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Characteristics describing the price formation of bioethanol used as the fuel for an internal combustion engine

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Abstract. A wider introduction of bioethanol as a biorenewable fuel is hindered by low awareness. The main problems related with its use are related to the properties of bioethanol fuel as well as the differences arising from its energetic value in comparison with regular fuels. This raises questions concerning the economic purposefulness of using bioethanol. In order to describe bioethanol as a motor fuel, a comparative analysis was performed based on experimental research. Experimental research allows for establishing a calculation model that describes the use of bioethanol as a fuel for an internal combustion engine in case of different ethanol content and various mixture ratios with regular fuels. The parameters to be studied and compared include the quantity and price of the fuel based on ethanol content. The comparative characteristics derived from the calculation model are indicated in tables and in figures. Calculation model creates a connection between using bioethanol as a motor fuel, and its production, thus providing useful information when choosing the production technology.

Keywords: dual fuel supply system, engine with compression-ignition, fuel mixtures, hydrous ethanol.

Introduction

The objective of this present study is to identify the problems related to the spread of using bioethanol as motor fuel. Bioethanol stands for liquid made of lignocelluloses with different ethanol content. A wider use of bioethanol as a motor fuel makes it possible to meet the requirements specified in European Directive 2009/28/EC in order to achieve the 10% target for the share of biofuels in transport petrol by 2020 (European Parliament, 2009). One option is to promote the use of bioethanol in the agricultural sector. The advantage of using biofuels in agriculture can be a complex solution, where the fuel to be consumed is produced locally. This solution allows more efficient use of their own resources, such as land use, creation of jobs, energetic autonomy, etc. However, the problem lies in a low level of awareness and the study of economic impact. One major question in case of this complex solution for using bioethanol is that of the fuel consumption. Another common issue is the impact of using bioethanol with lower ethanol content. It concerns the extent to which fusel oils affect the values of engine output and economic parameters.

In their earlier works the authors have dealt with the problems arising from the chemical-physical properties of bioethanol and their impact on engine components (Olt et al., 2011). The impact on the motor component surfaces exposed to the bioethanol is significant, yet not many studies have been performed with regard to describing the impact of bioethanol on the specific cost of work (€ (kW h)$^{-1}$). Another important factor is the change in the expenses related to the introduction of bioethanol with regard to the cost of fuel consumption in comparison with regular fuels. In order to describe the changes in cost when using bioethanol fuel, they can be divided into two groups. The expenses in the first group are associated with the machine (engine) and the expenses in the other group are associated with the price formation in the course of fuel production.

Machine-related expenses mostly arise from the structural specifics of the engine. The expenses on reconstruction or adjustment depend on the type of engine used. Although this is a one-time expenditure, the change in cost is also affected by specific fuel consumption (kg (kW h)$^{-1}$), associated with the difference in the calorific value of bioethanol (J).

The expenditure associated with fuel price include the production cost of bioethanol fuel (€ kg^{-1}), state taxes and subsidies. During the transition to biofuels it is crucial to use local raw materials for production. Therefore the raw material resource is important.

The main task is to examine the impact of the properties of bioethanol (ethanol content) on the cost of fuel consumed in the internal combustion engine, and – vice versa – the effect resulting from the cost of fuel consumption on the development of suitable production technology. The study carried out on the basis of bioethanol use provides the fuel manufacturers with the necessary a priori knowledge for producing bioethanol fuel at a competitive price.

Materials and methods

Direct expenses on certain field area unit C_S, which takes into account the productivity of aggregate (W), depreciation (a_T, a_M), technical maintenance and repairs (p_T, p_M), fuels and lubricants, and wages (c_p), are expressed as follows (Reintam, 1982):

$$C_S = \frac{1}{W}\left[\frac{B_T(a_T + p_T)}{100T_T} + \frac{B_T(a_M + p_M)}{100T_T} + \frac{q_T \cdot v_p \cdot R_x \cdot c_f}{\eta_T \cdot \xi} + c_p\right] \tag{1}$$

where the component of the formula

$$\frac{q_T \cdot v_p . R_x c_f}{\eta_T \cdot \xi} \tag{2}$$

describes the expenditure on fuel and lubricants during one working hour and it can therefore be referred to as the hourly cost of fuel consumption C_f (€ h^{-1}). An important parameter in determining the hourly cost of fuel consumption is the fuel sales price c_f, i.e. fuel price in filling station (€ kg^{-1}).

Considering the work resistance of agricultural machine R_x and $R_x/(\eta_T \cdot \xi) = F_h$, where F_h is the drawbar force, and knowing that power P is the product of force F and velocity v, we can express the drawbar power of the tractor P_h as follows:

$$P_h = \frac{R_x \cdot v_p}{\eta_T \cdot \xi}, \tag{3}$$

where v_p – working speed of the agricultural vehicle;
η_T – driving efficiency of the tractor;
ξ –nominal driving force efficiency of the tractor.

Thus we can express the relation (2) as follows:

$$C_f = \frac{q_T \cdot v_p \cdot R_x}{n_T \cdot \xi} \cdot c_f = q_T \cdot P_h \cdot c_f, \tag{4}$$

where q_T – specific fuel consumption (kg kJ^{-1}).

Relation (4) indicates that product $q_T \cdot P_h$ expresses hourly fuel consumption B_f, thus we can bring forward the following relation between the hourly cost of fuel consumption C_f and fuel sales price c_f (€ kg^{-1}):

$$C_f = B_f \cdot c_{f,} \tag{5}$$

where B_f – hourly fuel consumption (kg h^{-1}).

As for raw material selection, the purpose was to examine the price formation of bioethanol fuels made of lignocelluloses and having different ethanol content. Due to the rather large quantity of fuel required for engine testing and the time-consuming production process in laboratory conditions, the engine testing was performed by using ethanol diluted with distilled water.

At first tests were performed to compare the differences of bioethanol made of lignocelluloses and ethanol diluted with distilled water during engine testing. In order to ensure maximum residue content and steady engine operation, liquids with minimum ethanol content (60%) were chosen for testing. The differences in the comparison of output and economic parameters were non-significant (Küüt et al., 2012). The production of bioethanol by using lignocelluloses has been described in the section concerning the bioethanol production price formation. Cost price analysis was performed for bioethanol made of hay. Tested ethanol fuels were subject to the comparative analysis of the properties, which contains the results gained from the analysis of residues and is presented numerically in Table 1.

Table 1. The chemical and physical characteristics of ethanol and farmstead ethanol

Property	Testing method	Ethanol 60%	Farmstead ethanol 58.9%
Density, g (cm^3)$^{-1}$ 20°C	DIN EN ISO 12185	0.908	0.917
Recrement, g l^{-1}	ASTM D381-04	**0.0081**	**0.050**
Colour		Colourless	Yellow
Flashpoint, °C	DIN EN ISO 2719	24.5	24.5
Vaporpressure, kPa 37.5°C	ASTM D5191-07	14.5	14.5

The components used for preparing tested ethanol fuels were 96% ethanol and distilled water. Ethanol fuels were prepared by mixing distilled water into ethanol, resulting in mixtures with absolute alcohol content of 60%, 70%, 80%, and 90% (Table 2).

Table 2. Fuels selected for testing

Test	Fuel
T1	Diesel fuel
T2	Diesel fuel + ethanol 60 % (V/V)
T3	Diesel fuel + ethanol 70 % (V/V)
T4	Diesel fuel + ethanol 80 % (V/V)
T5	Diesel fuel + ethanol 90 % (V/V)

Engine testing was carried out in the engine testing laboratory of the Estonian University of Life Sciences by using D-120 engine with compression-ignition and braking stand Schenck Dynas 3 LI-250. Test engine was chosen based on its structural characteristics. This engine is air-cooled and allows using an additional supply system and measuring devices. According to the results achieved, comparative graphs were prepared and analysis was performed. An additional supply system was used for supplying the engine with different ethanol fuels. The main fuel supply system was used for igniting the fuel mixture with regular fuel (diesel fuel), because of the poor ignition properties of the ethanol mixture. The additional supply device consisted of a carburettor connected between the intake manifold and air measurement system. Carburettor main jet throughput adjustment was used to determine the optimum pre-supply amount of ethanol fuel which ensured the stability of engine operation. Engine tests chosen for analysis were performed at load mode $n_{e,t1}$ = 1,800 min^{-1} and $T_{e,t2}$ = 90 N m, without readjusting the engine. Measurements included fuel consumption b_f, air consumption b_a, temperature of exhaust gases t_{egt}, and oil temperature t_o. Fuel consumption was measured separately for diesel fuel used in case of pilot injection and for ethanol fuels used in case of an engine with an additional fuel supply device. Measurement results were registered by means of electronic scales. Measured test results were used to calculate the hourly fuel consumptions B_{fet} *and* B_{fdk}. The values of the cost of fuel consumption and ethanol limit prices were calculated.

Calculation model was prepared on the basis of the cost price of bioethanol production and the bioethanol limit price generated in the course of use. Thus the model has two sides or characteristics (two regression equations). In the first case the cost of fuel consumption is determined, depending on the ethanol content, followed by calculation of the limit price of bioethanol fuel. In the second case, bioethanol price generated in the course of fuel production is found, depending on the ethanol content and production method. The model allows determination of optimum ethanol content, in which case the production and use of bioethanol is considered economically reasonable in comparison with regular fuel. The relation between the highest given production price of bioethanol (limit price when used) and the actual production price of bioethanol can be presented as follows:

$$\Delta \mathrm{c_f} = c_{fet} - c_{fetp}, \tag{6}$$

where c_{fet} – bioethanol limit price;

c_{fetp} – bioethanol production price, depending on ethanol content.

The first part of the model c_{fet} enables to estimate the highest limit price of bioethanol fuel in comparison with the regular fuel price, provided that the cost of bioethanol fuel consumption C_{fbio} is lower than the cost of regular fuel C_{freg} used for performing the same amount of work. Additionally it is possible to assess the variation in the required amount of fuel upon the partial or full-scale introduction of bioethanol fuel.

In order to maintain or reduce the price of the product or service, the relation (7) is expressed through the following relation when using the cost of fuel used in tests:

$$C_{fbio} \leq C_{freg} \tag{7}$$

This result (fuel limit price) is particularly important if one desires to prepare bioethanol fuel on their own. In that case the model needs to be supplemented with another part describing the formation of the production price of bioethanol depending on bioethanol quality.

If more than one type of fuel is simultaneously used in the engine, the cost of fuel consumption is expressed as follows (8):

$$C_f = C_{fdk} + C_{fet}, \tag{8}$$

where C_{fdk} – cost of diesel fuel consumption, € h^{-1} and
C_{fet} – cost of ethanol consumption, € h^{-1}.

In this study a two-fuel supply system (on diesel engine) has been used to supply the engine with fuel, which – in view of formulas (5) and (7) – leads to the following:

$$B_{fdT1} \cdot c_{fdT1} \geq B_{fdT2 \ldots T5} \cdot c_{fdT2} + B_{fetT2 \ldots T5} \cdot c_{fetT2 \ldots T5} \tag{9}$$

where B_{fdT1} – diesel fuel consumption in regular test, kg h^{-1};
$B_{fdT2 \ldots T5}$ – diesel fuel consumption in case of a two-fuel supply system, kg h^{-1};
$B_{fetT2 \ldots T5}$ – bioethanol consumption in case of a two-fuel supply system, kg h^{-1};
c_{fdT1} – diesel fuel price in regular test, € kg^{-1};
$c_{fdT2 \ldots T5}$ – diesel fuel price in case of a two-fuel supply system, € kg^{-1};
$c_{fetT2 \ldots T5}$ – bioethanol price in case of a two-fuel supply system, € kg^{-1}.

The given limit price for using or producing bioethanol in comparison with using regular fuel is shown in formula (10).

$$c_{fetT2 \ldots T5} \leq \frac{B_{fdT1} \cdot c_{fdT1} - B_{fdT2 \ldots T5} \cdot c_{fdT2 \ldots T5}}{B_{fetT2 \ldots T5}} \tag{10}$$

If diesel fuel at the same price is used for both tests $c_{fd} = c_{fdT1} = c_{fdT2 \ldots T5}$ (€ kg^{-1}), then $c_{fdT2 \ldots T5}$ can be written down as follows:

$$c_{fetT2 \ldots T5} \leq \frac{(B_{fdT1} - B_{fdT2 \ldots T5}) c_{fd}}{B_{fetT2 \ldots T5}}. \tag{11}$$

The second part of the model describes the formation of the production price of c_{fetp} bioethanol depending on the ethanol content. Bioethanol was manufactured from lignocelluloses, more specifically pasture hay dried and stored during the previous summer. Biochemical analysis was performed with the material in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences, in order to estimate the content of lignin, cellulose and hemi-cellulose, which are presented in Table 3.

Table 3. Test results of lignocellulosic material used for producing farmstead ethanol

Sample	Dry ingredient %	Lignin %	Cellulose %	Hemicellulose %
Perennial grass	94.78	4.96	32.92	25.53

For cellulose degradation the herbaceous biomass was pre-treated by heating it in weak acid solution (H_2SO_4). This was followed by performing enzymatic hydrolysis with enzyme *Accelerase 1500* and fermentation with dry yeast *Saccharomyces cerevisiae*. After completion of fermentation, liquid fraction was separated and distilled (Tutt & Olt, 2010).

The first distillation resulted in 10..12% ethanol content, the second distillation resulted in ca 50…60% and the third in ca 90% ethanol content, which allowed for calculating the product prices based on three different ethanol contents (€ kg^{-1}).

When researching the cost of production c_{fetp} dependence of ethanol concentration *et* by interpolation (Stewart, 2009), we obtain the following function:

$$c_{fetp} = U \cdot e^{V \cdot a_c}, \tag{12}$$

where a_c − ethanol content;
$U; V$ − parameters of exponential distribution;
U − parameter from input.

Fig. 1 shows the relative values of formation of the production price of bioethanol made of lignocelluloses. In the analysis of the production price, the price of 90% bioethanol is equal to 100% bioethanol. In this case it was reasonable to present the result in relative values, because the actual production price values were too high for using testing technology (testing equipment) for large-scale bioethanol production. The quantities used in experimental bioethanol production were small and thus the effect generated by increasing the production capacity was not taken into account when calculating the production price.

When studying the use and production of bioethanol as a complex solution, we are first and foremost interested in the characteristic in the graph area referring to 60…90% ethanol content (Fig. 2). This area can be characterised by using the linear regression model:

$$c_{fetp} = U \cdot a_c + V\,, \tag{13}$$

$U; V$ − regression coefficients (initial ordinate and slope),
a_c − ethanol content (60…90%).

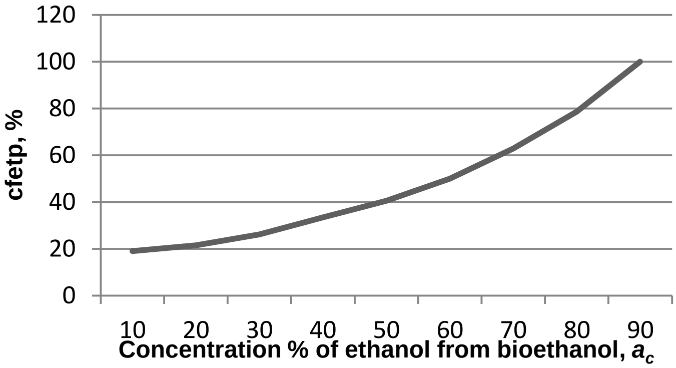

Fig. 1. Cost price formation of bioethanol made of lignocelluloses in the Fuel Laboratory of the Estonian University of Life Sciences, depending on ethanol content.

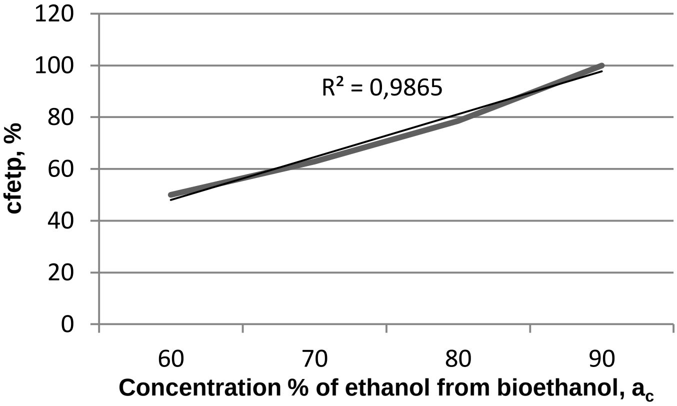

Fig. 2. Cost price formation of bioethanol made of lignocelluloses in the Fuel Laboratory of the Estonian University of Life Sciences, depending on ethanol content of 60…90%.

This relation applies when using the given production method and raw material. The method for determining the bioethanol cost price is suitable for preparing the model. Other coefficients must be established when using different raw materials and production methods.

Results and discussion

Results gained from fuel cost and pricing in case of D-120 engine with compression-ignition. The formula in the first part of the calculation model was used to determine relative bioethanol limit prices in case of different ethanol content (Fig. 3) to describe the impact of bioethanol fuel on the D-120 engine.

Calculation and comparison of absolute limit prices is based on the diesel fuel price c_{fd} = 100%. When using 60% bioethanol with diesel fuel, the production price must be ca 60% lower than that of diesel fuel. Meanwhile, when using 90% bioethanol, the limit price is ca 44% lower than that of diesel fuel. As a result of that, when substituting the 60% bioethanol with 90% bioethanol, one has to expect ca 40% increase in the bioethanol production price. This can be used for ensuring a competitive production price when choosing the method for bioethanol production. One factor in calculating the bioethanol limit price is the quantity of fuel consumed. Given the quantities of consumed fuel it is possible to calculate the required resource of raw material. The measured fuel quantities consumed in the course of the described tests are shown in Fig. 4. The figure also indicates a comparison of the proportion of diesel fuel and bioethanol fuels in the fuel mixture.

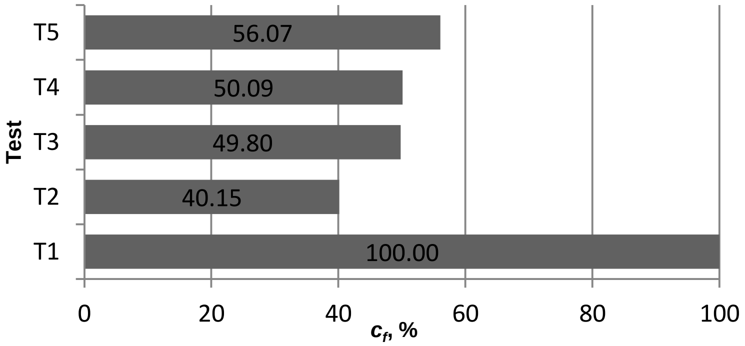

Fig. 3. Relative limit prices of bioethanol in case of different ethanol content in comparison with diesel fuel.

The relation between the limit price of fuel in D-120 engine and our production price was determined on the basis of the calculation model. Fig. 5 provides a graphical presentation of the change in case of lowering the ethanol content in bioethanol, i.e. when producing bioethanol of a lower quality. In this case we also have to consider the change in the proportion of diesel fuel (Fig. 4), which affects the formation of the bioethanol limit price. The calculation is different in case of a single fuel supply system (engine with high-tension ignition) and therefore not considered in this present study.

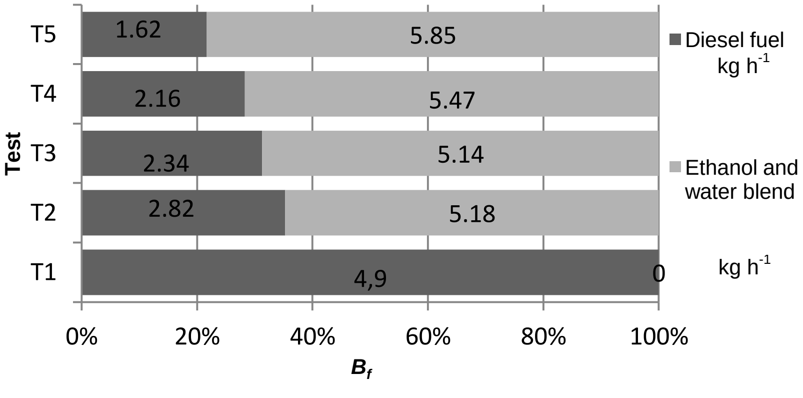

Fig. 4. Absolute quantities of fuel used for testing and their relative proportion when comparing diesel fuel and ethanol.

Graph (Fig. 5) created on the basis of the model has in this case been prepared so that the relative production price of 90% bioethanol and relative limit price are equal to 100%. A change in ethanol content causes an alternating difference in price Δc_f. If the limit price for using low-content bioethanol (60%) drops by 28.4% in comparison to high-content bioethanol (90%), then the decrease in the production price (minus 50%) is much bigger. Therefore we may argue that the production of low-content bioethanol is reasonable under the conditions used in the study.

However, one has to take into account that when using low-content bioethanol, the engine with compression-ignition requires a larger quantity of diesel fuel. When using 90% bioethanol the engine needs 21% of the total diesel fuel consumption, but when using 60% bioethanol it needs 36% of the diesel fuel.

The production price of 60% bioethanol is 30% lower than the limit price for using it in the engine, which means a lower cost of fuel consumed, which in turn is seen in the specific cost per field area.

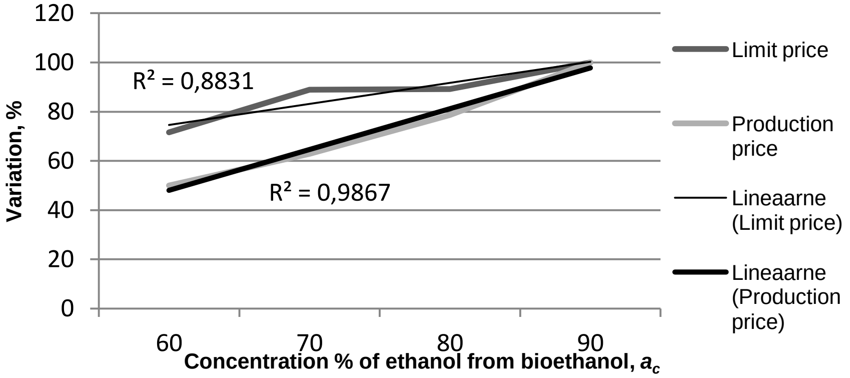

Fig. 5. Comparative price formations of the bioethanol limit price and actual bioethanol production price, depending on the ethanol content.

The drop ΔC_f in the cost of fuel consumption (€ h^{-1}) in case of bioethanol is expressed when using formulae (6) and (5):

$$\Delta C_f = \left(B_{fdT1} \cdot c_{fd}\right) - \left(B_{fdT2..T3} \cdot c_{fd} + B_{fetT2...T5} \cdot c_{fetpT2...T5}\right), \qquad (14)$$

where $c_{fetpT2...T5}$ – bioethanol production prices according to ethanol content.

Thus the relative cost of fuel consumption does not decrease by 30%, but is expressed with the following formula:

$$\Delta C_f\% = \frac{100 \cdot \Delta C_f}{C_{fd}} \qquad (15)$$

This results in a 14.4% relative decrease in the fuel cost when using 60% bioethanol as opposed to using 90% bioethanol, which is directly associated with the machinery expenses (Persitski, 2006). Use of relative values allows a comparison of bioethanol use in the vehicles with different types of internal combustion engines.

Conclusions

1. The model used enables to assess the relation between the greatest given bioethanol production price (limit price when using) and actual bioethanol production price in case of different ethanol contents.

2. The fuel limit price must be ca 60% lower in comparison with diesel fuel when using 60% bioethanol with diesel fuel in D-120 engine with compression-ignition, and ca 44% lower when using 90% bioethanol, in order to avoid an increase in the cost of fuel consumed.

3. In quantitative terms we can use less 60% bioethanol as opposed to 90% bioethanol of the total fuel quantity. In case of 90% bioethanol the engine needs 21% of the total diesel fuel consumption, but in case of 60% bioethanol it needs 36% of diesel fuel. Thus, using low-content bioethanol sets limits for increasing the share of bioethanol in transport fuels.

4. As a whole, the model provides an opportunity to assess the change in the specific cost of fuel depending on the bioethanol used. Our selection of use and production of bioethanol resulted in a 14.4% relative decrease in fuel cost when using 60% bioethanol as opposed to using 90% bioethanol.

5. Further characteristics need to be compiled to describe the use of bioethanol in different engines and the formation of the bioethanol production price in case of different production technologies. Calculations must be done and analysis performed by using currently valid values, in order to assess the potential use of bioethanol.

References

European Union: ‘Directive 2009/28/EC/ of the European Parliament and the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending Subsequently Repealing Directives 2001/77/EC and 2003/30/EC’.

Olt, J., Mikita, V., Ilves, R., Küüt, A., Madissoo, M. 2011. *Impact of ethanol on the fuel injection pump of diesel engine. 10th International Scientific Conference ‘Engineering for Rural Development’*, Jelgava, Latvia, 254–259.

Reintam A. 1982. Optimum width of agricultural vehicles: *Collection of research work of the Estonian Agricultural Academy*, 13–27. (in Russian).

Küüt, A., Ilves, R., Mikita, V., Olt, J. 2012. *Use of bioethanol fuel as regular fuel.40th International Symposium on Agricultural Engineering. ‘Actual Tasks on Agricultural Ebgineering’*. Zagreb, Croatia, pp.117–125.

Tutt, M. & Olt, J. 2008. *Research on the opportunities of producing liquid biofuel from herbaceous biomaterial. In: Research and use of renewable energy sources,* Tartu, Estonian University of Life Sciences, 106–114. (in Estonian)

Persitski, H. 2006. *Calculation of contribution margin in plant production and animal husbandry*. Jäneda Training and Advisory Centre, pp. 13–35. (in Estonian).

Stewart J. 2009. *Calculus. 6th edition*. McMaster University and University of Toronto, Metric international version, pp. 392–399.