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Emission behaviour of vegetable oil fuel compatible tractors fuelled with different pure vegetable oils

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HIGHLIGHTS

- Eight vegetable oils and one mixture were tested in two vegetable oil compatible engines.
- Vegetable oils differed in their emission behaviour dependent on the engine operation mode.
- Increasing unsaturation of the oils led to higher NO_X emission at medium and high torque.
- Increasing unsaturation of the oils led to higher emissions of CO, HC and PM at idle mode.

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ABSTRACT

The emission behaviour of pure vegetable oils to be used as a fuel was researched using two vegetable oil fuel compatible tractors. The tractor engines were equipped with a common-rail and pump-line injection system. For the research eight different vegetable oils, one vegetable oil mixture and diesel fuel were used. Vegetable oils are basically triacylglycerides and can be characterised by the two structure indices average number of carbon atoms (AC) and average number of double bonds (ADB). The results show that both tractors can be operated with vegetable oils and diesel fuel at about the same level of efficiency. Specific test cycle emissions of nitrogen oxides (NO_X) tend to be higher while specific carbon monoxide (CO), hydrocarbon (HC) and particle mass (PM) emissions tend to be lower with the vegetable oils compared to diesel fuel.The emission behaviour of the two tractors was influenced by the type of vegetable oil used.

The differences were dependent on the operation mode. At average and high load operation points the emissions of CO, HC and PM were at the same level, whereas the NO_X emissions were rising with increasing ADB of the vegetable oils. At low load and idle operation the emissions of CO, HC and PM were rising with increasing unsaturation respectively increasing ADB of the vegetable oils. The observed increase of NO_X at average and high load could not be recognized anymore at low load and idle and is even reversed for one tractor. This indicates deteriorated combustion with increasing unsaturation of the vegetable oils at idle and low load.

1. Introduction

The usage of decentrally produced rapeseed oil for agricultural machinery can contribute to the security of fuel supply for food production. It is beneficial for climate, soil and water protection and can lead to a higher added value in agriculture [1–3]. In Germany, decentral oil mills have a processing capacity in the range of 500 kg to 2500 kg of rapeseed per day. The oil is produced by cold pressing with subsequent sorbent treatment and filtration. Decentral oil mills are often operated by farmers or farm cooperatives, the oil seeds typically originate from the local region. On the other hand industrial oil mills can have a processing capacity of up to 300,000 kg seed per day and the feedstock is obtained internationally. The oil is extracted by warm pressing and solvent extraction with subsequent refining [2].

Fleet tests in Europe demonstrated the suitability of pure rapeseed oil as fuel for agricultural machinery [4–7]. It could be shown that for modified engines rapeseed oil fuel is an appropriate alternative to diesel fuel. Quality requirements for rapeseed oil fuel are

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defined in the German standard DIN 51605 [8]. Regarding the quality requirements of other vegetable oils the standard DIN SPEC 51623 [9] and a CEN Workshop Agreement CWA 16379 [10] were established.

Vegetable oils are basically triacylglycerides with a low amount of minor components [11], whereas common diesel fuel is a mixture of many different hydrocarbon compounds such as n- and iso-alkanes, cycloalkanes, alkenes, alkynes and aromatic compounds [12]. Triacylglycerides are differing in the type of fatty acids bonded to the glyceride. Most naturally occurring fatty acids in vegetable oils can be differentiated by their carbon chain length and their number of double bonds (unsaturation) [11]. Many differences in physical and chemical properties of vegetable oils are determined by the composition of the fatty acids of the triacylglycerides. To get information about the molecular structure indices like iodine or saponification value are used [13]. The iodine value is a measure for the unsaturation of the vegetable oils and the saponification value for the relative average molecular mass [11,13]. For the characterisation and estimation of fuel properties based on the fatty acid composition also the average number of double bonds *ADB* and average number of carbon atoms *AC* of the fatty acids bonded to the glycerides can be used. With these two structure indices *AC* and *ADB* it is possible to directly calculate or estimate by regression models important fuel properties such as the average molar mass, elementary composition, stoichiometric air–fuel-ratio, density, net calorific value, kinematic viscosity and surface tension of the vegetable oils and also other structure indices like iodine value and saponification value [14]. For example, the kinematic viscosity and calorific value of vegetable oils decrease with increasing unsaturation and decreasing fatty acid chain length [14,15]. A detailed discussion of correlations between the molecular structure and physical and chemical fuel properties of vegetable oils is conducted in Emberger et al. [14].

Also, the ignition and combustion behaviour in a constant volume combustion chamber is influenced by the fatty acid composition of the vegetable oils. Especially a higher amount of double bonds in the fatty acids leads to a longer ignition delay [14,16]. Same was observed for fatty acid methyl esters (FAME) in constant volume combustion chambers, where a higher number of double bonds led to an increase of the ignition delay or a decrease of the derived cetane number respectively [16–19].

Furthermore, it could be shown that the fatty acid structure seems to influence the emission behaviour of diesel engines operated with FAME [20–25]. With a higher amount of double bonds in FAME the nitrogen oxides (NO_X) emissions are rising [20–25]. The increase of NO_X emissions is probably caused by several overlaid effects like differences in injection timing, ignition delay or adiabatic flame temperatures. Concerning PM emissions Knothe et al. [21] and Schönborn et al. [22] determined an increase of particle mass (PM) with rising unsaturation, whereas McCormick et al. [20] could not identify a clear trend.

For vegetable oils Munack et al. [26] and Hellier et al. [27] researched the influence of the fatty acid composition on the emission behaviour of diesel engines. Munack et al. [26] investigated a direct injection engine with pump-line-nozzle injection system applying the European stationary cycle ESC. An increase of NO_X with increasing saturation was observed whereas for PM no clear trend was visible. Hellier et al. [27] used a single cylinder direct injection research engine equipped with a common-rail system for the investigation of one low load operation point. An increase of PM was observed for increasing ignition delay, probably caused by the increasing unsaturation and by fuel impingement at the cylinder walls or piston bowl.

It can be summarized that currently only little information is available about the influence of molecular structure of vegetable oils on their emission behaviour in modern direct injection diesel engines. Thus, purpose of this work was to investigate the emission behaviour of different vegetable oils in vegetable oil compatible engines and to relate the results to the molecular structure. In the last years developments in the area of vegetable oil compatible engines were made for agricultural machinery mainly [28]. Hence, vegetable oil compatible tractors were used to measure the emission behaviour.

2. Materials and methods

2.1. Fuels

For the experiments eight different vegetable oils and one mixture of two vegetable oils were chosen. The selection was made to cover a wide range of different fatty acid compositions. We have chosen coconut oil (CC), palm oil (PA), high-oleic sunflower oil (HO), rapeseed oil (RA) and sunflower oil (SU). Furthermore soybean oil (SO), corn oil (CR) and jatropha oil (JA) were included because these oils are either available in relevant quantities or discussed as promising alternative fuels. CC, PA, HO, RA, SU and SO are refined oils originating from industrial oil mills (delivered from Brökelmann + Co., Germany and Henry Lamotte Oils, Germany). CR and JA originated from the oil mill Öl und Bioenergie GmbH, Austria. CR and JA were cold pressed, sorbent treated and filtered to reduce the content of Phosphorus, Calcium and Magnesium to meet the limit values of these components according to the fuel quality standard DIN SPEC 51623 [9].

The fatty acid composition of all vegetable oils was determined according to ISO 5508 [29] and is shown in Table 1.

Additionally, following fuel properties were analysed, using the methods according to DIN SPEC 51623 [9]:

- Acid number according to EN 14104 [30]
- Calcium content according to EN 14538 [31]
- Density at 15 °C according to EN ISO 12185 [32]
- Iodine value according to EN 14111 [33]
- Kinematic viscosity at 40 °C according to EN ISO 3104 [34]
- Magnesium content according to EN 14538 [31]
- Net calorific value according to DIN 51900-1 [35]
- Phosphorous content according to EN 14107 [36]
- Sulphur content according to EN ISO 20884 [37]
- Water content according to EN ISO 12937 [38]

The fatty acids of the triacylglycerides are characterised by the length of the carbon chain and the amount of double bonds within the chain. The average number of carbon atoms (*AC*) and the average number of double bonds (*ADB*) were calculated, based on the analysis of the fatty acid composition (Eqs. (1) and (2)) [14].

$$AC = \frac{\sum\left(\frac{w_i}{M_i} \times N_{\mathrm{C},i}\right)}{\sum \frac{w_i}{M_i}} \tag{1}$$

$$ADB = \frac{\sum\left(\frac{w_i}{M_i} \times N_{\mathrm{DB},i}\right)}{\sum \frac{w_i}{M_i}} \tag{2}$$

$N_{\mathrm{C},i}$ is the number of carbon atoms of the fatty acid i, $N_{\mathrm{DB},i}$ is the number of double bonds of the fatty acid i, M_i is the molar mass of the fatty acid i and w_i is the mass fraction of the fatty acid i, taken from the fatty acid composition. Thus, we were left with two structure indices that account for the two most important differences in the triacylglycerides of vegetable oils.

The elemental composition of the vegetable oils was calculated using the approach described in Emberger et al. [14]. The calculated structure indices, elemental composition and analysed fuel properties are shown in Table 2. Most of the vegetable oils are