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## ***Influence of the molecular structure of vegetable oil fuel on the emission behaviour of tractors***

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### **Abstract**

The usage of rapeseed oil as a fuel for agricultural machinery is beneficial for climate, soil and water protection and can lead to a higher added value in agriculture. In fleet tests the operational reliability of rapeseed oil fuelled tractors was demonstrated and the emission behaviour was researched. For other vegetable oils only little information is available about operation or emission behaviour. Research from the area of fatty acid methyl esters (FAME) showed that the emission behaviour of engines is influenced by the fatty acid composition. However, for pure vegetable oils almost no research is available in this regard. Thus, target of the research was to determine the influence of different vegetable oils on the emission behaviour of tractors.

Therefore, the emission behaviour of two tractors of different development stages (exhaust gas stage I and IIIA), operated with eight different vegetable oils and a vegetable oil mixture, was researched at a tractor test stand. In this work the average number of double bonds *ADB* and the average number of carbon atoms *AC* of the fatty acid chains of the triacylglycerides were used as molecular structure indices to judge the emission behaviour.

The emission behaviour of the researched tractors was influenced by the different vegetable oils. At operation points of medium and high load the nitrogen oxides emissions ( $\text{NO}_x$ ) were increasing with higher average number of double bonds *ADB* in the fatty acid chains of the triacylglycerides of the vegetable oils. The amount of products of incomplete combustion, carbon monoxide (CO), hydrocarbons (HC) and particle mass (PM), were not influenced by the type of vegetable oil at this load modes. The observed increases of  $\text{NO}_x$  at medium and high load for higher *ADB* were not recognized at low load and idle. But the concentrations of CO, HC and PM were increasing with higher *ADB* in the fatty acid chains. For *AC* no relevant effect on the emission behaviour could be found.

It can be concluded that vegetable oils characterised by a low *ADB* will have a better emission behaviour than those with higher *ADB*. Vegetable oils with similar *ADB* should also have similar emission behaviour. *ADB* can be used as a parameter for a first assessment of the expected emission behaviour of unknown vegetable oils or vegetable oil mixtures compared to other vegetable oils.

**Keywords:** tractor, emission, biofuel, vegetable oil

### **1 Introduction**

The usage of rapeseed oil as a fuel for agricultural machinery is beneficial for climate, soil and water protection and can lead to a higher added value in agriculture. In several fleet tests the usage of pure rapeseed oil as fuel for agricultural machinery was demonstrated (Hassel et al., 2006; Rathbauer, Krammer, Zeller, & Prankl, 2009; Emberger, Thuneke,

Gassner, & Remmele, 2010; Dieringer & Pickel, 2011). It could be shown that rapeseed oil is an appropriate alternative to diesel fuel, provided that the engine is modified for rapeseed oil operation. Quality requirements for rapeseed oil fuel are defined in the German standard DIN 51605. Concerning the usage as a fuel in agricultural machinery most experiences were made for rapeseed oil. Only little information is available for other vegetable oils. Regarding the quality requirements of other vegetable oils the pre-standard DIN SPEC 51623 and a CEN Workshop Agreement CWA 16379 were developed.

Vegetable oils are triacylglycerides with a low amount of minor components, whereas diesel fuel is a mixture of many different hydrocarbon compounds. Triacylglycerides are differing in the type of fatty acids bonded to the glyceride. Naturally occurring fatty acids in vegetable oils can be differentiated by their carbon chain length and their number of double bonds (Bockisch, 1993). Many differences in physical and chemical properties of vegetable oils are caused by the composition of the fatty acids of the triacylglycerides. 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 and thus to a different combustion behaviour (Emberger, Thuneke, & Remmele, 2013a).

For fatty acid methyl esters (FAME) it could be shown that the fatty acid structure seems to influence the emission behaviour of diesel engines operated with FAME (e.g. McCormick, Graboski, Alleman, Herring, & Tyson, 2001; Knothe, Sharp, & Ryan, 2006; Schönborn, Laddomatos, Williams, Allan, & Rogerson, 2009). For vegetable oils only little research work is available concerning the influence of the fatty acid composition on the emission behaviour of engines (e.g. Kollar, 1999; Dobiasch, 2000; Munack, Bünger, & Krahl, 2010). Most of the research was made with engines that are not state of the art anymore or which were not adapted to vegetable oil fuel.

Thus, purpose of this work was to research 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 only. Hence, tractors were used to measure the emission behaviour.

## 2 Materials and methods

For this research eight different vegetable oils and a vegetable oil mixture were used (see Table 1). Based on the fatty acid compositions of the vegetable oils, the two structure indices average number of double bonds *ADB* and average number of carbon atoms *AC* of the fatty acid chains were calculated. Details about the calculation procedure can be found in Emberger et al., 2013a. By those two indices the most important differences in the molecular structure of the most naturally occurring vegetable oils can be described. An overview about the used vegetable oils, the calculated structure indices, the net calorific value *NCV* and the density  $\rho$  is given in Table 1.

Table 1: Average number of carbon atoms *AC* and average number of double bonds *ADB* of the fatty acids chains, net calorific value *NCV* and density  $\rho$  (15 °C) of the used vegetable oils.

Vegetable oil	<i>AC</i>	<i>ADB</i>	<i>NCV</i> in MJ/kg	$\rho$ (15 °C) in kg/m <sup>3</sup>
Coconut oil	13.04	0.121	34.97	926 <sup>a)</sup>
Palm oil	17.10	0.624	36.82	921 <sup>a)</sup>
Mixture 1	15.91	0.629	36.21	n.d.
High oleic sunflower oil	17.99	0.998	37.14	916
Jatropha oil	17.72	1.216	36.93	919
Rapeseed oil	17.96	1.287	37.06	920
Corn oil	17.82	1.423	37.13	922
Soybean oil	17.89	1.433	37.12	922
Sunflower oil	17.93	1.477	37.11	923

<sup>a)</sup> measured at solid state; n.d.: not determined

The emission measurements were performed at the tractor test stand of the Technologie- und Förderzentrum (TFZ). A detailed description of the test stand is given in Emberger, Thuncke, & Remmele, 2013b. The applied procedure was an adapted version of ISO 8178-1 with the engine mounted on the tractor and the power taken off at the power take-off (PTO) with a dynamometer. Testing cycle was the stationary 8-mode-test defined in DIN EN ISO 8178-4, which is shown in Figure 2.

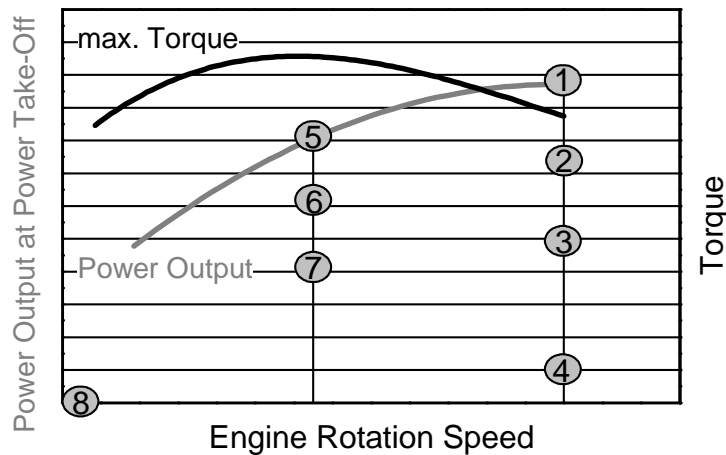


Figure 1: Eight test modes within the engine operating map according to DIN EN ISO 8178-4.

The tractors used were a Fendt Farmer Vario 412 and a John Deere 6930 Premium prototype machine. Technical data of the tractors are shown in Table 2. Both engines were adapted to be operated with rapeseed oil fuel according to DIN 51605.

Table 2: Technical data of the tractors used.

Parameter	Tractor 1	Tractor 2
Type	John Deere 6930 Premium	Fendt Farmer Vario 412
Engine type	PowerTech Plus	Deutz BF4M2013C
Number of cylinders	6	4
Displacement in ccm	6788	3802
Rated power / speed in kW / rpm	114 <sup>1)</sup> / 2100	94 / 1950
Injection system	Common-Rail	Pump-Line-Nozzle
Year of manufacture	2008	2003
Exhaust gas stage	IIIA	I
Exhaust gas recirculation	External and cooled	-

<sup>1)</sup> Intelligent power management deactivated

The experiments were carried out using all vegetable oils mentioned in Table 1 for tractor 1 and using coconut oil, palm oil, mixture 1, high oleic sunflower oil and rapeseed oil for tractor 2. Coconut oil, palm oil and mixture 1 were heated to a level of 45 °C to keep them at liquid state. All measurements were made in triplicates.

Multiple regression analysis was used to identify relations between the emission behaviour and the structure indices *AC* and *ADB*. Basis for the regression analysis were the calculated mean values of the results of the three trials, which were made for every single vegetable oil. The regression analysis was performed by using the software package Origin 8.1 (OriginLab Corporation, Northampton, U.S.A.).

### 3 Results and Discussion

The results showed that the tractor engines had about the same efficiency using the different vegetable oils, which is in accordance with the results obtained by Tschöke, 1997. Fuel con-

sumption and mass based injection rate were about the same for all vegetable oils. Because of differences in net calorific value  $NCV$  (see also Table 1) and density  $\rho$  the amount of energy delivered into the cylinder is varying. This resulted in lower power output at the power-take-off for the vegetable oils with lower  $NCV$ . The lowest power output was observed for coconut oil, which also had the lowest  $NCV$ . Table 3 shows the power output at the power-take-off for tractor 2 at operation point 5 of the 8-mode-test.

Table 3: Power output (arithmetic mean  $\pm$  span) at the power-take-off for tractor 2 at intermediate speed (1350 rpm) and 100 % torque ( $n=3$ ).

Vegetable oil	Coconut	Palm	Mixture 1	High oleic sunflower	Rapeseed
Power output in kW	81.7 $\pm$ 0.4	84.6 $\pm$ 1.1	85.0 $\pm$ 0.5	88.0 $\pm$ 0.2	88.2 $\pm$ 0.5

Figure 2 shows the nitrogen oxides emissions ( $NO_x$ ) of tractor 2 in relation to the imparted energy content of the fuel  $Q$ . For every speed level the  $NO_x$  concentration in the exhaust gas is increasing with a higher amount of energy delivered to the cylinder. This is caused by higher peak temperatures in the cylinder during combustion, which leads to the formation of thermal  $NO$ . The highest  $NO_x$  concentrations were recognized at the operation points with 100 % torque, where the highest amount of energy per stroke was delivered into the cylinder. The differences of  $NO_x$  between the vegetable oils were up to 130 ppm. These differences cannot be explained solely by the varying energy content delivered into the engine. In principle, tractor 1 showed the same behaviour concerning the differences in  $NO_x$  between the vegetable oils, but was influenced by the exhaust gas recirculation rate.

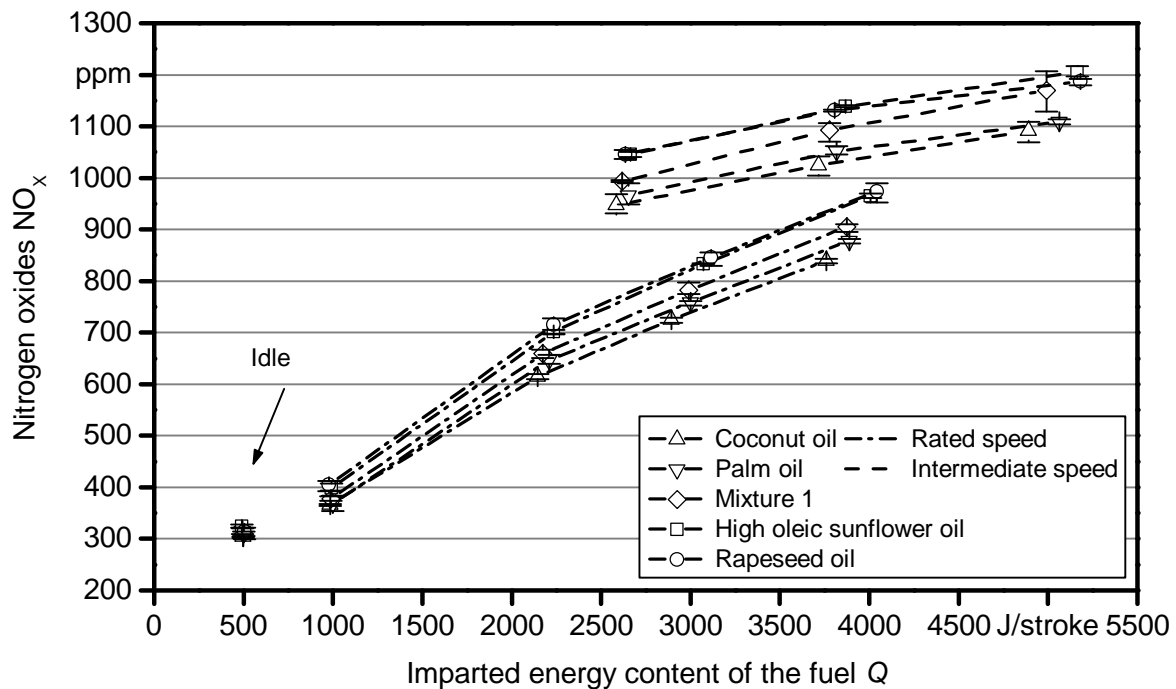


Figure 2: Nitrogen oxides emissions ( $NO_x$ ) of tractor 2 in relation to the imparted energy content of the fuel  $Q$ .

A multiple regression analysis was performed for every single test mode to find relations between the structure indices and the  $NO_x$  emissions. In a first step, no significant model could be developed using the average number of carbon atoms  $AC$  and average number of double bonds  $ADB$  as variables to explain the differences in  $NO_x$  concentrations. A t-test of the regression coefficients  $AC$  and  $ADB$  indicated that  $ADB$  has a significant influence on  $NO_x$ . This was not the case for  $AC$ . Therefore,  $AC$  was excluded from the regression analysis and a linear regression analysis was made using only  $ADB$  as variable.

Figure 3 shows the  $NO_x$  emissions of tractor 1 and 2 for every single test mode in relation to  $ADB$ . Significant linear relations between  $NO_x$  and  $ADB$  are indicated by a line and the stated

adjusted coefficient of determination  $R^2_{corr}$ . With the exception of test mode 5 of tractor 2, for all test modes with a torque  $\geq 50\%$  a linear increase of  $\text{NO}_x$  with rising  $ADB$  was recognized with reasonable  $R^2_{corr}$ . The relative increase compared to the average of all vegetable oils varied in a range of 8 to 14 % per one  $ADB$  for those single test modes. For the test mode at rated speed and 10 % torque the  $\text{NO}_x$  emissions of tractor 2 showed an increase of 10 % per  $ADB$ , whereas  $\text{NO}_x$  of tractor 1 seemed not to be influenced by  $ADB$  in this test mode. At idle mode the increase of  $\text{NO}_x$  with rising  $ADB$  disappeared for tractor 2. For tractor 1 even a decrease of  $\text{NO}_x$  was observed with rising  $ADB$  of the vegetable oils.

Emission tests using different fatty acid methyl esters (FAME) as fuel for engines also showed increasing  $\text{NO}_x$  emissions with a higher amount of double bonds contained in FAME (e.g. McCormick et al., 2001; Schönborn et al., 2009). Schönborn et al., 2009 concluded that the increase of  $\text{NO}_x$  with rising amount of double bonds is caused by several superimposed effects, but a longer ignition delay with higher amount of double bonds seems to be one of the most important factors. With a longer ignition delay the amount of fuel that is burning very rapidly with high local peak temperature is rising. This results in the formation of more thermal  $\text{NO}$ . Investigations by Emberger et al., 2013a for vegetable oils burnt in a constant volume combustion chamber indicate that with rising  $ADB$  the ignition delay is rising. Therefore, a longer ignition delay caused by a higher amount of double bonds within the vegetable oils could also explain the rising  $\text{NO}_x$  concentrations of the tractors. Findings for FAME seem to be transferable to vegetable oil combustion in tractor engines.

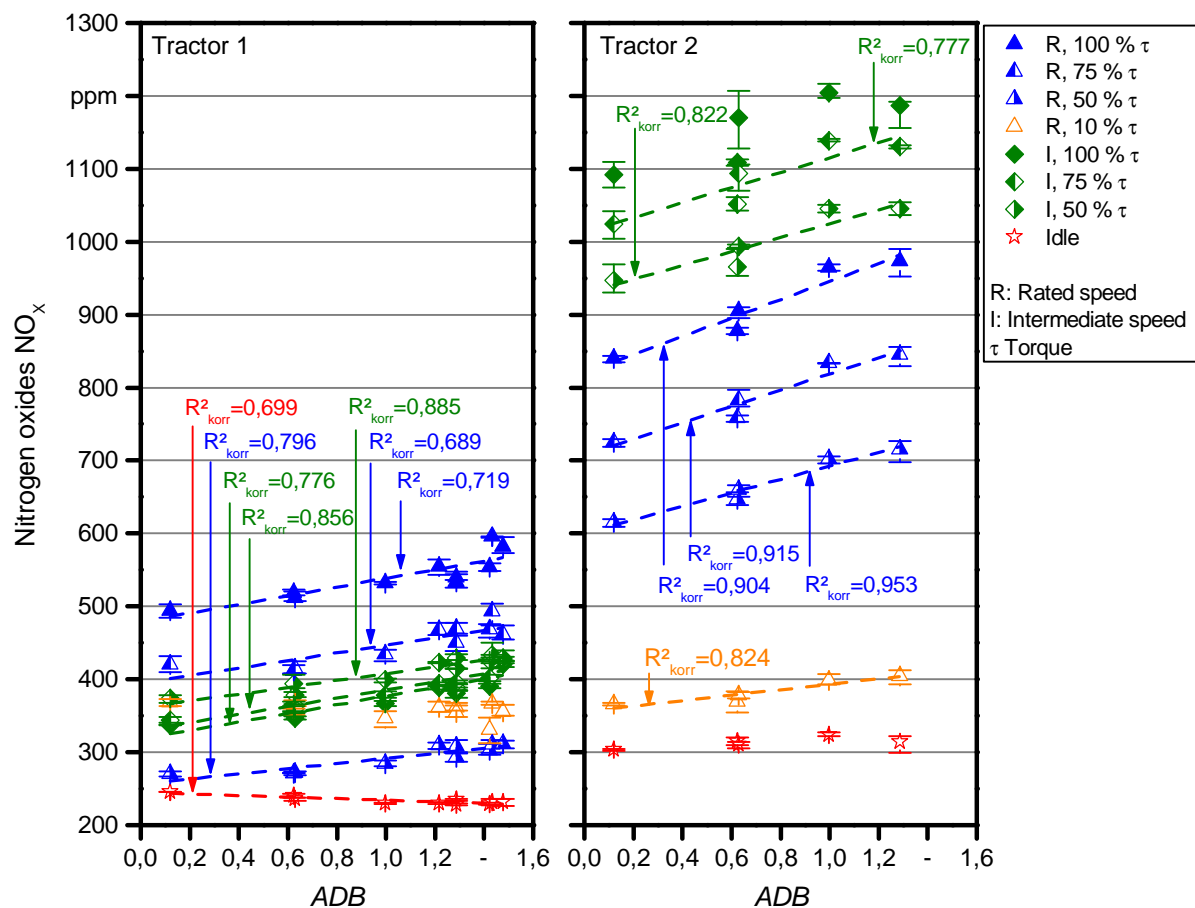


Figure 3: Nitrogen oxides emissions ( $\text{NO}_x$ ) of the tractors against the average number of double bonds  $ADB$  of the vegetable oils.

The carbon monoxide ( $\text{CO}$ ) emissions were at the same level for all vegetable oils at the test modes with a torque  $\geq 50\%$ . Only for partial load and idle test modes some differences between the vegetable oils could be observed. A regression analysis was performed finding that  $AC$  could not be used to explain differences in  $\text{CO}$  concentrations between the vegetable oils, while  $ADB$  could be used.

Figure 4 shows the CO concentrations in the exhaust gas of the tractors in relation to *ADB*. For both tractors at the idle test mode an increase of CO with rising *ADB* was recognized. The increase of CO as a function of *ADB* was higher for tractor 1 (286 ppm/*ADB*) than for tractor 2 (139 ppm/*ADB*). Furthermore, tractor 1 showed an increase of CO with rising *ADB* at the partial load test mode with 10 % torque at rated speed, but at a lower level of 66 ppm/*ADB*.

Similar results as for the CO emissions were gained for hydrocarbon (HC) and particle mass (PM) emissions. All of them are products of incomplete combustion.

The results indicate that at test modes with a torque  $\geq 50\%$  there is no difference in the exhaust gas concerning products of incomplete combustion. For a complete oxidation of the hydrocarbons, the duration of the combustion during the expansion phase of the cylinder is important. With ongoing expansion, pressure and temperature in the cylinder are falling and the conditions for a complete oxidation of the fuel are deteriorating. The results for incomplete combustion products indicate that there is no major difference in the late combustion of the vegetable oils at these test modes. Results of Emberger et al., 2013a obtained by vegetable oil combustion in a constant volume combustion chamber showed no differences in the late combustion of vegetable oils as well.

Partial load and idle test modes are characterised by lower cylinder pressures and temperatures. The conditions for a good spray quality and evaporation of the fuel are poor compared to high load test modes and the ignition delay is getting longer. With a longer ignition delay there is more time for mixing with air and a higher amount of fuel is getting in zones outside the flammability range. In these zones the temperatures are often not sufficient for a complete oxidation of the fuel, especially at low load operation. This leads to an increase of CO, HC and PM emissions. A longer ignition delay because of rising *ADB* can be used to explain the rising emissions of CO, HC and PM at low load operation. The missing increase of NO<sub>x</sub> with higher *ADB* at these test modes can be used as indicator for lower combustion temperatures.

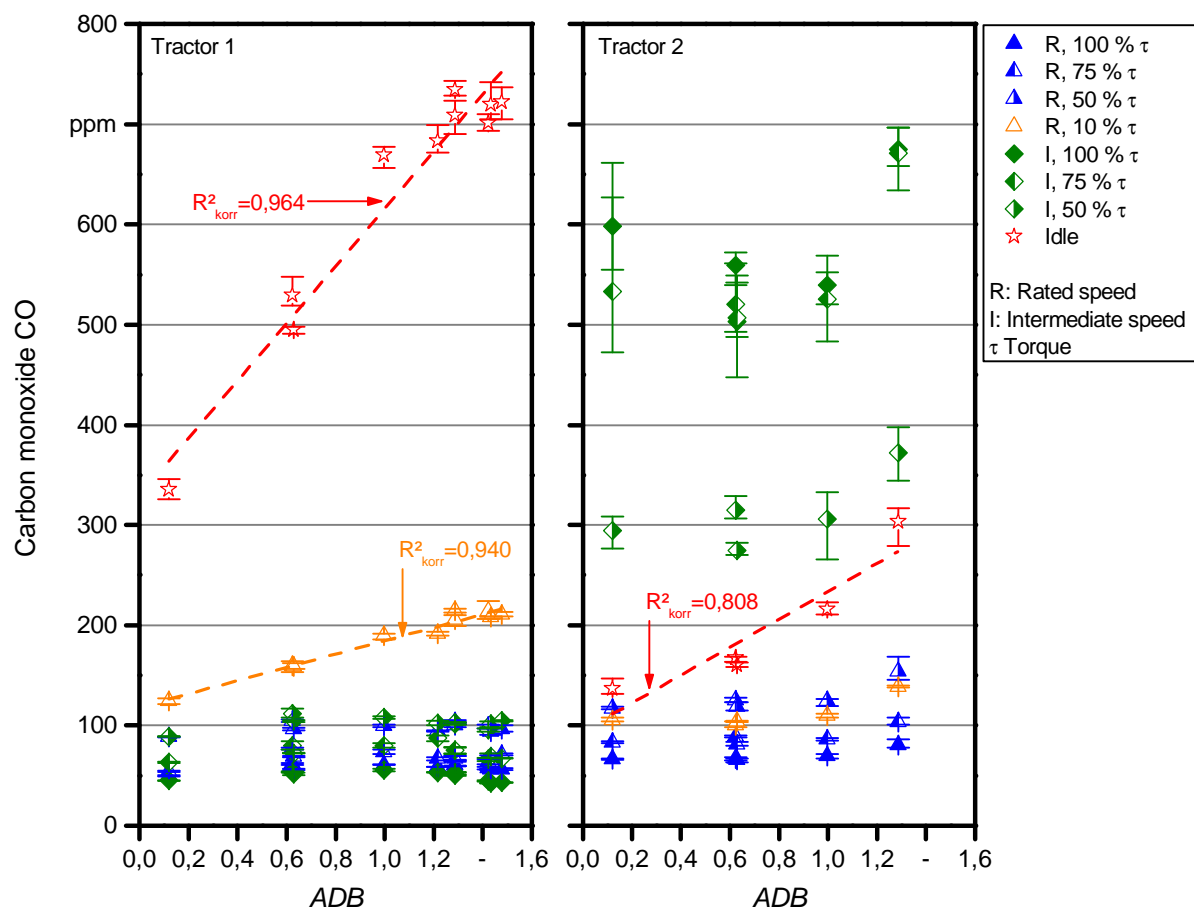


Figure 4: Carbon monoxide (CO) emissions of the tractors against the average number of double bonds *ADB* of the vegetable oils.

## 4 Conclusions

The emission behaviour of vegetable oil compatible tractors is influenced by the type of vegetable oil used as fuel. The most important differences between the vegetable oils are the number of carbon atoms and double bonds in the fatty acids of the triacylglycerides. The amount of double bonds within the vegetable oils seems to be the most important parameter affecting the emission behaviour. In this work, the average number of double bonds *ADB* was successfully used as structure index to judge the emission behaviour.

An increase in *ADB* leads to an increase in  $\text{NO}_x$  emissions at medium and high load operation points, whereas the CO, HC and PM emissions are not affected. At low load operation the  $\text{NO}_x$  increase is disappearing or inverting but the products of incomplete combustion (CO, HC and PM) are rising.

It can be concluded, that vegetable oils characterised by a low *ADB* will have a better emission behaviour than those with higher *ADB*. Vegetable oils with similar *ADB* should also have similar emission behaviour. *ADB* can be used as a parameter for a first assessment of the expected emission behaviour of unknown vegetable oils or vegetable oil mixtures compared to other vegetable oils.

## 5 Acknowledgements

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