines has recently been provided within the EU project "2ndVegOil" [2]. This result is presupposed in the following.

Mathematical model

For the purpose of a targeted optimization of the GHGE of vegetable oil fuels, a mathematical model has been formulated that translates the provisions of the FQD [1] into calculation rules for complex production processes. The provisions which are relevant for the calculations done with this model can also be found with identical wording in the Renewable Energies Directive (RED) [3]. The developed model is equivalent to the public version 4 of the BioGrace GHG Tool [4]. In contrast to the latter, it is designed to assess clearly structured and notated process chains with any number of steps and by-products at each step. This allows calculating GHGE of the production of pure vegetable oils in mixed cultivation, and notably the influence of changes of the input parameters on the results, in a stringent and transparent manner. At the same time, the model is open to take into account further process steps and potential further co-products. This opens the possibility for a targeted climate design of pure vegetable oil fuels.

Optimization of the GHG emissions of pure rape seed oil

This model has first been tested and verified on the example of the standard production process for pure rape seed oil which has entered in the FQD and the BioGrace GHG Tool. Then the potential for optimization of the production of rape seed oil was explored. At this point the agricultural cultivation method is decisive. 82% of the GHGE of pure rape seed oil are produced during the cultivation and only 18% in the subsequent processing steps. The biggest contributions are N_2O field emissions, nitrogen fertilizer production, and fuel for agricultural equipment which produce, respectively, 36%, 32% and 10% of the total GHGE of rape seed oil.

However the minimum GHGE saving of 60% can be achieved simply if the produced rape seed oil is itself used as fuel in the rape seed oil production process instead of diesel. In this case the GHGE of the produced rape seed oil can be described by the following formula:

$$\mathbf{E_B = a + b \cdot I}$$

Here, E_B denotes the GHGE of the rape seed oil, I the specific GHGE that result from the use of diesel fuel in the production of rape seed oil, a the part of E_B that is not due to the part of diesel that is going to be substituted by rape seed oil, and b a proportionality coefficient. E_B and a are indicated in g $CO_{2\text{-eq}}$/$MJ_{\text{oil in the tank}}$ (the GHGE are based on the energy content of the biofuel that finally arrives in the tank), I in $gCO_{2\text{-eq}}/MJ_{\text{diesel in the tank}}$, and b has no physical dimension. I is in the following considered to be the variable quantity that depends on the kind of substituting fuel. For purely fossil diesel it takes the value of 87.64 $gCO_{2\text{-eq}}/MJ_{\text{diesel in the tank}}$ [4]. b is a number smaller than 1, if replacing diesel by rape seed oil makes sense, i.e. if this lowers the GHGE. This condition is equivalent to E_B being smaller than I. Then it follows that b is smaller than 1.

If the produced rape seed oil is used again and again to substitute diesel in a continuous production process of rape seed oil, the GHGE of the latter amount to:

$$\mathbf{E_B = \lim_{n\to\infty}\left[a\cdot\sum_{i=0}^{n-1} b^i + I\cdot b^n\right] = \lim_{n\to\infty}\left[a\cdot\frac{1-b^n}{1-b} + I\cdot b^n\right] = \frac{a}{1-b}}$$

The values of a and b depend on that part of diesel that is substituted by rape seed oil, and thus on the allocation of the GHGE to the constant term a and the variable term b·I. **Table 1** shows the GHGE saving that can be achieved for different substitution scenarios.

The GHGE saving has been calculated according to the formula which is fixed by the FQD:

$$\mathbf{SAVING = (E_F - E_B)/E_F}$$

For the GHGE of the diesel reference fuel, E_F, the value of 87.64 $gCO_{2\text{-eq}}/MJ_{\text{diesel in the tank}}$ was used. The FQD stipulates a fossil fuel comparator of 83.8 $gCO_{2\text{-eq}}/MJ_{\text{diesel in the tank}}$, what is in contradiction to the sources on which the FQD is essentially based [1; 4; 5] and therefore represents an inconsistency within the FQD in the authors' opinion.

If one does not share this opinion and takes for E_F the value of 83.8 $gCO_{2\text{-eq}}/MJ_{\text{diesel in the tank}}$ that is indicated in the FQD, one obtains the slightly lower value of 56.98% instead of 58.86% for the GHGE saving without diesel substitution by rape seed oil (first line in Table 1). Rounded off to 57% that equals the value which is indicated in the FQD and which is calculated by the BioGrace GHG Tool. For the GHGE saving after diesel substitution one then obtains values between 59.69% and 60.12%. i.e. one meets, rounded off to the first digit before the comma, also the threshold of 60%. This result is therefore independent of the position which one takes with regard to the indicated inconsistency within the FQD.

GHGE of camelina sativa oil fuel from mixed cultivation

In the next step the model was applied for a calculation of the GHGE of camelina sativa oil that is produced in mixed cultivation with wheat. Mixed cultivation of cereals with camelina sativa allows reducing significantly the use of plant protection chemicals [5] and thus paves the way for a comprehensive ecologisation of agriculture. The camelina sativa part provides a bio-fuel without requiring large additional amounts of acreage – in the conflict between food and energy production a weighty aspect. The results are shown in **Figure 1**. The minimum GHGE saving of 60 % is clearly exceeded for a wide range of mixing ratios (see CS-W curves).

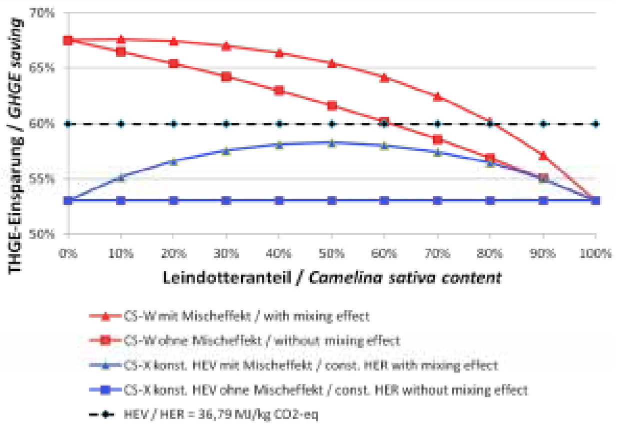
The key parameter is the lower heating value to GHGE ratio of the cultivation phase (HER), i.e. the ratio of the lower heating value of the produced crop to the GHGE related to the cultivation. Wheat has a better HER than 36.79 MJ/g $CO_{2\text{-eq}}$, which was found to be the minimum value for a crop mixture achieving a GHGE saving of 60 % if the oil crop is processed in a manner equivalent to the standard rape seed oil production process (see black horizontal curve for fictitious mixture where both components have a HER of 36.79 MJ/g $CO_{2\text{-eq}}$). The minimum HER is different if deviations from the standard produc-

Table 1

GHGE saving exceeding 60 % thanks to substitution of diesel by rape seed oil in a continuous rape seed oil production process

Ersatz von Diesel durch Rapsöl bei... ***Substitution of diesel through rapeseed oil for...***	**a [g $CO_{2\text{-äq}}/MJ_{\text{Öl\_im\_Tank}}$]** ***a [g $CO_{2\text{-eq}}/MJ_{\text{Oil\_in\_tank}}$]***	**b**	**E_B [g $CO_{2\text{-äq}}/MJ_{\text{Öl\_im\_Tank}}$]** ***$E_B$ [g $CO_{2\text{-eq}}/MJ_{\text{Oil\_in\_tank}}$]***	**THGE-Einsparung** ***GHGE saving***
Keinem Prozessschritt/*No process step*	36,051	0,000	36,051	58,86 %
Anbau/*Cultivation*	32,358	0,042	33,782	61,45 %
Anbau und Rapssaattransport *Cultivation and rape seed transport*	31,989	0,046	33,544	61,72 %
Anbau und Rapsöltransport *Cultivation and rape seed oil transport*	32,178	0,044	33,666	61,59 %
Anbau und Rapssaat- und -öltransport *Cultivation and rape seed and rape seed oil transport*	31,809	0,048	33,427	61,86 %
Anbau, Rapssaattrockung und Rapssaat- und -öltransport *Cultivation, rape seed drying, and rape seed and rape seed oil transport*	31,793	0,049	33,416	61,87 %

Fig. 1



GHGE saving as a function of the camelina sativa (CS) content in mixtures with wheat (W) or a fictitious grain crop (X) with the same HER as camelina sativa

tion process occur (e. g. different oil yield during pressing), but the difference is small in most cases.

Hence for a wide range of mixtures, the high HER of wheat compensates the low HER of camelina sativa. If the latter was combined with a crop X that has the same HER as camelina sativa, the GHGE saving would remain below 60 % for all mixtures (see CS-X curves).

Mixed cropping has shown to produce higher yields for the crop fractions than it would be expected from linear interpolation of the monoculture yields [5; 6]. For this reason, the yields have been interpolated not only linearly, but also by a square function that fits with literature values. The bent curves in **Figure 1** compared to the straight ones show the effect of this square function interpolation, i. e. the effect of the higher yields obtained by mixed cropping compared to monocultures. There is a gain of a few percent of GHGE saving!

Hence, mixed cropping is an effective option for optimizing the GHGE saving. The decisive parameters are the HER and those which describe the mixing effect. With these parameters suitable mixtures of oil crops with accompanying crops can be selected.

Rules for a climate design of vegetable oil fuels

From the achieved results rules for a climate design of vegetable oil fuels can be derived. In the following these are formulated for the production of vegetable oil fuels from mixed cultivation:

1. One of the associated crops should have a higher HER than 36.79 MJ/kg $CO_{2\text{-eq}}$ if the oil press yield in terms of energy content and the GHGE of the subsequent process chain have the same values as for the standard rape seed oil production process that is underlying the FQD. Otherwise a slightly different threshold applies for the HER that then has to be calculated anew.
2. At first an oil crop should be chosen whose HER is as high as possible.
3. If the oil crop does not reach the threshold for the HER, it should be associated with a grain crop whose HER is above the threshold.
4. If point 3 applies the mixture of both crops should be adjusted such that their HER is above the threshold. The smaller the HER of the oil crop, and the less the HER of the associated crop exceeds the threshold, the bigger the part of the associated crop must be in the mixture.
5. If the HER of the mixture exceeds the threshold for a broad range of mixing ratios, the mixture should be chosen such that the synergy effects are maximised. Besides optimising the climate balance, other targets can be addressed.
6. The produced pure vegetable oil should be used as much as possible as heating and/or engine fuel in its own production, first and foremost as fuel in agricultural machines for the cultivation of the oil crop, and secondly in CHP which produce heat and power for oil seed drying and pressing. Thirdly its use as heating and/or engine fuel within the closer region should be considered, for instance in neighbouring agricultural enterprises.

Further need for research and adaptation of the legal framework

Further need for research exists notably with regard to the functional relationships of N_2O field emissions, nitrogen fertilisation, soil conditions and climate/weather. This work has also shown that GHGE calculations with European average values, as those underlying the FQD, can lead to big differences to actual GHGE under real cultivation and production conditions. Here, further research is needed about the possibilities to conduct more precise regionally differentiated calculations with a reasonable effort.

In the course of this work, we noticed an inconsistency in the use of the GHGE reference value for diesel fuel within the FQD and its implementation. This calls for an adjustment of the FQD in the course of the next revision. The authors advocate further for a marginality limit in the consideration of carbon stock changes caused by indirect land use changes for bio-fuels which are produced by an agricultural enterprise for own use or consumption within the closer region. For further specifying this criterion, a limit could be set at 10 % of the agricultural area of a country or region that is used for the production of bio-fuels covering the own demand of agriculture and nearby consumers.

For assessing with greater reliability differences in GHGE that are due to regional characteristics, the cooperation is recommended with regional marketing initiatives which certify the regional origin of products. The use of typical regional values for the GHGE calculations for bio-fuels could be legitimised by a certification of such bio-fuels by accredited certification systems of regional marketing initiatives.

Conclusions

It has been shown that pure vegetable oil fuels can save 60% and more of the GHGE in diesel engines. This was done with a comprehensive mathematical modelling and calculations of the GHGE for vegetable oil production paths in compliance with the FQD 2009/30/EC. Hence pure vegetable oil fuels are an option to respond to climate protection requirements which are presently discussed to be placed on manufacturers of mobile off-road machinery by the European Commission.

A particularly interesting candidate among the bio-fuels that have been successfully demonstrated in the field in modern tractors is camelina sativa oil from mixed cultivation. Camelina sativa oil does not only allow achieving GHGE savings close to 70% by means of a targeted climate design, but also provides the path towards a comprehensive ecologisation of agriculture. It provides a bio-fuel without requiring large additional acreage – a weighty aspect in the conflict between food and energy production.

Literature

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A comprehensive presentation of the mathematical model and the performed calculations has been published in December 2011 as a monograph in the series „Agrartechnische Schriften aus Halle“ and can be ordered from the Institute for Agriculture and Nutrition Science at the Martin Luther University Halle-Wittenberg. An English version of the monograph is going to be prepared.