VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Oleksandra SHEPEL

RESEARCH ON ENERGETIC AND ECOLOGICAL INDICATORS OF A COMPRESSION IGNITION ENGINE FUELLED BY ANIMAL NON-EDIBLE FATS AND BIOFUEL BLENDS

DOCTORAL DISSERTATION

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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GYVULINIAIS NEMAISTINIAIS RIEBALAIS IR BIODEGALŲ MIŠINIAIS VAROMO SLĖGINIO UŽDEGIMO VARIKLIO ENERGINIŲ IR EKOLOGINIŲ RODIKLIŲ TYRIMAS

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Abstract

The dissertation investigates the energy and environmental performance of a compression ignition engine operating on biodiesel blends derived from animal-based non-food fats and first- and second-generation biodiesel fuels.

The research encompasses experimental and numerical analyses, evaluating how diverse biodiesel compositions influence engine operation. Nine fuel blends, including hydrotreated vegetable oils (HVO) and fatty acid methyl esters (FAME), were prepared and tested under controlled conditions. The research examined key parameters such as ignition delay, combustion pressure, temperature variations, CO_2 , CO, NO_x, HC emissions, and particulate matter (PM). A numerical model using AVL BOOST was developed to simulate in-cylinder combustion processes, providing insights into pressure rise rates, heat release dynamics, and fuel efficiency under various load conditions. The results highlighted the impact of biodiesel composition on combustion phases, revealing that HVO-based blends exhibit shorter ignition delays, improved combustion efficiency, and lower emissions compared to FAME-rich blends. The findings of this dissertation indicate that HVO-based biodiesel blends offer the most promising alternative to diesel, maintaining high energy efficiency while significantly reducing CO, HC, and particulate emissions. However, FAME-rich blends require further optimisation due to their higher viscosity, increased NO_x emissions, and greater fuel consumption.

The dissertation consists of an introduction, four chapters, a summary of findings, references, and a list of scientific publications by the author. The First Chapter provides an overview of biodiesel properties and their relevance in the transport sector. The Second Chapter details the experimental methodology, including biodiesel preparation, engine testing, and data acquisition techniques. The Third Chapter presents numerical and experimental results, evaluating combustion characteristics, energy indicators, and emission trends. The Fourth Chapter applies machine learning models to predict fuel performance and optimise biodiesel blends. The dissertation concludes with a discussion of the feasibility of biodiesel use in diesel engines and recommendations for future research. This research represents a significant step towards integrating alternative biofuels into the transportation sector, supporting global efforts to reduce greenhouse gas emissions and enhance energy sustainability.

Five scientific articles have been published on the dissertation topic: two in the Web of Science database with a citation index, two in the Web of Science database, conference proceedings, one in other international databases and two in other peer-reviewed scientific journals. Two papers were presented at conferences in Lithuania and one in Poland.

Reziumė

Disertacija nagrinėja energinius ir ekologinius rodiklius suspaudimo uždegimo variklyje, veikiančiame su biodegalų mišiniais, pagamintais iš gyvulinės kilmės nemaistinių riebalų ir pirmosios- bei antrosios-kartos biodyzelino.

Tyrime taikyti eksperimentiniai ir skaitiniai metodai, nagrinėjantys, kaip skirtingos biodegalų sudėtys veikia variklio darbą. Buvo paruošti ir išbandyti devyni degalų mišiniai, įskaitant hidroapdorotą augalinį aliejų (HVO) ir riebalų rūgščių metilo esterius (FAME). Eksperimentuose analizuoti pagrindiniai parametrai, tokie kaip uždegimo vėlavimas, degimo slėgis, temperatūros pokyčiai ir CO_2 , CO, NO_x, HC bei kietųjų dalelių emisijos. Norint detaliau įvertinti degimo procesus, buvo sukurtas skaitinis modelis naudojant AVL BOOST programinę įrangą. Rezultatai parodė, kad HVO pagrindu sudaryti biodegalų mišiniai pasižymi trumpesniu uždegimo vėlavimu, didesniu degimo efektyvumu ir mažesnėmis emisijomis nei FAME turintys mišiniai. Tyrimas parodė, kad HVO pagrindu pagaminti biodegalai yra perspektyviausias dyzelino pakaitalas, nes jie leidžia išlaikyti didelį energijos konversijos efektyvumą ir reikšmingai sumažinti CO, HC ir kietųjų dalelių emisijas. Tačiau FAME turintys degalai reikalauja papildomos optimizacijos, nes dėl jų didesnio klampumo stebimas didėjantis NO_x emisijų lygis ir didesnės degalų sąnaudos. formavime, siekiant palaikyti perėjimą prie ekologiškesnių transporto sprendimų.

Disertaciją sudaro įvadas, keturi skyriai, rezultatų santrauka, literatūros sąrašas ir autoriaus mokslinių publikacijų sąrašas. Pirmame skyriuje pateikiama biodegalų savybių apžvalga ir jų svarba transporto sektoriuje. Antrame skyriuje išsamiai aprašoma eksperimentinė metodika, įskaitant biodegalų gamybą, variklio bandymus ir duomenų rinkimo procesus. Trečias skyrius pateikia skaitinių ir eksperimentinių rezultatų analizę, įvertinant degimo procesų efektyvumą ir emisijų pokyčius. Ketvirtame skyriuje pristatomi mašininio mokymosi modeliai, skirti numatyti biodegalų poveikį variklio parametrams ir optimizuoti kuro mišinius. Disertacijos išvadose pateikiamos rekomendacijos dėl biodegalų pritaikymo ir tolimesnių tyrimų kryptys. Atliktas tyrimas yra svarbus žingsnis siekiant integruoti alternatyvius biodegalus į transporto sektorių, prisidedant prie pasaulinių pastangų mažinti šiltnamio efektą sukeliančių dujų emisijas ir skatinti energetinį tvarumą.

Disertacijos tema buvo publikuoti penki moksliniai straipsniai: du *Web of Science* duomenų bazėje su citavimo indeksu, du – *Web of Science* duomenų bazėje, konferencijų medžiagose, vienas – kitose tarptautinėse duomenų bazėse ir du – kitose recenzuojamuose mokslo žurnaluose. Du pranešimai buvo pristatyti konferencijose Lietuvoje, o vienas – Lenkijoje.

Notations

Symbols

a	combustion efficiency parameter of the Wiebe function (liet. *Wiebe funkcijos degimo efektyvumo parametras*);
b_e $(BSFC)$	brake specific fuel consumption, g/kWh (liet. *stabdymo specifinės degalų sąnaudos*);
C	mass of carbon in the fuel, kg (liet. *anglies masė degaluose*);
c	specific heat capacity, J/kg·K (liet. *savitoji šilumos talpa*);
D	cylinder bore, mm (liet. *cilindro skylė*);
dQ	heat release, J (liet. *šilumos išsiskyrimas*);
$dQ/d\varphi$	rate of heat release, J/°CA (liet. *šilumos išsiskyrimo greitis*);
$dp/d\varphi$	pressure-rise in the cylinder, MPa/°CA (liet. *slėgio padidėjimas cilindre*);
h	unit of measurement for oxidation stability, h (liet. *oksidacijos stabilumo matavimo vienetas*);
i	number of cylinders of the engine (liet. *variklio cilindrų skaičius*);
K_L	dependence factor on temperature increase (liet. *priklausomybės nuo temperatūros padidėjimo koeficientas*);
$i_{\%}$	percentage of the selected component, % (liet. *pasirinkto komponento procentinė dalis*);
l	actual amount of air entering the engine, kg (liet. *faktinis į variklį patenkančio oro kiekis*);
l_0	amount of air required to burn 1 kg of fuel, kg (liet. *oro kiekis, reikalingas 1 kg kuro sudegti*);
M_e	effective torque of the engine, Nm (liet. e*fektyvus variklio sukimo momentas*);

M_i	molar mass of the selected component, g/mol (liet. *pasirinkto komponento masė, gramai molyje*);
M_{ex}	molar mass of exhaust gas, g/mol (liet. *išmetamųjų dujų masė, gramai molyje*);
m_v	combustion intensity shape parameter (liet. *degimo intensyvumo formos parametras*);
n	engine speed, rpm (liet. *variklio greitis*);
n_c	constant of proportionality (liet. *proporcingumo konstanta*);
N	number of moles of main reactants, mol (liet. *pagrindinių reagentų skaičius, moliai*);
N_0	number of moles of main reactants at the start of combustion, mol (liet. *pagrindinių reagentų skaičius degimo pradžioje, moliai*);
m_{air}	mass of air sucked into the cylinder during one work cycle, kg (liet. *į cilindrą per vieną darbo ciklą įsiurbiamo oro masė*);
m_f	mass of fuel, kg (liet. *degalų masė*);
P_{ind}	indicated power, kW (liet. *nurodyta galia*);
P_e	engine effective power, kW (liet. *variklio efektyvioji galia*);
p	pressure, MPa (liet. *slėgis*);
p_c	pressure at the end of compression, MPa (liet. *slėgis suspaudimo pabaigoje*);
p_i	indicator power generated in the engine cylinder, kW (liet. *variklio cilindre generuojamos indikatoriaus galios*);
p_{max}	maximum in-cylinder pressure, MPa (liet. *maksimalus slėgis cilindre*);
p_e	mean effective pressure, MPa (liet. *vidutinis efektyvus slėgis*);
p_k	pressure in the engine crankcase, MPa (liet. *slėgis variklio karteryje*);
λ	coefficient of excess air (liet. *oro pertekliaus koeficientas*);
Q	amount of heat released by the fuel during the work cycle, J (liet. *kuro išskiriamas šilumos kiekis darbo ciklo metu*);
Q_{cycl}	amount of heat released during the engine work cycle, J (liet. *variklio darbo ciklo metu išsiskiriantis šilumos kiekis*);
Q_{lcs}	heat losses through the cooling system, J (liet. *šilumos nuostoliai per aušinimo sistemą*);
Q_f	fuel energy, J (liet. *kuro energija*);
Q_w	energy to perform useful work, J (liet. *energija naudingam darbui atlikti*);
Q_{ex}	losses through the exhaust system, J (liet. *nuostoliai per išmetimo sistemą*);
Q_{LFcycl}	amount of heat released during combustion of liquid fuel per cycle, J (liet. *šilumos kiekis, išsiskiriantis per ciklą skysto kuro degimo metu*);
t	time, s (liet. *laikas*);
t_c (φD)	combustion duration, °CA (liet. *degimo trukmė*);
T_{cyl}	temperature in the cylinder, K (liet. *temperatūra cilindre*);

T_{ex}	exhaust gas temperature, K (liet. *išmetamųjų dujų temperatūra*);
T_{in}	intake gas temperature, K (liet. *įsiurbiamųjų dujų temperatūra*);
T_{LF}	temperature of liquid fuel, K (liet. *skysto kuro temperatūra*);
T_{max}	maximum in-cylinder temperature, K (liet. *maksimali cilindro temperatūra*);
V	volume, cm³ (liet. *tūris*);
V_i	in-cylinder volume of the combustion chamber, cm³ (liet. *degimo kameros tūris cilindre*);
V_{SOC}	in-cylinder volume at the time of the start of combustion, cm³ (liet. *cilindro tūris degimo pradžios metu*);
V_{EOC}	in-cylinder volume at the time of the end of combustion, cm³ (liet. *cilindro tūris degimo pabaigos metu*);
V_c	compression volume, cm³ (liet. *suspaudimo tūris*);
V_s	stroke volume, cm³ (liet. *smūgio tūris*);
V_b	volume of the burned fraction, cm³ (liet. *sudegintos frakcijos tūris*);
V_u	volume of the unburned fraction, cm³ (liet. *nesudegusios frakcijos tūris*);
V_{air}	volume flow rate of air, cm³ (liet. *oro tūrio srautas*);
V_{airLF}	stoichiometric flow rate of air for liquid fuel, cm³ (liet. *skysto kuro oro stechiometrinis srautas*);
ε	degree of compression (liet. *suspaudimo laipsnis*);
τ	number of engine cycles (liet. *variklio ciklų skaičius*);
φ	crankshaft rotation angle, °CA (liet. *alkūninio veleno sukimosi kampas*).

Abbreviations

A/F	air-fuel ratio (mass) (liet. *oro ir degalų santykis (masė)*);
ANFIS	Adaptive Neuro-Fuzzy Inference System (liet. *adaptyvi neapibrėžtais neuroniniais tinklais paremta išvedimo sistema*);
AVL Boost	software for the numerical analysis of the combustion process (liet. *degimo proceso skaitmeninės analizės programinė įranga*);
BSFC	brake-specific fuel consumption (liet. *specifinės degalų sąnaudos*);
BTE	brake thermal efficiency (liet. *šiluminis efektyvumas*);
CART	classification and regression trees (liet. *Klasifikavimo ir regresijos medžiai*);
CD	combustion duration (liet. *degimo trukmė*);
CFPP	cold filter plug point (liet. *šalto filtro užkimšimo taškas*);
CI	compression ignition (liet. *kompresinis uždegimas*);
CN	cetane number (liet. *cetaninis skaičius*);
CO	carbon monoxide (liet. *anglies monoksidas*);
CO_2	carbon dioxide (liet. *anglies dioksidas*);
CP	cloud point (liet. *debesies taškas*);
D	diesel fuel (liet. *dyzelinas*);

ECU	electronic control unit (liet. *elektroninis valdymo blokas*);
EU	European Union (liet. *Europos Sąjunga*);
F100	pure duck fat (liet. *gryni ančių riebalai*);
F25	25% duck fat and 75% HVO (liet. *25 % ančių riebalų ir 75 % HVO*);
F50	50% duck fat and 50% HVO (liet. *50 % ančių riebalų ir 50 % HVO*);
F75	75% duck fat and 25% HVO (liet. *75 % ančių riebalų ir 25 % HVO*);
FAME	fatty acid methyl ester (liet. *riebiųjų rūgščių metilo esteris*);
FE100	fatty acid methyl ester (liet. *riebiųjų rūgščių metilo esteris*);
FE25	25% fatty acid methyl ester and 75% HVO (liet. *25 % riebiųjų rūgščių metilo esterio ir 75 % HVO*);
FE50	50% fatty acid methyl ester and 50% HVO (liet. *50 % riebiųjų rūgščių metilo esterio ir 50 % HVO*);
FE75	75% fatty acid methyl ester 25% HVO (liet. *75 % riebiųjų rūgščių metilo esterio 25 % HVO*);
FFA	free fatty acids (liet. *laisvosios riebiosios rūgštys*);
Flash Point	temperature at which a stoichiometric mixture vapour forms in the air naturally (liet. *temperatūra, kurioje natūraliai susidaro stechiometrinis jo garų ir oro mišinys*);
GPR	Gaussian Process Regression (liet. *Gauso procesais paremta regresija*);
H/C	hydrogen/carbon ratio (liet. *vandenilio ir anglies santykis.*);
HC	hydrocarbon (liet. *angliavandenilis*);
HDC	hydro decarboxylation (liet. *hidrodekarboksilinimas*);
HDO	hydrodeoxygenation (liet. *hidrodeoksigenacija*);
HVO	hydrotreated vegetable oils (liet. *hidrinti augaliniai aliejai*);
ID	ignition delay (liet. *uždegimo uždelsimas*);
IT	information technologies (liet. *informacinės technologijos*);
LCV	lower calorific value (liet. *mažesnis kaloringumas*);
LHV	lower heating value (liet. *mažesnė šildymo vertė*);
NO_x	nitrogen oxides (liet. *azoto oksidai*);
O_2	oxygen (liet. *deguonis*);
PM	particulate matter (liet. *kietosios dalelės*);
ppm	parts per million (liet. *milijoninės dalys*);
ROHR	higher heat release rates (liet. *didesnis šilumos išsiskyrimo greitis*);
rpm	rotations per minute (liet. *apsisukimai per minutę*);
SOC	the start of combustion (liet. *degimo pradžia*);
SVR	support vector regression (liet. *palaikomojo vektoriaus regresija*);
TDC	top dead centre (liet. *viršutinis mirties taškas*);
UCO	used cooking oil (liet. *panaudotas kepimo aliejus*).

Contents

Introduction

Problem Formulation

The energy and transport sectors are increasingly concerned about fossil fuel resources and their impact on the environment. Fuels used in compression-ignition engines are one of the main causes of air pollution. The intensive use of petroleum products contributes to climate change, making it necessary to search for alternative fuels that could ensure energy efficiency and, at the same time, reduce harmful emissions. Given these problems, the European Union (EU) and other international organisations are promoting the transition to renewable energy sources, and biodiesel is becoming one of the most promising alternatives. Biodiesel, produced from vegetable oils or animal fats, is distinguished by better environmental properties, but its effect on engine performance and exhaust gas composition is still a subject of scientific debate. However, the effect of these biofuel combinations on the energetic and ecological performance of the engine has not yet been sufficiently analysed.

After reviewing various literature reviews of alternative fuels for diesel engines, it was concluded that the literature does not discuss biodiesel based on fuel mixtures from second-generation biofuels, HVO, and fatty acid methyl ester. This motivated the dissertation author to research the combustion, energy, and ecological parameters of these mixtures.

Relevance of the Dissertation

The transportation sector actively seeks more sustainable alternatives, motivated by environmental challenges and the imperative to reduce dependence on fossil fuels. However, conventional first-generation biodiesels – which come from consumable vegetable oils – have ethical and financial difficulties, given the competition for agricultural raw materials. Rising as a more sustainable substitute are second-generation biodiesels that include hydrotreated vegetable oils (HVO) and fatty acid methyl esters (FAME) generated from waste or non-food fats. These developments could help to build a circular economy and lessen the effect on the food chain.

Although biodiesel has benefits, the impact of various biofuels and their combinations on the running characteristics of a compression-ignition engine remains not properly investigated. In particular, insufficient data are available on the impact of diverse proportions of first- and second-generation biodiesel blends on the combustion process, engine efficiency and emission composition.

The relevance of this dissertation is based on the need to analyse in detail the prospects for using animal-derived non-food fats and first- and second-generation biodiesel blends in compression ignition engines. Experimental research will allow for the determination of optimal fuel blends that would ensure the best balance of ecological and energy indicators. The results will contribute to a more efficient application of alternative biofuels in the transport sector, reducing the negative impact on the environment and increasing the possibilities of using renewable energy sources. The dissertation's conclusions can be significant for developing scientific research and for the practical use of biofuels.

Research Object

The research object is the combustion process of mixtures containing renewable components for operating in the compression-ignition engine.

Aim of the Dissertation

The dissertation aims to determine the impact of animal-derived non-edible fats and first- and second-generation biodiesel blends on the environmental and energy performance of a compression ignition engine to assess their suitability as an alternative to conventional diesel.

Tasks of the Dissertation

The following tasks were solved to achieve the objective:

1. To prepare and analyse biofuel blends consisting of non-edible animal fats and first- and second-generation biodiesel, evaluating their physical and chemical properties.
2. To conduct experimental research for determining the effect of animal fat and first- and second-generation biofuel mixtures on the operating parameters of a compression ignition engine, including the course of the combustion process, pressure changes in the cylinder and ignition delay.
3. To analyse the energy performance of the engine when running on various biofuel mixtures, including the assessment of fuel consumption, brake thermal efficiency, and conversion of thermal energy under different engine loads and operating conditions.
4. To evaluate the ecological impact of the biofuel mixtures by analysing exhaust gas emissions (CO_2, CO, NO_x, HC, and smoke) and determining their compliance with environmental standards.
5. To develop a mathematical model for analysing the combustion processes of fuel blends in a compression ignition engine and predicting their effect on engine efficiency and emissions.

Research Methodology

Experimental research has been conducted in two stages.

- Fuel samples were prepared at the Department of Mechatronics and IT Education in Olsztyn, Poland;
- Fuels were tested in a four-cylinder internal combustion engine, featuring direct fuel injection into the combustion chamber of the piston at the Laboratory of the Transport Engineering Faculty of Vilnius Gediminas Technical University, Lithuania;
- For experimental tests, nine fuel mixtures of diverse compositions were selected and compared in terms of performance with diesel fuel. The fuel combustion processes were further analysed using the software AVL Boost.

Scientific Novelty of the Dissertation

The following new results for the science of Transport Engineering were obtained during the preparation of the dissertation:

1. A new hybrid experimental-numerical method was developed to evaluate the effect of fuel mixtures on engine performance, integrating pressure wave analysis, AVL BOOST simulation and physicochemical characteristics of bio-based fuels, which have not been previously applied in research of animal fats and HVO/FAME mixtures.
2. The effect of optimal HVO and animal fat proportions on combustion delay, heat release rate and NO_x emissions at different engine loads was experimentally determined for the first time, providing new knowledge about the combustion dynamics of these fuel mixtures.
3. Regression tree-based prediction models were developed that predict emission levels and engine efficiency indicators with an accuracy of >0.94 pseudo-R^2 according to fuel composition, excess air (λ) and load, which is an original data analysis solution in biofuel research.

Practical Value of the Research Findings

1. Optimal biofuel blends have been identified that can be applied in compression ignition engines to reduce emissions and maintain engine efficiency.
2. Experimental data and analysis methods can be applied in transport engineering and the biofuel industry, developing new fuels and optimising their use.
3. The research results contribute to the implementation of EU ecological requirements, promoting the use of renewable energy sources and reducing dependence on fossil fuels.
4. The research conclusions can be applied to engine manufacturers and the fuel supply sector to better match the properties of biofuels with modern diesel engine technologies.

Defended Statements

1. The composition of biofuel blends significantly impacts the combustion process, emission levels and energy performance of a compression ignition engine, compared to conventional diesel.
2. Second-generation biodiesel and animal fat blends can provide lower CO, HC and particulate emissions, but their effect on NO_x emissions depends on the fuel composition and engine operating conditions.
3. Properly selected biofuel blends can be used in compression ignition engines without requiring significant structural modifications while preserving their operational performance characteristics.

4. Mathematical modelling allows for accurate prediction of the impact of fuel blends on engine operating parameters and emissions, creating prerequisites for optimising fuel composition according to environmental and energy criteria.

Approval of the Research Findings

Five scientific papers related to the topic of the doctoral dissertation have been published: two in scientific journals, included in the *Web of Science* database with a citation index (Shepel et al., 2021, 2022), two in the Conference Proceedings publication of the *Web of Science* database (Rimkus et al., 2020, Shepel et al., 2021), and one in other peer-reviewed scientific publications (Shepel et al., 2018).

The results of the research conducted in the dissertation were published in three scientific conferences in Lithuania and abroad:

- The 11th international scientific conference “TRANSBATICA XI: Transportation Science and Technology”, 2019, Vilnius, Lithuania.
- The 17th International Conference of Young Scientists on Energy and Natural Sciences Issues “CYSENI 2021”: 2021, Kaunas, Lithuania.
- “VII Young Scientists Academy”: 2023, Lesna, Poland.

Structure of the Dissertation

The dissertation consists of an introduction, four chapters and conclusions, a summary in Lithuanian and a list of references.

The scope of the work is 84 pages; the text contains 19 numbered formulas, 38 figures and eight tables. The dissertation used 127 literature sources.

Acknowledgement

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1

Overview of the Properties and Usage of Biodiesel in Compression-Ignition Engine

This chapter discusses the sources of raw materials for the production of biodiesel and their physicochemical properties. It presents the advantages of biodiesel fuel, discusses the influence of alternative fuels on the environmental and energy performance of the engine, and offers a review of experimental research on this topic by other authors.

Two articles have been published on the topic of the chapter (Shepel et al., 2021; Shepel & Matijošius, 2018).

1.1. Analysis of the Biodiesel Relevance in the Transport Sector

The advancement of renewable energy sources is increasingly recognised as a vital goal in the transportation sector, aiming to reduce dependence on fossil fuels and mitigate greenhouse gas emissions. In response, the European Union and various international bodies have enacted strict regulations to curb vehicle emissions and promote the adoption of alternative fuels, such as biodiesel (Potrč et al., 2021; Abdul Hakim Shaah et al., 2021). While biofuels derived from various organic materials offer a promising substitute for diesel, their effects on engine performance and emissions remain subjects of ongoing research (Chong et al., 2021; Prabakaran et al., 2023).

Biodiesel is produced through transesterification of vegetable oils or animal fats. The CO_2 released during its combustion is part of the natural carbon cycle, contributing to a net reduction in greenhouse gas emissions (Banković-Ilič et al., 2014). Biofuels also tend to provide better lubrication than conventional diesel, potentially reducing engine wear (Mahlia et al., 2020; Athar & Zaidi, 2020). However, first-generation biodiesel, made from edible oils, raises concerns about food-versus-fuel conflicts and feedstock availability (Bessou et al., 2011). In contrast, second-generation biofuels like hydrotreated vegetable oils (HVO) and fatty acid methyl esters (FAME) are produced from waste or non-food sources, including used cooking oils and animal fats (Othman et al., 2017; Vafakish & Barari, 2017; Kinnal et al., 2018).

Biofuels can be used in their pure form or blended with conventional diesel, depending on their physical and chemical properties (Candeia et al., 2009). While their impact on exhaust emissions varies, blends of HVO or FAME with diesel generally support comparable engine performance. FAME, however, tends to have higher acidity and water affinity, which can affect fuel system durability (Suarez-Bertoa et al., 2019). HVO, with its higher cetane number and lower density, is more aligned with the operational demands of modern diesel engines.

Despite these benefits, several technical challenges hinder widespread biofuel adoption. Differences in fuel composition necessitate a thorough evaluation of their effects on combustion timing, peak cylinder pressure, and energy conversion efficiency (Heywood, 2018). Moreover, fuel blends may influence emission profiles, particularly the formation of nitrogen oxides (NO_x), which can increase with some biofuels (Yesilyurt et al., 2020).

Within the scope of this dissertation, particular emphasis is placed on examining the properties of animal-based non-edible fats, as well as first- and second-generation biodiesel blends, and their compatibility with compression ignition engines. Given the higher viscosity and lower oxidative stability of animal fats compared to conventional vegetable oils, it is essential to assess their impact on fuel system performance and exhaust emission composition in detail (Kirubakaran & Selvan, 2018; Navas-Anguita et al., 2020). Experimental research plays a critical role in identifying optimal blend ratios that maintain engine efficiency while minimising environmental impact (Knothe et al., 2005).

Amid tightening environmental regulations and the growing need to diversify energy sources, the development of biofuels in the transportation sector is becoming increasingly essential (Navas-Anguita et al., 2020). Investigating the blending of animal fats with various biodiesel types deepens our understanding of their potential as viable diesel alternatives – offering a pathway to reduce greenhouse gas emissions without compromising engine performance or durability (Abed et al., 2019; McCaffery et al., 2022). Figure 1.1 demonstrates the share of biofuel use in Europe. Figure 1.2 shows the EU consumption of biodiesel fuel.

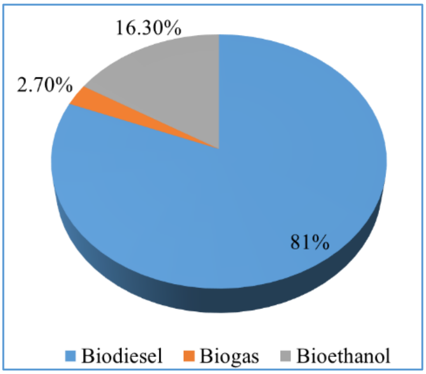

Fig. 1.1. Total EU 2021 consumption for transport by biofuel type (Lescot, 2023)

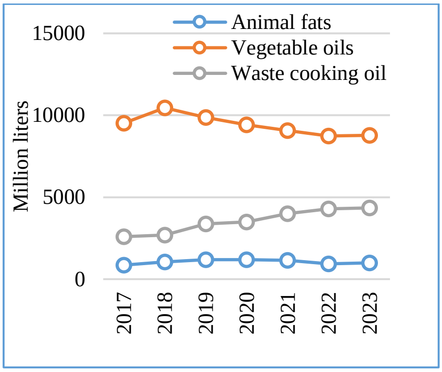

Fig. 1.2. EU production of renewable diesel (Flach et al., 2024)

In Lithuania, developments are most intensively carried out in the field of production of biodiesel fuel from rapeseed raw materials (Katinas et al., 2018). MESTILLA is a leading producer of rapeseed oil and biodiesel in Europe. According to the EU Fuel Quality Directive on climate change, diesel fuel must contain 7% biofuel (Directive 98/70/EC) (European Parliament…, 2023). By 2030, the EU plans to provide 25% of its fuel needs from clean and efficient types of biological raw materials (Koyunoğlu, 2023). This leads to the conclusion that the development of biocomponents in fuels is an urgent task in the development of the fuel and energy complex of Lithuania.

According to national biofuels policies, Lithuania has biofuel in diesel with about 6.2% biodiesel content in the fuel mixture with diesel fuel (ePURE …, 2023). The largest network of gas stations in Lithuania, VIADA, is one of the main consumers of Lithuanian biofuels in the country. The company launched the campaign “We use Lithuania’s economic resources”, which expresses support for Lithuanian rapeseed producers, which includes raw materials for biofuel production (Viada LT). Biodiesel produced in Lithuania reduces CO_2 emissions by up to 72% compared to mineral fuels (Biodegalų asociacija, 2025).

According to the British Vehicle Certification Agency, diesel vehicles exhibit slightly lower CO_2 emissions compared to their gasoline counterparts. Diesel engines consume approximately 26% less fuel on average and emit around 5% less CO_2 under normal operating conditions when assessing energy efficiency and environmental performance. Emissions of other pollutants – such as carbon monoxide, hydrocarbons, and nitrogen oxides – are relatively low as well, largely due to the higher thermal efficiency of diesel engines (Vehicle Certification Agency, 2024).

A promising advancement in biodiesel development is the adoption of hydrotreated vegetable oil (HVO) as a renewable diesel alternative (Roque et al., 2023). HVO is produced through the catalytic hydrogenation of vegetable oils, resulting in a fuel that delivers excellent performance, reduced emissions, and full compatibility with existing diesel engines – whether used in pure form or as a blend (Singh et al., 2018).

The production of HVO involves the initial hydrogenation of triglyceride feedstock, leading to the formation of intermediates such as monoglycerides, diglycerides, and carboxylic acids. These intermediates are then transformed into alkanes through three key reaction pathways: hydrogenation, hydrodeoxygenation (HDO), and hydro decarboxylation (HDC). The resulting hydrocarbons closely resemble those found in conventional diesel fuels (European Technology and Innovation Platform, 2024).

HVO stands out for its low density and superior fuel properties. It has the highest cetane number among conventional diesel and biofuels, contributing to improved combustion characteristics (Suarez-Bertoa et al., 2019; Dimitriadis et al., 2020). Additionally, HVO demonstrates one of the highest lower heating values, indicating strong energy content (Soam & Hillman, 2019). These attributes collectively underscore the viability of transitioning from fossil diesel to HVO-based biofuels in pursuit of cleaner and more sustainable transportation.

1.2. Potential Resources for Power Supply of Compression Ignition Engines

Fuels used in the transport sector must meet physical and chemical specifications and economic and environmental standards. In the pursuit of reducing dependence on fossil fuels, growing attention is being directed towards alternative energy sources, among which biofuels represent one of the most promising options. These can be produced from a wide range of feedstocks, broadly categorised into first-, second-, third-, and fourth-generation sources, each with distinct implications for sustainability and engine compatibility (Demirbas et al., 2009; Kathirvel et al., 2016; Rafa et al., 2021; Verma et al., 2021; Topare et al., 2022).

First-generation biofuels are derived from food crops such as sugarcane and corn and edible vegetable oils like rapeseed, soybean, and sunflower oil (Balasubramanian & Steward, 2019). While these fuels can be blended with diesel and offer acceptable combustion characteristics, their use raises ethical and economic concerns due to competition with food production (Atabani et al., 2012; Brahma et al., 2022). The rising demand for such biofuels could also drive agricultural expansion, posing risks to natural ecosystems (Tolmac et al., 2014; Bereczky et al., 2017).

In contrast, second-generation biofuels produced from waste fats used cooking oils, and agricultural or forestry residues (Chen et al., 2019; Zhao et al., 2021; Cherwoo et al., 2023) are gaining attention for their environmental and economic advantages. These biofuels are derived from non-food resources, thereby avoiding competition with food supply chains, and are typically less expensive to produce (Yesilyurt et al., 2018; Gebremariam & Marchetti, 2018). Animal fats such as duck, chicken, and lard, in particular, are emerging as viable alternatives due to their high energy density, availability, and suitability for conversion into hydrotreated vegetable oils (HVO) or fatty acid methyl esters (FAME) (Mikulski et al., 2016; Singh et al., 2023). Estimates suggest that an average urban resident produces approximately 4 kg of waste fat annually – an amount that could be repurposed into biofuel (Abomohra et al., 2020).

Third-generation biofuels are produced from microalgae or heterotrophic bacteria (Prabakaran et al., 2023; Redoy Masum Meraz et al., 2023). These organisms offer high oil yields and can be cultivated without occupying arable land, thus eliminating direct competition with agriculture (Mofijur et al., 2019). However, the large-scale commercialisation of these biofuels remains limited due to the high technological demands and costs associated with cultivation and oil extraction (Lin et al., 2011; L. Xiao et al., 2013; Allwayzy & Yusaf, 2017).

Fourth-generation biofuels represent the latest development and are synthesised using genetically engineered microorganisms. These organisms convert carbon dioxide (CO_2) into lipid-rich compounds through advanced biotechnological processes (Lin et al., 2013). While this approach holds significant long-term promise, it remains in the early stages of development, requiring further innovation and cost optimisation.

This dissertation focuses on second-generation biofuels produced from non-edible animal fats and their blends with hydrotreated vegetable oils (HVO) and fatty acid methyl esters (FAME). Through experimental investigations, it seeks to evaluate how these biofuels influence the operation of compression ignition engines, combustion characteristics, and exhaust emission profiles. In light of the transportation sector's push for more sustainable fuel alternatives, the utilisation of animal fats for biodiesel production may represent a strategic path towards reducing the environmental impact of modern transport systems.

1.3. Physicochemical Properties of Raw Materials Used For the Production of Biodiesel

The performance of biodiesel in compression ignition engines is closely linked to the physical and chemical characteristics of the raw materials used in its production. Biodiesel is primarily synthesised from vegetable oils and animal fats, where triglycerides serve as the main constituents. Key fuel properties, such as viscosity, oxidative stability, ignition quality, and combustion behaviour, are largely influenced by the molecular structure of these triglycerides and the specific types of fatty acids present (Capuano et al., 2017; Ramos et al., 2019).

Biodiesel is typically produced via transesterification, a chemical reaction in which triglycerides react with alcohol – commonly methanol or ethanol – in the presence of an alkaline, acidic, or enzymatic catalyst. This process yields fatty acid methyl esters (FAME), the primary component of biodiesel, while minimising unwanted by-products when carried out efficiently (Zahan & Kano, 2019).

A key factor in determining the quality of biodiesel feedstock is the content of free fatty acids (FFA). While refined vegetable oils generally contain less than 0.05% FFA, animal fats and crude oils may contain between 2% and 30% FFA (Brahma et al., 2022). High levels of FFAs can impede the transesterification process and promote saponification, which negatively affects biodiesel yield and quality (Athar & Zaidi, 2020). Table 1.1 outlines the main requirements set by European standards for diesel fuel and biodiesel blends.

Among the most critical parameters of biodiesel is viscosity, which directly impacts fuel injection, evaporation rates, and combustion behaviour (Atabani et al., 2012; Dhamodaran et al., 2017). Excessively high viscosity can lead to incomplete combustion, injector fouling, and carbon buildup in the combustion chamber, thereby impairing engine performance (Heywood, 2018). The viscosity of biodiesel is determined by the chain length and saturation level of the fatty acids it contains, with longer chains and more saturated bonds generally increasing viscosity (Ghazali et al., 2015).

Fuel density is another essential property that influences combustion dynamics and emission characteristics. Higher-density fuels often lead to elevated combustion temperatures, which can result in increased nitrogen oxide (NO_x) emissions (Singh et al., 2021). Fuel composition also plays a role: unsaturated fatty acids typically increase density, while saturated ones tend to reduce it (Banković-Ilić et al., 2014; Suarez-Bertoa et al., 2019).

The calorific value or energy content of biodiesel is generally lower than that of conventional diesel due to the higher oxygen content of biofuels. This can lead to slightly reduced engine efficiency, requiring greater fuel consumption to achieve the same power output (Verma et al., 2021). Nevertheless, biodiesel exhibits superior lubricating properties, which contribute to reduced engine wear and improved overall performance (Mizik & Gyarmati, 2021).

Table 1.1. Physicochemical properties in accordance with fuel standards in the European Union (The Oil Center…, 2013; Specifications for EN 14214 …, 2007; Neste Renewable Diesel Handbook, 2020)

Indicators	EN 590:2013	EN 14214 (2007)	Neste Renewable Diesel for HVO
Density (kg/m^3) at 15°	820–845	860–900	780
Kinematic viscosity (mm^2/s) at 40°	2.0–4.5	3.5–5.0	3
Flashpoint °C (min)	55	101	70
Cetane number (min)	51	51	70
Sulphur content mg/kg (max)	50	10	5
Water content mg/kg (max)	200	500	200
Total contamination [mg/kg] (max)	24	24	12
Oxidation stability [h] (max)	20	8	–
Acid value [mg KOH/g]	0	0.5	–

The cetane number is a fundamental property of biofuels that reflects the fuel's ignition quality under compression. A higher cetane number corresponds to shorter ignition delay and improved combustion characteristics, enhancing overall engine performance (Knothe et al., 2005). Hydrotreated vegetable oils (HVO), which exhibit significantly higher cetane numbers than conventional biodiesel and fossil diesel, contribute to more efficient combustion and lower emissions (Dimitriadis et al., 2020).

Oxidative stability is another key quality parameter that determines the shelf life and storage requirements of biofuels. Due to their higher content of unsaturated fatty acids, biodiesel fuels are more prone to oxidative degradation than conventional diesel (Stattman et al., 2018). This issue can be mitigated through the use of antioxidant additives or by blending biodiesel with more stable hydrocarbons such as HVO (Gebremariam & Marchetti, 2018).

Cold flow properties are critical for ensuring reliable biofuel performance in low-temperature environments. The most relevant parameters include the cloud point (CP), cold filter plugging point (CFPP), and pour point (PP). Biodiesel typically exhibits higher values for these parameters compared to diesel, which can lead to flow issues and fuel system blockages in cold weather conditions (Sorate & Bhale, 2015).

As low-sulphur diesel inherently lacks sufficient lubricity. The incorporation of biofuels, which possess superior lubricating properties, can help reduce friction-related wear in fuel system components such as injectors and pumps. This added lubrication extends engine life and improves overall mechanical durability (Karmakar et al., 2010).

This dissertation centres on analysing the properties of non-edible animal fats and their interactions in blends with hydrotreated vegetable oils (HVO) and fatty acid methyl esters (FAME). Through a series of experimental investigations, the research aims to assess how these fuel combinations influence engine performance, exhaust emissions, and the long-term reliability of fuel system components.

1.4. Ecological Aspects of Animal-derived Non-food Fats and Biodiesel Blends in Compression Ignition Engines

The escalating environmental impact of the transport sector – particularly due to pollutant emissions from diesel engines – is driving an urgent need to identify alternative fuels that can reduce the sector's ecological footprint. While conventional diesel remains efficient in terms of energy density, it is also a major contributor to emissions of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and unburned hydrocarbons (HC), all of which exacerbate climate change and air quality deterioration (Chong et al., 2021; Athar & Zaidi, 2020). Biofuels have emerged as a leading alternative due to their favourable chemical structure, which enables reductions in specific emissions. However, the environmental impact of biofuels depends heavily on the type of feedstock, production processes, and combustion characteristics (McCaffery et al., 2022).

Among sustainable biofuel options, those derived from non-edible animal fats are gaining traction for their dual benefits: recycling waste-based lipids and reducing environmental burden. When processed into hydrotreated vegetable oils (HVO) or fatty acid methyl esters (FAME), animal fats, including those from poultry such as duck and chicken, can be transformed into viable biodiesel fuels. Blending these biofuels with conventional diesel can enhance combustion efficiency and reduce harmful emissions (Şen et al., 2018; Singh et al., 2023).

One of the key ecological advantages of biodiesel lies in its ability to reduce net CO_2 emissions. As biodiesel is produced from biological materials, the carbon released during combustion is generally considered part of the natural carbon cycle, unlike fossil diesel, which adds new CO_2 to the atmosphere (Islam et al., 2014). Reports suggest that substituting mineral diesel with biodiesel could reduce CO_2 emissions by up to 72% (Biodegalų asociacija, 2025).

In addition, the higher oxygen content in biofuels promotes more complete combustion, which leads to lower emissions of CO and HC (Şen et al., 2018; Abdalla, 2018). These effects are especially pronounced at low to medium engine loads, where biodiesel blends tend to oxidise more efficiently (Duda et al., 2018; Górski et al., 2020).

However, one of the key challenges associated with biofuel use is an increase in nitrogen oxide (NO_x) emissions. The elevated oxygen content and combustion temperature of biodiesel can promote NO_x formation (Jayabal et al., 2020; Barrios et al., 2014). Nevertheless, advanced fuel injection strategies and exhaust gas recirculation (EGR) systems have shown promise in mitigating this drawback (Yadav et al., 2015).

Particulate matter (PM) emissions also represent a significant environmental concern for diesel fuels. Conventional diesel combustion often results in high levels of soot due to incomplete fuel burning. Biodiesel, however, tends to produce significantly less particulate matter. Research indicates that animal fat-based biofuels, such as those from duck or chicken, contain fewer aromatic compounds, further reducing PM emissions (Yesilyurt et al., 2020; Kończak et al., 2020).

The environmental performance of biofuels is highly dependent on both fuel composition and combustion optimisation. For example, biofuels derived from chicken fat may exhibit slightly higher viscosity but longer combustion duration, which can lower CO and HC emissions (Selvam & Vadivel, 2012). Similarly, blends with higher proportions of animal fat may slightly increase NO_x levels while significantly reducing particulate emissions (Rimkus et al., 2021).

Experimental data underscore the importance of fuel formulation and engine calibration in determining ecological outcomes. Blending HVO and FAME may achieve an optimal balance between emission reduction and engine performance: HVO contributes high cetane numbers and low density, while FAME offers excellent lubricity and stable combustion characteristics (Kirubakaran & Selvan, 2018). Ultimately, the integration of first- and second-generation biofuels, particularly those derived from non-edible animal fats, into compression ignition engines holds strong potential for reducing CO, HC, and PM emissions. However, addressing the NO_x challenge and further improving fuel efficiency will require continued advancements in both engine design and fuel technology.

1.5. Analysis of Thermodynamic Processes in a Compression Ignition Engine Running on Animal-Derived Non-Food Fats and Biodiesel Blends

The combustion process in a compression ignition (CI) engine is governed by a combination of fuel properties, combustion parameters, and air–fuel mixture formation, all of which influence complex thermodynamic interactions. Key aspects, such as thermal energy conversion, combustion duration, cylinder pressure distribution, and pollutant formation, are significantly affected by the use of biofuels (Keskin et al., 2020). Given that biodiesel and blends incorporating non-edible animal fats differ notably from diesel in their physicochemical characteristics, it is essential to investigate their impact on the thermodynamic behaviour of CI engines (Gorji et al., 2015).

Fuel viscosity and combustion rate play a pivotal role in fuel injection dynamics, evaporation, and flame propagation. Biodiesel and animal fat-based fuels typically exhibit higher viscosity than conventional diesel, which can lead to the formation of larger fuel droplets and reduced evaporation rates (Ramalingam et al., 2018). As a result, optimising injection parameters, such as pressure and spray angle, is critical to minimising ignition delay and ensuring effective combustion (Lijewski et al., 2017).

The start of combustion and subsequent cylinder pressure evolution is also influenced by the cetane number of the fuel. Fuels with a higher cetane number, such as hydrotreated vegetable oils (HVO), ignite more readily, promoting improved combustion efficiency and reduced emissions (Dimitriadis et al., 2020). In contrast, fatty acid methyl esters (FAMEs) derived from animal sources, including duck and chicken fat, tend to have lower cetane numbers, resulting in longer ignition delays (Ghazali et al., 2015).

Cylinder pressure development and thermal energy conversion are key thermodynamic indicators of engine performance. Research has shown that blends of biodiesel can increase peak cylinder pressure due to intensified combustion driven by their higher oxygen content (Othman et al., 2017). However, if fuel injection systems are not adequately adapted to these conditions, the rapid rise in pressure may cause mechanical stress or damage to engine components (Yadav et al., 2015).

Research into combustion duration and thermal efficiency reveals that the elevated viscosity and lower volatility of biodiesel typically extend the combustion period (Jayaprabakar & Karthikeyan, 2016). For instance, biodiesel blends using rice bran or algal methyl esters have demonstrated reduced fuel consumption under optimised conditions. Nevertheless, the associated increase in ignition delay, primarily due to viscosity, is a critical parameter requiring control (Mikulski et al., 2016). Furthermore, thermal efficiency can vary depending on fuel composition, with saturated fatty esters often yielding higher performance, though requiring adjustments to injection pressure due to their viscosity (Hirkude & Padalkar, 2012).

Two additional important indicators of biofuel performance are energy conversion efficiency and exhaust gas temperature. The higher oxygen content of biofuels can lead to increased combustion temperatures, which in turn can enhance oxidation efficiency and reduce emissions of CO and HC (Mahmudul et al., 2017; Işık et al., 2017). On the downside, higher temperatures are also associated with elevated NO_x formation (Yesilyurt et al., 2020).

The application of mathematical models for simulating biofuel combustion processes, such as those using AVL BOOST, has proven effective in predicting changes in key thermodynamic variables like cylinder pressure, combustion duration, and exhaust gas temperature (Chuah et al., 2015). Experimental investigations into animal fat-based fuels further indicate that appropriate fuel formulations can stabilise combustion and reduce engine wear (Ashfaque Ahmed et al., 2023).

In summary, the thermodynamic behaviour of CI engines operating on blends of animal fat-derived and first- or second-generation biodiesel significantly influences both engine performance and emission profiles. Key factors affecting the viability of these alternative fuels include fuel viscosity, cetane number, combustion temperature, and fuel injection strategies. Future research should focus on optimising fuel blend compositions and refining engine control parameters to maximise environmental benefits and energy efficiency.

1.6. Application of Regression Models and Neural Networks in Alternative Fuel Analysis

The working processes of an internal combustion engine (ICE) are complex and involve the interaction of many interrelated parameters,e.g., fuel properties, combustion conditions, excess air (λ), fuel injection characteristics, etc. (Ramalingam et al., 2018). Traditional empirical or semi-empirical models cannot always accurately capture these nonlinear dependencies, especially when aiming to optimise engine efficiency and emission reduction simultaneously. Therefore, in the last decade, more and more attention has been paid to data-driven methods, including machine learning (ML) algorithms, which can “learn” complex relationships between input and output parameters from large experimental data sets and provide reliable predictions. ML methods provide an opportunity to quickly assess the influence of various factors on engine performance indicators without conducting expensive and time-consuming experiments in each case. This is especially relevant when implementing alternative fuels and combining diverse technical solutions to reduce pollution.

A wide range of ML algorithms are applied in IC Engine research. Some of the most popular are decision tree methods (e.g., regression trees) and their ensembles, such as the random forest algorithm and boosted regression trees methods. Artificial neural networks (DNT), adaptive neuro-fuzzy inference systems (ANFIS), and other advanced algorithms, such as Gaussian process regression and support vector methods, are also widely used. Each of them has its advantages in solving engine performance modelling problems.

Regression tree models are distinguished by their interpretability. They hierarchically divide the data set according to the most significant features; therefore, it is possible to establish, e.g., which factors (e.g., certain fuel properties or operating parameters) determine pollutant emissions the most. This is particularly useful when analysing the effects of fuel mixtures: the literature notes that fuel composition has a significant impact on engine performance and emissions (Ghazali et al., 2015). For example, diverse biodiesel feedstocks (vegetable oils, waste fats, etc.) result in diverse levels of smoke, CO, HC, and NOx (Ghazali et al., 2015). In such cases, regression trees help to reveal which combinations of fuel properties or operating conditions minimise pollution. However, individual decision tree models are prone to high variance (variability in model results). This means that small changes in the training data can change the tree structure and predictions. Ensemble methods are used to address this problem.

The Random Forest algorithm, introduced by Breiman (2001), is one of the best-known ensembles. It combines the predictions of many decision trees into a common mean, thus significantly reducing the problem of excessive variance. Each tree is trained with a random sample of data and features, which makes the model more resistant to overfitting and better able to generalise patterns. Research shows that the Random Forest method can achieve high accuracy in predicting engine performance. For example, when applying this method to analyse a biofuel blend engine, the obtained R^2 coefficient of determination of the modelling often exceeds 0.95, which means that the predictions are very close to the experimentally measured values. Such results confirm that ensemble tree methods effectively process complex relationships between fuel composition, combustion process and emissions, outperforming individual tree models.

Another direction of ensemble methods is boosting algorithms, where trees are trained sequentially, each trying to correct the errors of the previous one. This type includes, for example, the XGBoost algorithm, in which many small “weak” trees together form a powerful predictor. Although there are fewer works in the literature applying boosting to engine data compared to random forests or DNT, initial results show that boosting methods can achieve similar or even higher accuracy. True, their application requires careful parameter optimisation to avoid possible overfitting since sequential training can overfit the model to the training data. Nevertheless, such models have great potential in modelling engine processes, especially when the amount of data is large enough. Against the background of relationships that are difficult to describe with linear models, artificial neural networks are extremely promising. These bio-inspired algorithms can approximate functional relationships between inputs and outputs of practically any complexity as long as there is enough data to train them. DNTs have been successfully applied to various types of engines, e.g., gasoline, diesel, HCCI, etc., and the literature indicates that they have become an indispensable tool for accelerating the prediction of engine parameters. For example, DNT models can predict the power and emissions of a diesel engine much faster than full-cycle simulations or experiments, and the prediction error often does not exceed a few per cent. One research found that the DNT model predicted the combustion and emissions characteristics of a gas engine better than the random forest method when parameters such as ignition timing, air-fuel ratio, and engine speed were selected as model inputs. Although neural networks often outperform other models in terms of accuracy, their development requires more computational resources and experience as it is necessary to properly select the network architecture, activation functions, and training algorithm. In addition, DNTs act as "black boxes" and, therefore, have limited explainability. Unlike decision trees, they do not provide clear rules for how input factors determine the result. For this reason, recent work explores the use of hybrid methods to balance interpretability and accuracy, e.g., by combining the advantages of decision trees and neural networks or by using ANFIS algorithms, where classification rules are formed explicitly but, at the same time, adapted using neural learning principles.

ANFIS (Adaptive Neuro-Fuzzy Inference System) methods combine neural network training with fuzzy logic rules. This allows the model to have interpretable "if-then" regularities (as in a fuzzy system) but, at the same time, automatically optimise their parameters based on data (as in DNT). In engine research, ANFIS has been used, for example, to predict engine torque and emissions to create adaptive control systems. It is claimed that ANFIS models can achieve similar accuracy to pure DNT but require smaller data samples for training because part of the model structure is based on expert knowledge (fuzzy logic rules). ANFIS is particularly useful when the engine operating modes vary over a wide range. Then, this system can "switch" diverse rules for different conditions. However, building ANFIS models requires some expert parameter setting (selection of membership functions, etc.), so their application is not yet as widespread as DNT or random forests.

In addition to the above methods, other algorithms are also used to model engine parameters. Support Vector Regression (SVR) models are worth mentioning as they have been used in some research and have shown good accuracy in predicting engine power and torque, especially when the amount of data is limited. There are also examples of Gaussian Process Regression (GPR) applications in the academic literature. This Bayesian method allows for getting an estimate of uncertainty along with the forecast. This is attractive in emissions forecasting, where it is important to know the error with which the level of pollutants is predicted. GPR models have been successfully used in creating digital twins of engines, where the model is constantly calibrated based on sensor data and, thus, engine settings are optimised in real-time. Although GPR is computationally resource-intensive, with the acceleration of computer technology, this method is expected to be more widely used in engine diagnostics and control.

The benefits of ML methods are especially evident when analysing alternative fuels and mixtures. Recently, various fuel blends of biogas, biodiesel, hydrogenated vegetable oil (HVO), waste oil methyl esters, bioethanol, and synthetic and even nano-enhanced fuel blends have been intensively analysed. Each of these fuels has diverse physicochemical properties (cetane and octane numbers, viscosity, energy value, oxygen content, etc.), so their impact on engine efficiency and emissions can vary significantly (Ghazali et al., 2015). For example, biodiesel derived from waste fats generally reduces emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter due to the higher oxygen content in the fuel molecule but tends to increase the formation of nitrogen oxides (NOx) due to the higher combustion temperature (Abed et al., 2019). Meanwhile, hydrogenated vegetable oil (HVO) emits significantly fewer soot particles during combustion compared to traditional diesel due to its paraffinic composition; however, to control NOx emissions, engine control strategies need to be adapted accordingly (Suarez-Bertoa et al., 2019). Thus, for each new type of fuel, it is necessary to find optimal combinations of engine operating parameters. Here, ML algorithms come in handy, which can evaluate the abundance of such combinations and help find the best compromise between efficiency and pollution.

In addition to the properties of the fuel itself, the use of performance additives is another way to improve emissions. By adding oxygen additives (e.g., ethanol or ethers, such as diethyl ether) or nanoparticle catalysts to the fuel, the aim is to accelerate combustion reactions and reduce soot formation. Empirical research shows that such additives can increase engine efficiency and reduce pollution, but determining the optimal additive dose and interaction with other parameters (e.g., EGR intensity, injection timing) is a complex task. This is where ML models come in handy as they allow for “learning” from a multivariate data set, which combinations of fuel composition and operating modes give the best results in terms of pollution. For example, in a research in which diethyl ether (DEE) was added to a mixture of animal-derived biodiesel and diesel, it was found that combustion characteristics improved: the ignition delay time was shortened and, accordingly, CO and smoke were reduced (Ashfaque et al., 2023). However, modelling methods are required to quantitatively optimise the share of DEE in the fuel mixture.

Several research in the literature emphasise that combining several pollution reduction methods leads to unexpected interactions that are not captured by traditional analysis methods (Jayabal et al., 2020). For example, when changing the biodiesel/regular diesel ratio while applying exhaust gas recirculation (EGR) and adjusting the fuel injection timing, the final indicators change non-monotonically (Jayabal et al., 2020). Research by Lithuanian researchers used a biodiesel blend of chicken fat in a diesel engine and found that choosing the same EGR level as with pure fossil fuels increases CO emissions, which means that biofuels require a diverse optimal EGR value (Rimkus et al., 2021). To effectively find such optimal combination conditions, it would be very inefficient to experiment only by the “trial and error” method. However, by developing an integrated ML model that includes all the most important factors, it is possible to perform multi-objective optimisation, e.g., maximising thermal efficiency (*BTE*) while minimising NOx and particulate emissions. Some research efforts apply evolutionary optimisation algorithms together with ML models, allowing for the selection of compromise parameters considering the PM–NOx trade-off (Dimitriadis et al., 2020). In this way, ML tools become not only a forecasting tool but also a control optimisation tool.

It is worth noting that ML methods are applicable not only to liquid biofuels but also to gaseous fuel mixtures. For example, models developed to predict the results of using compressed biogas (biomethane) in a converted spark-ignition engine have shown that by properly selecting the ignition timing and air-fuel ratio, it is possible to achieve efficiency close to that of a diesel engine with significantly lower CO_2 emissions. The effect of hydrogen as an additive in diesel engines is also being analysed. Although hydrogen does not increase carbon emissions, its combustion can increase the amount of NO_x; ML models can help find the right hydrogen fraction and injection parameters to manage this trade-off (Syed et al., 2017). These multivariate analyses, where several fuels and parameters are evaluated simultaneously, clearly demonstrate the flexibility of ML methods.

Summarising the literature, it can be stated that machine learning methods in the field of internal combustion engines have already proven their effectiveness. Regression trees and their ensembles (RF, boosting) are characterised by an excellent combination of accuracy and interpretability. Methods can explain which factors are most important for a given indicator and, at the same time, provide reliable forecasts (often $R^2 > 0.9$). Neural networks usually allow for achieving even greater accuracy, especially when modelling complex emission processes, but require more data and computing resources. The integration with fuzzy logic systems (ANFIS) or physical models is a promising direction for achieving more understandable but not deteriorating accuracy solutions. Meanwhile, the Gaussian process or support vector methods find their niche when data is not abundant or the uncertainty of forecasts needs to be assessed. A comparison of diverse algorithms does not provide the unequivocally best one, as it all depends on the nature of the available data and the research goals. For example, if it is important to obtain a fast and interpretable result, preference is given to ensembles of decision trees or even simple correlation regressions. If maximum accuracy is sought in a complex multivariate system, DNT or their combinations are often chosen. In practice, a combined approach is often used: first, random forest models identify the most important factors and approximate relationships, and then a neural network model is trained in that concentrated factor space to more precisely reproduce the observed results. Such a combination allows for the use of both methods' advantages, e.g., interpretation and accuracy.

As for the applicability of models, today, ML algorithms can be applied not only in a research environment but also in real engine control. Adaptive engine control systems are developed using artificial intelligence models for continuous engine calibration during operation. This is relevant in hybrid and other advanced engines, where sensor flow data constantly feeds the ML model, allowing for the adjustment of fuel injection and other parameters to achieve optimal results. Future research directions include the use of larger data sets, e.g., by combining data sets from diverse laboratories or manufacturers, it is possible to train more universal models that can predict engine operation with various fuels and under various conditions. The first steps are also taken in applying deep learning, e.g., complex neural networks (such as convolutional or recurrent networks) could detect regularities directly from sensor signals or even the engine acoustic signal. However, for now, simpler ML models are more popular due to their clearer operating principle and lower computational costs. It is important to emphasise that the accuracy of ML models depends largely on the quality and coverage of the training data. Models reliably predict only within the limits that they "saw" during training, so it is necessary to ensure that the training data covers the entire range of the most important engine modes. This requires careful selection of experimental points and validation of the model with independent data. A properly validated ML model can provide over 90% prediction accuracy in real-world conditions, but without validation, the model's predictions can be misleading.

The application of ML algorithms to ICE parameter prediction and emission reduction has significantly enriched the traditional research arsenal. Based on the sources provided, it can be stated that these methods allow for a more accurate assessment of the impact of alternative fuels, finding optimal engine settings in complex trade-off situations, and reducing the amount of experimental work without sacrificing the reliability of the results (Ghazali et al., 2015). Further development in this direction is a step towards smarter, adaptive engine systems that can adapt to changing fuel types and stricter environmental requirements.

1.7. Conclusions of the First Chapter and Formulation of the Dissertation Tasks

The following issues should be considered to assess the value of biodiesel and the requirements it should meet for an automotive engine:

1. Biodiesel is regarded as a viable alternative to petroleum-based fuels in the transportation sector due to its reduced environmental impact and potential to decrease greenhouse gas emissions. Various biodiesel blends influence engine performance and emissions in distinct ways; the long-term impacts on engine systems remain inadequately explored.
2. Second-generation biodiesel and non-food animal fats enable the recycling of waste raw materials while not competing with food production, making them a potentially more sustainable alternative. The physicochemical parameters of these fuel combinations differ significantly from regular diesel, necessitating compatibility with compression-ignition engines, regardless of their possible usage in transportation.
3. Direct effects on the engine combustion process are found in the physicochemical characteristics of biodiesel and animal fats: viscosity, cetane number, heat of combustion and oxidative stability. Whereas reduced oxidative stability might cause fuel breakdown during storage, higher fuel viscosity can influence fuel injection and combustion.
4. Ecological aspects show that the use of biodiesel can significantly reduce CO_2 , CO and particulate emissions, but in some cases, NO_x emissions may increase. Animal fat-based biofuels may have diverse emission dynamics, so it is necessary to analyse their impact on pollution in detail, especially with regard to combustion temperature and fuel injection parameters.
5. Fuel blends consisting of HVO and up to 75% animal-derived fats reduced CO, HC, and smoke emissions while maintaining acceptable *BTE* levels, supporting their applicability as a viable alternative to fossil diesel in the transport sector.

Thermodynamic processes in compression-ignition engines using biodiesel blends may differ from those of traditional diesel since the chemical composition of the fuel determines the ignition delay, the variation of the maximum pressure in the cylinder and the efficiency of energy conversion. These differences can affect both engine efficiency and emissions, so detailed experimental and numerical analyses are necessary.

Considering these generalisations, the following tasks were set to achieve the goal:

1. The composition of biofuel blends has a significant impact on the combustion process, emission levels and energy performance of a compression ignition engine, compared to conventional diesel.
2. Second-generation biodiesel and animal fat blends can provide lower CO, HC and particulate emissions, but their effect on NO_x emissions depends on the fuel composition and engine operating conditions.
3. Properly selected biofuel blends can be used in compression ignition engines without requiring significant structural modifications while preserving their operational performance characteristics.
4. Mathematical modelling allows for accurate prediction of the impact of fuel blends on engine operating parameters and emissions, creating prerequisites for optimising fuel composition according to environmental and energy criteria.

2

Experimental Research Methodology and Mathematical Modelling of Biodiesel Blends Using Regression Trees

This chapter provides a comprehensive examination of biodiesel blend selection, the advancement of an experimental research methodology, and the application of mathematical modelling through the regression trees approach. The selection of fuel mixtures is contingent upon their physicochemical properties, ecological sustainability, and potential applicability in a compression ignition engine. The evaluation of performance and emissions across diverse fuel mixtures involves a systematic experimental research methodology, which includes the configuration of engine testing, the utilisation of measurement instruments, and the application of data analysis techniques. Furthermore, this chapter elucidates the regression trees methodology as an analytical instrument for exploring the relationship between fuel mix composition, engine performance metrics, and emissions. This approach enables the discernment of essential elements affecting fuel efficiency and emissions, thus promoting the refinement of alternative fuel compositions prior to undertaking extensive experimental assessments. This chapter delineates a thorough experimental and modelling framework that underpins the forthcoming assessments of biodiesel blends in authentic engine operating scenarios (Shepel et al., 2022).

2.1. Fuel Preparation and Analysis

This research presents the findings from an experimental evaluation of six fuel blends, all composed entirely of renewable raw materials. These blends were compared against conventional diesel fuel (D) to assess their performance. Two series of mixtures were prepared: the first involved hydrotreated vegetable oil (HVO) blended with fatty acid methyl esters derived from duck fat (FE100) in volumetric ratios of 25%, 50%, and 75% (designated as FE25, FE50, and FE75, respectively). The second series consisted of HVO (HVO100) blended with pure duck fat (F100) in the same volumetric proportions (F25, F50, and F75). In addition to these blends, the pure components HVO100, FE100, and F100 were also analysed independently.

Animal fat methyl esters were obtained at the Biofuel Quality Research Laboratory located in the Department of Mechatronics and IT Education of the University of Warmia and Mazury, where the mixtures were also prepared and researched for the composition and physicochemical properties of the analysed fuels (Uniwersytet Warmińsko-Mazurski w Olsztynie, 2024).

One of the methods applied and analysed in this research for biofuel production was transesterification, which is the most widely used technique for converting fatty materials into biodiesel. This process involves the reaction of fat with an alcohol, typically methanol or ethanol, in the presence of a catalyst.

Transesterification is relatively straightforward and can be easily automated, making it suitable for large-scale applications. A key aspect of this research is the utilisation of duck fat as a feedstock, which not only provides a renewable raw material but also supports the valorisation of non-edible by-products from the meat industry, contributing to sustainable waste management.

Biodiesel production involves the chemical processing of lipids derived from various biological sources. In this research, duck fat was utilised as a renewable feedstock for biofuel production in the transport sector. The experimental procedure for biodiesel production was carried out in the laboratory using transesterification, resulting in the formation of fatty acid methyl esters (FAMEs).

The reaction conditions, such as temperature, reaction time, reagent ratios, and catalyst type, are determined by the chemical composition of the feedstock and are experimentally optimised to maximise the yield of the desired product (Barua et al., 2020). Among these parameters, temperature and reaction duration are critical factors influencing the biodiesel yield. An increase in temperature typically accelerates the transesterification of triglycerides by reducing the viscosity of the lipids.

However, if the temperature exceeds the optimal level, the yield may decrease due to the increased rate of undesirable side reactions, such as the saponification of triglycerides. Generally, the optimal reaction temperature is aligned with the boiling point of the transesterifying alcohol.

When using alkaline catalysts, the reaction time typically does not exceed 90 minutes. In contrast, acidic and fermented catalysts may require several hours to days for the reaction to complete. Homogeneous alkaline catalysts, such as potassium hydroxide, ensure nearly 100% conversion of fatty acids to methyl esters, meeting the EN 14214 standard for biodiesel quality.

In this research, biodiesel was produced using 500 g of duck fat, with a molar ratio of 6:1 methyl alcohol to fat and 1.67% potassium hydroxide by weight relative to the fat content. Methyl alcohol was chosen for its higher reactivity and cost-effectiveness compared to other alcohols. The reaction was carried out at 60°C, and the mixture was stirred with a mechanical stirrer for 45 to 50 minutes. After the reaction, the biodiesel was separated from glycerol, alcohol, impurities, and moisture, as shown in Figure 2.1.

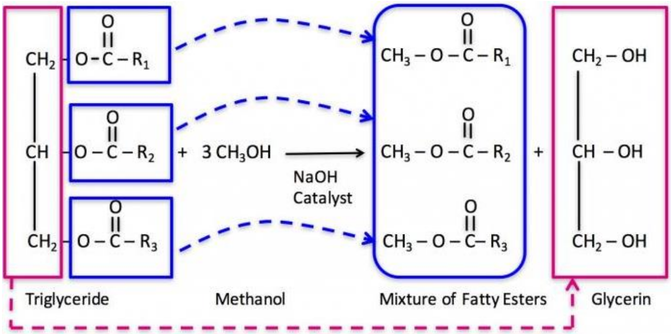

Fig. 2.1. Schematic representation of the biodiesel production phases (EGEE 439. Alternative Fuels from Biomass Sources, 2023)

Sample fuel was stored in clean and dry containers at +5° C. To minimise moisture condensation during storage, fuel tanks were drained and filled to the maximum.

Research Methodology consisted of standard methods and other analytical methods proposed for biodiesel analysis:

– methods for determining contaminants from raw materials;
– methods for evaluating the properties inherent to molecular structures;

– methods for monitoring the quality of biodiesel during the storage process.

The primary characteristics of biodiesel are regulated in most countries by national standards. In this research, the properties of fuel mixtures for diesel engines were analysed in accordance with three key standards: the European Union's EN 590 (2013), which applies to diesel fuel for diesel engines, and EN 14214 (2007), which pertains to fatty acid methyl esters (FAME) for diesel engines, outlining both requirements and test methods.

Additionally, Neste Renewable Diesel provides separate recommendations for Hydrotreated Vegetable Oil (HVO). Since HVO consists of paraffinic hydrocarbons, it does not meet the requirements set by EN 14214, as this standard is specifically designed for biodiesel derived from methyl esters, e.g., FAME. However, HVO meets the EN 590 standard, except for the minimum density requirement. For this research, the fuel standard used was that of Neste Oil, a Finnish company with four industrial facilities dedicated to producing renewable fuels through the hydrogenation of various vegetable oils. The fuel composition is detailed in Table 2.1, and a comparison of the physical and chemical properties of the different fuels is presented in Table 2.2.

Table 2.1. Composition of the prepared fuels

Designation	Fuel 1 fraction by vol.	Fuel 2 fraction by vol.
HVO	HVO (100%)	–
FE25	HVO (75%)	FE (25%)
FE50	HVO (50%)	FE (50%)
FE75	HVO (25%)	FE (75%)
FE100	–	FE (100%)
F25	HVO (75%)	F(25%)
F50	HVO (50%)	F(50%)
F75	HVO (25%)	F(75%)
F100	–	F (100%)

These figures show the comparative characteristics of the diverse kinds of mixtures shown in Table 2.1. An unsuitable sample of fuels is highlighted in blue.

It can be noted (Fig. 2.2) that the fuel mixtures presented are within the normal range; only F100 shows an increase in this parameter. The mixtures that have the best diesel-like properties are presented in sample F50 according to EN 590.

The kinematic viscosity of the experimental resulting biodiesel (Fig. 2.3) was almost always within the limits established by the European standard. For pure ester FE100, viscosity is normal. Only for F50, F75, F100 viscosity is higher than normal.

Table 2.2. Physicochemical properties of the analysed fuels

Sample	Density (kg/m³) at 15°	Viscosity (mm²/s) at 40°	Flash point °C	Sulphur content mg/kg	Water content mg/kg	Total contamination [mg/kg]	Oxidation stability [h]	Acid value [mg KOH/g]	Cold Filter Plug Point °C
Allowed value in accordance with quality standard EN 590									
	820–845	2–4.5	≥55	≤10	≤200	≤24	≥20	–	–
Allowed value in accordance with quality standard EN 14214									
	860–900	3.5–5	≥101	≤10	≤500	≤24	≥8	≤0.5	–
Allowed value in accordance with a word certificate Neste Renewable Diesel for HVO									
	770–790	2–4	≥61	≤5	≤200	≤10	–	–	–
D100	823	3.5	45	7.25	85	20	17	–	–10
HVO	776	2.9	79	4.16	20	5.52	≥6	0.04	–20
FE25	800	3.2	84	4.12	120	7.05	1.82	0.03	–7
FE50	824	3.4	87	4.27	150	12.35	1.79	0.05	–3
FE75	849	3.9	93	4.37	400	16.04	0.18	0.09	1
FE100	873	4.3	102	5.41	460	19.78	0.18	0.08	4
F25	800	4.7	86	4.52	690	43.27	1.35	0.1	6
F50	831	9.8	97	4.87	770	impossible to check this sample	0.70	0.3	10
F75	867	18.8	115	5.21	925		0.44	0.5	17
F100	908	34.8	197	5.31	1450		0.44	0.7	24
Sample	Hydrogen%	Carbon %	Oxygen%		C/H	Lower Heating Value (LHV) [MJ/kg]		Cetane number	
D100	0.130	0.870	0.000		6.69	42.70		45	
FE25	0.1460	0.8233	0.0308		5.6	42.30		69.95	
FE50	0.1400	0.7985	0.0615		5.7	41.05		64.52	
FE75	0.1340	0.7738	0.0923		5.8	39.53		59.41	
FE100	0.1280	0.7490	0.1230		5.8	38.00		58	
F25	0.146	0.827	0.027		5.64	42.40		72.04	
F50	0.141	0.804	0.055		5.70	40.70		67.19	
F75	0.136	0.782	0.082		5.77	39.00		62.34	
F100	0.130	0.760	0.11 0		5.85	37.30		57.49	
HVO100	0.152	0.848	0.00		5.58	43.70		76.89	

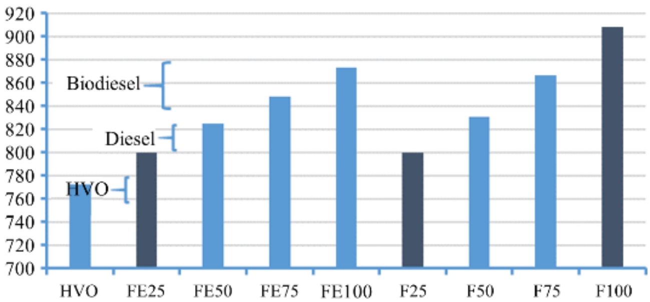

Fig. 2.2. Density (kg/m³) at 15°

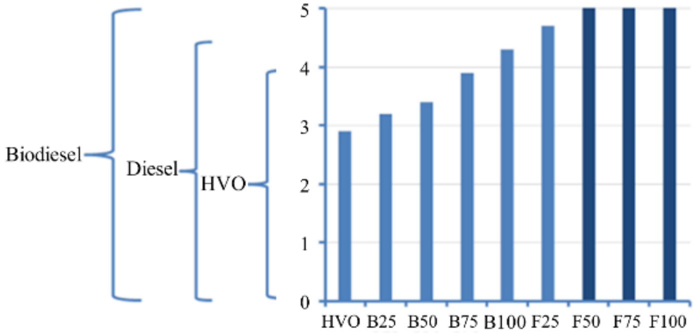

Fig. 2.3. Viscosity (mm^2/s) at 40°

The flash point values (Fig. 2.4) obtained for all experimental mixtures comply with the standard requirements. Although there is no corresponding standard for pure fat (F100), this sample also exhibited a normal flash point indicator.

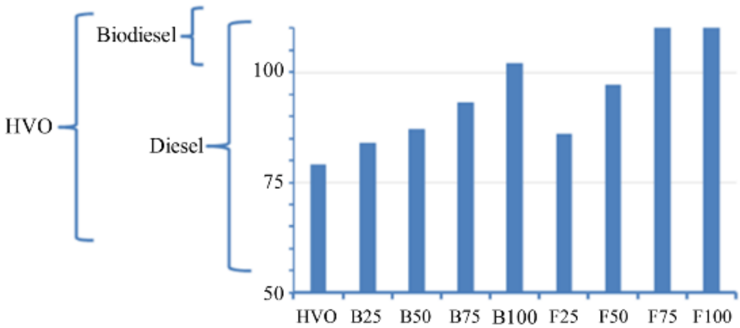

Fig. 2.4. Flash point °C

Table 2.2 presents the sulphur content results for nine samples. It was found that all mixtures did not exceed the permissible sulphur content limit.

Since biodiesel is hygroscopic, water content (Fig. 2.6) should be carefully monitored during storage. Standard EN 14214 specifies the maximum allowable water content at 0.05% by volume or 500 mg/kg. The pure HVO, FE25, FE50, FE75, and pure biodiesel mixtures all stayed within the maximum permissible water concentration. However, mixtures containing pure duck fat were found unsuitable for use in diesel engines due to higher water content.

The mass of insoluble residues left after biodiesel filtration is used to calculate a parameter called "total pollution". Standard EN 14214 (2007) sets a maximum limit of 24 mg/kg for this value. The samples containing fat showed a significant excess in precipitation.

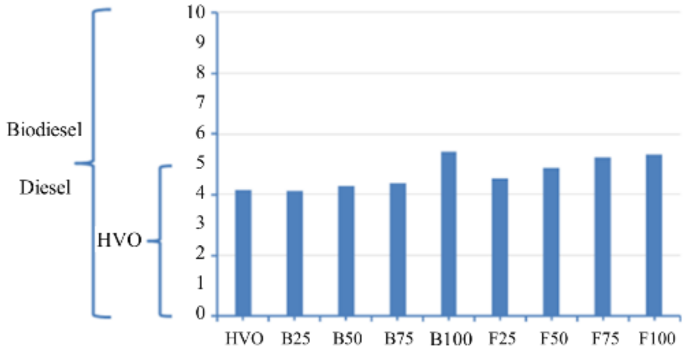

Fig. 2.5. Sulphur content mg/kg

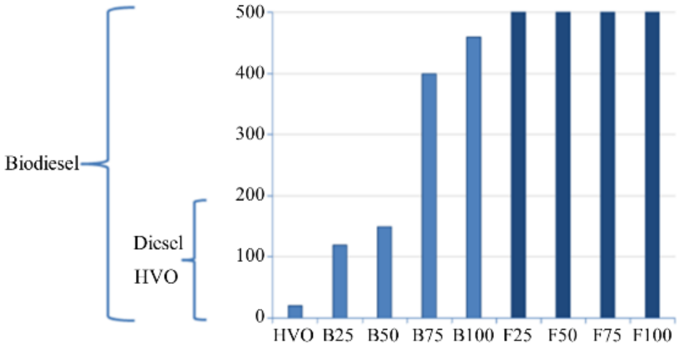

Fig. 2.6. Water content mg/kg

According to EN 14214 (2007), this parameter relates to the time required for the biodiesel to decompose, which directly impacts its storage stability. In the present research, the samples (Fig. 2.8) were monitored for 8.5 hours. The presence of fatty acids in biodiesel promotes oxidation. To maintain fuel quality in accordance with the required standards, antioxidants, either synthetic or natural, can be added to prevent oxidative breakdown and slow down the oxidation rate. The results indicate that all blends, except HVO, exhibited low oxidative stability.

The effect of the reaction on the acidity of various mixtures is summarised in Table 2.2. The acid value (Fig. 2.9) for nearly all samples, except F100, remained below the standard limit of 0.5 mg KOH/g, ranging from 0.03 to 0.5 mg KOH/g. The experiment, which examined the influence of catalyst concentration on acidity, showed that the acid value increased as the concentration of fatty acids increased.

The normal acid values observed for all samples confirm that the selected production method, specifically transesterification, effectively reduces the acidity of raw materials to levels compliant with current standards.

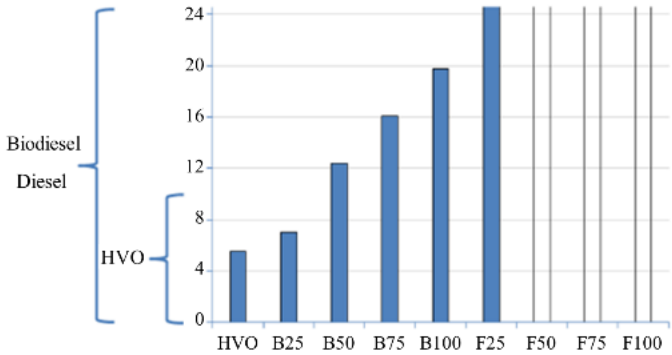

Fig. 2.7. Total contamination mg/kg

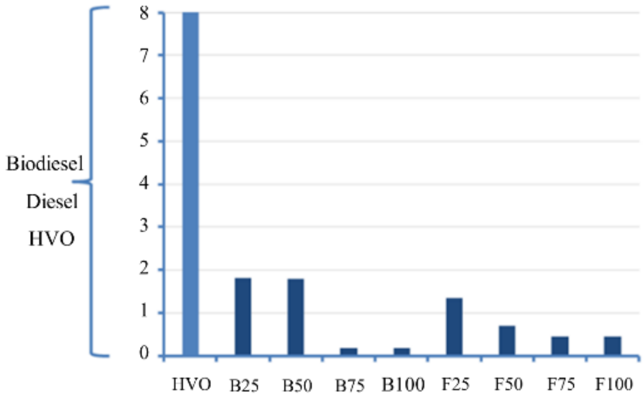

Fig. 2.8. Oxidation stability, h

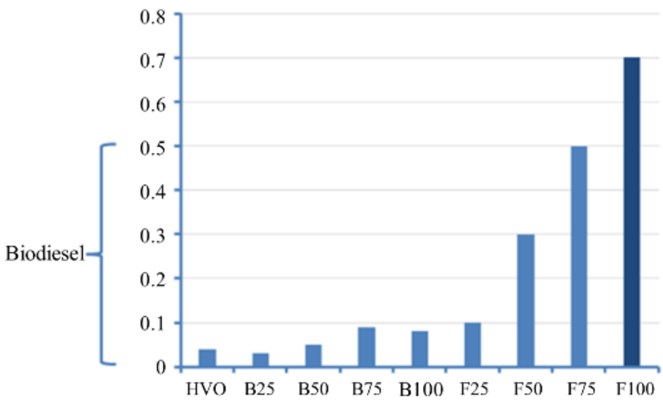

Fig. 2.9. Acid value, mg KOH/g

Low-temperature fuel properties are assessed by the Cold Filter Plugging Point (CFPP), which represents the lowest temperature at which a given volume of fuel can pass through a standardised filtration system within a set time. In this research, biodiesel mixtures derived from animal fats, which contain high amounts of methyl esters such as palmitic, oleic, and linoleic acids, begin to solidify and clog fuel filters at relatively high temperatures (CFPP = 10 ºC). The mixture F25 exhibited the highest CFPP value of 17 ºC, indicating the poorest low-temperature properties due to its significant content of long-chain saturated fatty acids.

The analysis (Fig. 2.10) reveals that the most resilient mixtures to low temperatures were pure HVO, B25, and B50, with CFPP values of –20 ºC, –7 ºC, and –3 ºC, respectively. These biodiesel blends are suitable for use during colder months.

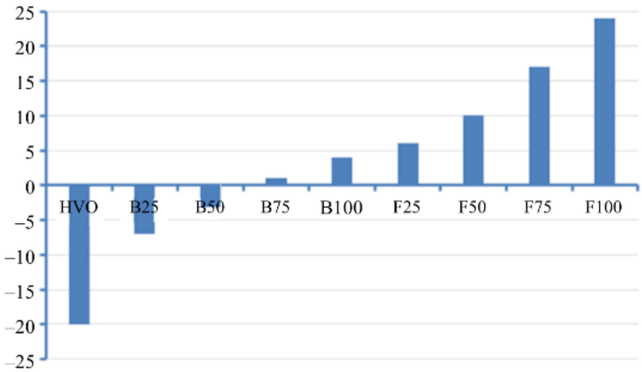

Fig. 2.10. Cold filter plug point, ºC

In conclusion, the fatty acid composition of the feedstock plays a major role in determining key operational characteristics of biodiesel. While chemical composition is crucial, it is not the only factor influencing the choice of raw materials for biodiesel production. Equally significant is the cost of the feedstock, which ultimately impacts the economic viability of the final product.

2.2. Methodology of Conducting Experimental Research of the Engine

Experimental research was carried out in the laboratory of the Transport Engineering Faculty of Vilnius Gediminas Technical University, Lithuania. Fuels were investigated in a four-cylinder internal combustion engine with direct injection of fuel into the combustion chamber in the piston (Fig. 2.11).

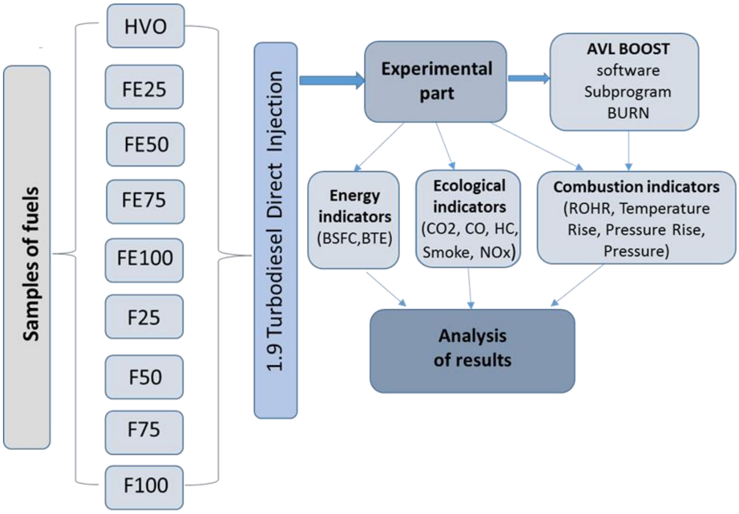

Fig. 2.11. Nomenclature of research

Engine tests to assess the operational properties of the analysed fuel compositions were carried out under established engine operating conditions at rotational speeds: n = 2000 rpm.

The primary factor in selecting the rotational speed was the operational characteristics of the injection system in the tested engine. For the proposed rotational speeds, the injection system applied the same fuel injection strategy across all fuel compositions, irrespective of changes in the set parameters. Furthermore, the engine typically operates at a similar rotational speed, with maximum torque being achieved at this speed.

Another reason for conducting experiments at this RPM was that it allowed for a broad range of load tests. At a rotational speed of 2,000 RPM, the tests were conducted at loads of 30 Nm, 60 Nm, 90 Nm, and 120 Nm. The scope of the research conducted is summarised in Table 3, which details the engine's operating parameters under the given conditions. The engine load and start of fuel injection are also shown in Table 2.3.

Throughout the research, particular attention was given to ensuring that all measurements were carried out under consistent conditions. Before starting the measurements, the engine was warmed up to ensure the cooling system temperature was maintained at 85 ºC ± 2 ºC, and the oil temperature fluctuated around 90 ºC, with an accuracy of ±2 ºC. At each stage of the research, the engine's operation was monitored by an ECU provided by the manufacturer.

Table 2.3. Engine load and start of fuel injection

Test cases	1	2	3	4
Engine speed *n*, rpm	2000	2000	2000	2000
Engine load M_B, Nm	30	60	90	120
BMEP, MPa	0.2	0.4	0.6	0.8
SOI, CAD	–4	–5	–6	–7

The engine speed was controlled by the dynamometer system. The operator set the engine crankshaft speed and torque, with both parameters stabilised within ±5 RPM and ±2 Nm accuracy. In response to the operator's commands, the dynamometer control system automatically adjusted the accelerator pedal deflection and brake load to maintain the specified operating conditions. Once the task parameters were stabilised, measurements began. During this phase, data were collected on the engine's operational parameters, combustion chamber pressure patterns, fuel and air amounts, and concentrations of exhaust gas compounds. Each experiment lasted approximately 180 seconds to gather a representative dataset.

Directly measured parameters, such as air consumption, fuel consumption, and the intake manifold air temperature, were recorded throughout the measurement period, and their values were averaged.

The tests were carried out in such a way that after the engine started operating on a given fuel composition, tests were carried out at all measurement points.

The fuel composition in the fuel tank was replaced with a new sample. During the "fuel system cleaning" operation, repeated measurement of exhaust gases was cleaned by rinsing the analysers with compressed and purified air. This operation was carried out based on a special procedure provided by the device manufacturer.

2.3. Set-up of Experimental Engine

Experimental research was carried out in the laboratory of the Transport Engineering Faculty of Vilnius Gediminas Technical University, Lithuania. Fuels were investigated in a four-cylinder internal combustion engine with direct injection of fuel into the combustion chamber in the piston (Table 2.4).

The engine's main parameters (Table 2.4) consisted of a 1900 cc turbocharged internal combustion engine with an electronic fuel injection pump. The start of the injection (SOI) was managed by the engine electronic control unit (ECU) with one injection procedure.

Fuel consumption for the tested samples was determined by weighing them on an electronic scale, CK-5000, with a precision of 1.0 g. Airflow was measured using a BOSCH HFM 5 air meter, which offered an accuracy of 2%. The turbocharger pressure was monitored by a Delta OHM HD 2304.0 pressure sensor, with an accuracy of 0.0002 MPa. Temperature was measured with a thermoelectric converter, providing an accuracy of ±1.5°C (Fig. 2.12).

Table 2.4. Engine main parameters

Specification	Parameter
Engine	1.9 L Turbodiesel Direct Injection
Number of cylinders	4
Compression ratio	19.5
Stroke	95.5 mm
Bore	79.5 mm
Maximum power output	66 kW at 4 000 rpm
Maximum torque	182 Nm at 2 000–2 500 rpm

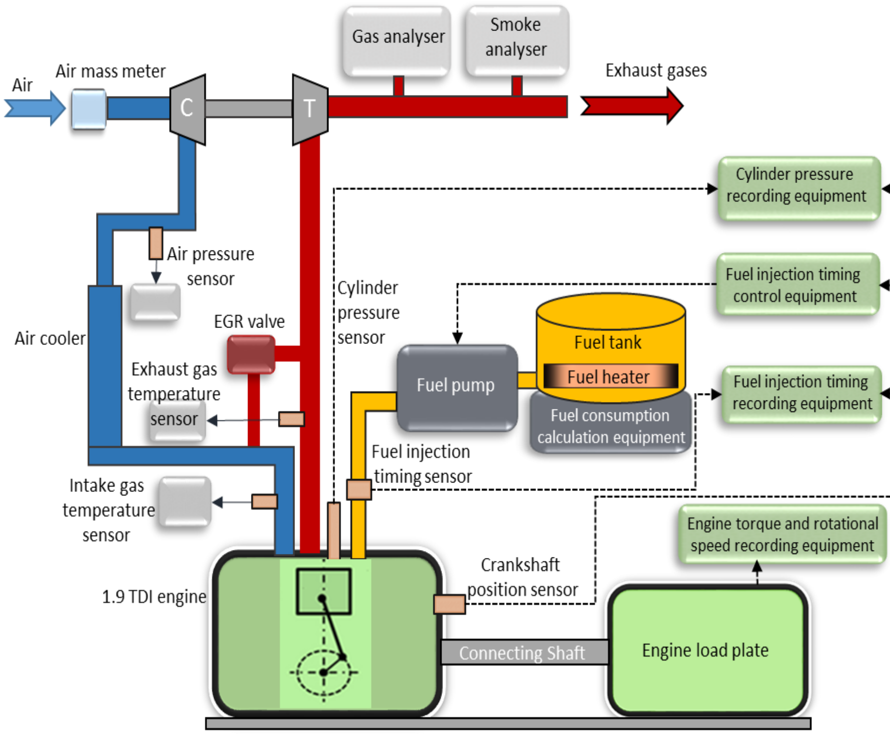

Fig. 2.12. Schematic internal combustion engine testing equipment (made by the author)

The tests were conducted on a test bench with a direct injection CI engine equipped with an electronic control unit (ECU). The composition of the exhaust gases, including CO, HC, NOx, smoke, and CO_2, was measured using the AVL DiCom 4000 instrument. This device provided high precision with results accurate to 0.01% for CO, 1 ppm for HC and NOx, 0.01 m^{-1} for smoke, and 0.1% for CO_2. The testing equipment's accuracy is outlined in Table 2.5.

Table 2.5. Accuracy of testing equipment

Parameter by vol	Measurement limits	Accuracy
CO, %	0–20	0.1
CO_2, %	0–10	0.01
HC, ppm	0–20 000	1
NOx ppm	0–5 000	1
O_2, %	0–25	0.01
λ	0–9.999	0.001
Smoke absorption coefficient, m^{-1}	0–99.99	0.01
Engine speed, rpm	250–9 990	10

Each test point was repeated five times to ensure uniformity of results and to avoid random errors. Such repeatability showed that during the test, the recording of the results was done only when the smooth operation of the engine was established.

During the experimental tests, the CO concentration was measured, and the accuracy of the table measurement was 0.01%. At low engine load (*BMEP* = 0.2 MPa) and the engine running on HVO fuel, the CO concentration was 0.01%; with F100 fuel, the CO concentration was close to 0.03%. When the engine was running at a load of BMEP = 0.8 MPa, the CO concentration of all fuels was the same – 0.01%. The pollutant concentration was recalculated into a specific emission g/kWh, and the obtained results correlate with the experimental data.

2.4. Methodology for Determining Engine Operating Parameters

Data from sensors was recorded during engine operation on a test bench. This data was used to calculate engine efficiency parameters. The analysis was based on the calculation of the filling factor, specific fuel consumption and overall engine efficiency.

Parameter analysis is fundamental when trying to compare parameters describing the engine's operation, especially in the case of using fuel compositions with diverse characteristics and properties. Moreover, the presented parameters seem to constitute a valuable criterion comparative when assessing the operational properties of the tested compositions.

The cylinder filling factor with the fresh air charge was defined as the mass of the fresh charge in the cylinder before the combustion process begins, to the mass of the fresh charge corresponding to the displacement volume of the cylinder.

The filling factor was calculated according to the formula (Heywood, 2018):

$$\eta v = \frac{m}{m_s}, \tag{2.1}$$

where: m means the actual air mass flow supplied to the engine, given working conditions [$kg \cdot h^{-1}$]; m_s is the theoretical air mass flow resulting from the engine displacement in given operating conditions [$kg \cdot h^{-1}$];

BSFC (brake-specific fuel consumption) is a parameter enabling comparison of engine performance in the case of analysis efficiency of using energy stored in various types of fuels. The value of the parameter indicates the amount of fuel the engine consumes to generate a specific power.

Specific fuel consumption was determined according to (Heywood, 2018):

$$BSFC = \frac{m_{fuel}}{2\pi NT}. \tag{2.2}$$

To determine the efficiency with which the energy supplied converted fuel into the mechanical energy of the engine crankshaft, the work ratio was determined, which was performed by the engine in a given time, to the amount of energy supplied during this time.

The beginning and the end of the fuel injection process were determined by analysing the current to the injector coil. The received signal was associated with information from the encoder and then divided into engine operating cycles. Calculation of the average load change on the injector coil from 50 consecutive cycles made it possible to accurately determine the moment of opening the injector and the time of fuel injection. Depending on the measurement method, the inertia of the injector operation was not considered hence the delay between the appearance of a pulse on the injector coil and the start of injection.

It should be noted that the inertia of the nozzle is a constant value independent of the type of fuel used; therefore, the results presented for individual fuels are based on the same error, so they do not affect the quality of the data presented.

When discussing data regarding the beginning of the introduction of individual compositions, attention was paid to the reaction of the injection system controller, which depended on the currently used fuel composition.

2.5. Methodology for Determining the Parameters of the Combustion Process Based on Pressure Waveforms

The start of fuel ignition in the cylinder was determined based on a mathematical analysis of pressure changes in the cylinder. For this purpose, the second derivative of pressure with respect to the angle was calculated crankshaft rotation, which reaches its maximum at the moment of spontaneous ignition of the fuel or slightly after it (Heywood, 2018).

The recorded pressure curves in the combustion chamber as a function of the crankshaft rotation angle were used to calculate the combustion process parameters. For each pressure curve, 50 consecutive engine operation cycles were analysed. The initial data assessment consisted of collecting the analysed data in the form of a dense graph indicator created to eliminate errors that may have occurred during signal recording. After ensuring that the data did not contain gross errors, they were divided into individual engine operation cycles.

Determination of the repeatability of the recorded pressure waveforms was carried out based on the determination of the coefficient of variation of the indicated pressure C_{Vpi} determined according to (Heywood, 2018):

$$C_{Vpi} = \frac{\sigma_{pi}}{pi}, \tag{2.3}$$

where σ_{pi} – the standard deviation of the indicated pressure [MPa]; pi – the average value of the indicated pressure [MPa].

Heat release curves were calculated based on the averaged and smoothed pressure waveform values. The calculations were based on the first equation of the first law of thermodynamics equation of state for the closed part of the cycle, from α_1=220°CA (inlet valve closing angle) to α_2=490°CA (exhaust valve opening angle).

The calculations assumed that:

- the change in system energy due to fuel injection is negligible,
- the behaviour of the gases (working body) in the cylinder can be compared to the behaviour of ideal gas.

Based on the above assumptions, the heat release rate was calculated as:

$$\frac{dQ_n}{d\alpha} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\alpha} + \frac{1}{\gamma-1} V \frac{dp}{d\alpha}, \tag{2.4}$$

where Q_n – the net amount of heat released in the combustion chamber [J]; α – the angle crankshaft rotation [°CA]; γ – the isentropic exponent; p – the pressure combustion chamber [Pa]; V – the volume of the combustion chamber [m^3].

In further calculations, a constant heat coefficient was assumed, following Heywood's (1988) constant specific heat coefficient $\gamma = c_p \cdot c_v{}^{-1}$ = 1.36, where c_p is the specific heat of the charge at constant pressure [J·kg^{-1}·K]; c_v is the specific heat of the charge at constant volume [J·kg^{-1}·K].

The calculated $dQ_n/d\alpha$ values were corrected for energy exchange heat between the cylinder walls, the head surface and the piston crown. In this way, the $dQ/d\alpha$ course was obtained, the value of which describes the course of the combustion process as follows:

$$\frac{dQ}{d\alpha} = \frac{dQ_n}{d\alpha} = \frac{dQ_S}{d\alpha}, \tag{2.5}$$

where: Q is the total amount of heat released in the combustion chamber [J]; Q_S means the amount of corrected heat released in the combustion chamber [J]; $dQ_s/d\alpha$ means flux heat exchanged with the cylinder walls, piston crown and head.

It was also assumed that the exchange of thermal energy occurs only in the form of convection between the medium and the cylinder walls, according to

$$\frac{dQ_S}{d\alpha} = H_c(\alpha) \cdot A_s(\alpha) \cdot (T(\alpha) - T_s), \tag{2.6}$$

where: $H_c(\alpha)$ – the heat transfer coefficient; $A_s(\alpha)$ – the area of the cylinder walls, piston crown and head [m^2]; T – the temperature of the cylinder, piston crown and head [K]; $T(\alpha)$ – the temperature of the charge in the cylinder for each angle CA [K]; T_s – the average temperature of the cylinder walls, piston crown and head [K].

The average temperature of the cylinder walls, piston crown and head based on data from a CI engine with similar specific power is assumed to be 393.15 K (120 º C). The surface area of $A_s(\alpha)$ walls was calculated considering the relationship kinematics of the crank system. The temperature of the charge in the cylinder for each point measurement $T(\alpha)$ was determined based on the equation of state considering the number of moles load in the cylinder calculated from air and fuel consumption data.

The heat transfer coefficient $H_c(\alpha)$ was calculated as in the Hohenberg model. The total heat released during combustion was calculated by integrating the course of heat release dQ/dα in the range from α_1 to α_2.

2.6. Methodology of Numerical Analysis of In-cylinder Pressure and Combustion Parameters Using Software for the Numerical Analysis of the Combustion Process

AVL BOOST software was used to analyse the combustion processes using various biodiesel mixtures and a CI engine. The following data was set into the AVL BURN utility: bore, stroke, compression ratio, combustion chamber volume, length of the connecting road, number of strokes, volumes of intake and exhaust manifolds, engine speed, *BMEP*, SOC, CD, mv, and LHV of fuels. The simulation of the engine operation cycles was performed using a created simulation model in AVL BOOST software. The AVL BOOST model depicted at the SOC was considered the crank angle at which the curve of the ROHR changes its value from negative to positive at the zero line cross. The ROHR becomes negative due to the heat transfer to the combustion chamber and by the evaporation of the liquid fuel droplets. The time interval between the start of liquid fuel injection and the start of combustion of the mixture is referred to as auto-ignition delay and is a significant parameter of compression ignition engine. The analysis of the AVL BOOST results of diverse mixtures co-combustion with HVO.

2.7. Methodology of Mathematical Model of Using the Regression Trees Method

To predict the engine performance and emission parameters depending on the fuel mixture composition, excess air ratio (λ), engine load (Me), and fuel injection start angle (Θ), the regression trees method was applied. The purpose of the model is to determine the influence of the main input parameters on the output indicators: brake thermal efficiency (*BTE*), specific fuel consumption (*BSFC*), carbon monoxide (CO), hydrocarbons (*HC*), nitrogen oxides (NO_x), smoke (Smoke), and carbon dioxide (CO_2) emissions.

Schematically (Fig. 2.13), the structure of this model corresponds to a multifactor system in which:

Input variables (X): fuel mixture type (*Fuel*), engine load (*Me*), excess air (λ), and injection angle (Θ);

Output variables (Y): *BTE*, *BSFC*, CO, CO_2, HC, NO_x, and Smoke.

The model is built on an array of experimental data obtained during engine tests with nine diverse biofuel blends (HVO, FAME, duck fat and their combinations). Measurements were performed at four loads (30, 60, 90, 120 Nm) and diverse ranges of λ values.

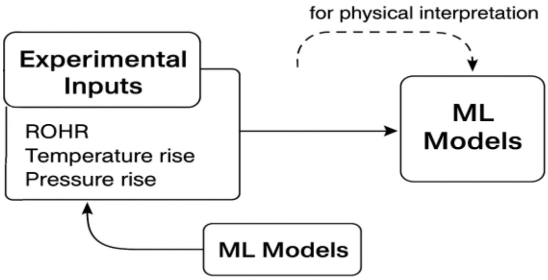

Fig. 2.13. Schematic view of the integrity of ROHR, temperature rise, pressure rise, and in-cylinder pressure in creating regression trees and Random Forests (made by the author)

The basis of the modelling is the CART algorithm (Breiman et al., 1984), in which the data set is iteratively divided into subsets according to criteria that minimise the sum of squared deviations between the observed and predicted values. Suppose we have a training set:

$$D = \{(x_i, y_i)\}_{i=1}^{n}, x_i \in R^p, y_i \in R, \quad (2.7)$$

where x_i is a vector describing the fuel composition, λ, load, and Θ, and y_i is a specific output parameter.

The task of the model is to divide the space X into disjoint regions R_1, R_2, ..., R_M, in which the forecast value will be a constant:

$$f(x) = \sum_{m=1}^{M} c_m \cdot 1_{\{x \in R_m\}}, \quad (2.8)$$

where cm=mean$\{yi|xi∈Rm\}$ is the prediction for each region. The optimal partitioning is performed by minimising the sum of squared residuals:

$$\min_{\{R_m\},\{c_m\}} \sum_{m=1}^{M} \sum_{x_i \in R_m} (y_i - c_m)^2, \quad (2.9)$$

However, due to computational complexity, hierarchical optimisation is used in practice – the tree is grown from the top, choosing the best splitting criterion (e.g., Gini or MSE) at each step and stopping according to stopping rules (maximum depth, minimum leaf sample, etc.).

The dependences of Smoke, *BSFC*, *BTE*, CO, CO_2, O_2, HC, and NO_x on engine parameters Fuel, EGR, Me, Θ, and λ are presented below. Decision trees were used to develop predictive models.

Decision trees are a family of machine-learning methods that can be used for both classification and regression tasks. The presented case used the regression trees to model the influence that Fuel, Me, Θ, and λss had on Smoke, *BSFC*, *BTE*,

CO, CO_2, HC, and NO_x. In this research, the CART (Breiman et al., 1984) algorithm has been used to determine the dependencies.

Let $D = \{(x_i, y_i)\}_{1 \le i \le n}$ be a training set, where $x_i \in \mathbb{R}^p$, $y_i \in \mathbb{R}$.

CART splits the training set into separate regions $R_1, R_2, \dots, R_m$, where $R_i \cap R_j = \emptyset$ for $i \neq j$, $1 \le i, j \le m$. The data are partitioned according to specific rules. Based on this partition, the response variable is constant for the region and can be presented as follows:

$$f(x) = \sum_{j=1}^{m} c_j \, I_{R_j}(x), \tag{2.10}$$

where

$$I_R(x) = \begin{cases} 1, & for \quad x \in R, \\ 0, & for \quad x \notin R, \end{cases} \tag{2.11}$$

and

$$c_j = \frac{1}{n_j} \sum_{x_i \in R_j} y_i, \tag{2.12}$$

$$n_j = \#\{x : x \in R_j\} \tag{2.13}$$

and $n_1 + n_2 + \cdots + n_m = n$. The best partition corresponds to minimising the sum of square differences between real values of output variables and its predictions are generally computationally infeasible. The auxiliary criteria are used to stop tree growth (growth of the number of separated regions) and to avoid overfitting the model. To create the tree, the following task is solved:

$$min_{(R_1, R_2, \dots, R_m)} \sum_{i=1}^{n} \big(y_i - f(x_i)\big)^2 + \alpha m. \tag{2.14}$$

The parameter $\alpha \ge 0$ governs the trade-off between the number of separated regions (leaves, terminal nodes in the tree) and the goodness of fit to the data.

To create the prediction of ecological and energetic models are defined (Eq. 2.7) for each feature, e.g., Smoke, *BSFC*, *BTE*, CO, CO_2, HC, and NO_x.

The Random Forest method is one of the most effective decision models for forecasting problems, especially when analysing complex, multifactorial processes, such as internal combustion engine emissions or energy indicators. Although the generalised forecasting accuracy indicators of this method were presented in the fourth chapter, this is not enough to fully explain the decision-making mechanism of the model and the main factors important to it.

The Random Forest method, in contrast to a single decision tree, works as an ensemble of many individual regression trees. Each tree is trained with a different, randomly selected data sample (using the bagging technique), and only a part of the features is used in each branching step. In this way, the trees become poorly correlated with each other, and the final forecast is obtained as the average of all trees. Such a method not only increases the forecasting accuracy but also significantly reduces the risk of the model overfitting, i.e. becoming too adapted to the specifics of the training data.

To examine which factors had the greatest influence on the decisions of the Random Forest model, a feature importance analysis was performed (Fig. 2.14). The results showed that the excess air ratio (λ) had the greatest influence on the model's predictions, accounting for about 42% of the total weight. In second place was the type of fuel mixture (33%), while the engine load and injection start angle had a lower weight – 18% and 7%, respectively. This indicates that the air-fuel ratio and fuel chemical composition have the greatest influence on emissions and efficiency, while engine operating parameters are significant but to a lesser extent.

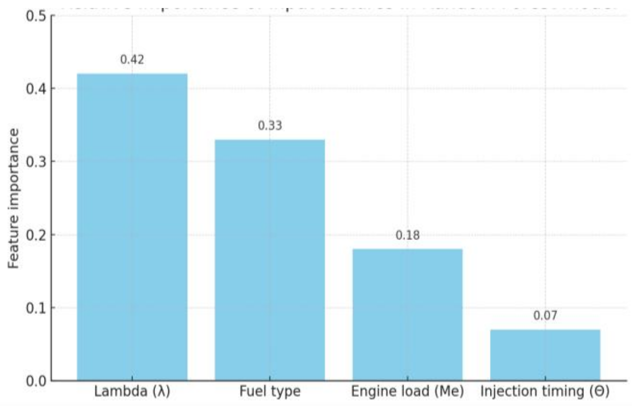

Fig. 2.14. Relative importance of input features in the Random Forest model

To better understand how the Random Forest model makes decisions, one example of an individual tree structure was analysed. Let's say we are predicting NO_x emissions at a given load (90 Nm) and fuel mixture (e.g., FE50). One tree analyses these parameters as follows:

First branching level: is $\lambda < 2.8$? If yes, go in one direction (e.g., lower NO_x emissions), if not, go in the other;

Second level: if $\lambda \geq 2.8$, check the fuel type (e.g., HVO or FAME dominance);

Third level: depending on the fuel type, evaluate the load or injection angle;

Finally, reach the terminal node (leaf), which contains the average NO_x emission value based on the data subset that meets these conditions.

Since each tree analyses a diverse combination of features and uses a diverse data subset, the final Random Forest prediction is obtained by summing the results of all trees and dividing by their number – this way, a stabilised prediction is received that is less sensitive to data noise or random anomalies.

This principle of operation helps to understand not only what the model predicts but also why. For example, the model can predict higher NO_x values when using FAME-containing fuels, and λ is above 3.5, and this is visible from the tree structure of decisions, as branches for such conditions lead to leaves with higher emissions.

It is important to note that although Random Forest does not have a single common “visible” decision logic like a separate tree, the decisions of each tree can be analysed separately, and the analysis of the importance of features allows to reveal a general trend in the whole model. This ensures a high level of interpretability of the model, which is especially important in engineering applications when decisions must be based on technical reasons and not just statistical predictions.

In summary, the supplemented analysis explains how the Random Forest model processes the input data, how it reaches the predictions and why certain combinations of variables lead to certain results. This explanation, together with visual diagrams (importance of features and structure of tree branches), allows for the strengthening of the methodological validity and transparency of the model.

To evaluate the influence of the number of trees on model performance, a comparative analysis was performed using Random Forest models with 10, 50, and 500 trees. The results are summarised in Table 2.6, illustrating the trade-off between accuracy and computational time.

Table 2.6. Random Forest tree count comparison

Number of Trees	Pseudo RÂ²	RMSE (g/kWh)	MAPE (%)	Training Time (s)
10	0.924	3.5	6.4	4.2
50	0.954	3.2	5.9	9.8
500	0.957	3.1	5.7	57.3

Random Forest contains 10 trees. Only three predictors were chosen randomly to create a tree. To compare a tree and a Random Forest, the pseudo-R-squared coefficient has been used,

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}, \quad (2.15)$$

where y_i – denotes an observed value, $\hat{y}_i$ – predicted values for the case $i = 1,2,\ldots,n$, $\bar{y}$ – mean value of the output variable.

The presented results demonstrate that the regression tree method enables accurate prediction of engine performance and emission parameters based on the composition of biofuel blends and engine operating conditions.

2.8. Evaluation of Residual Errors and Model Deviations

The discrepancies between actual and forecast values were used to analyse the differences:

– Mean squared error

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2. \quad (2.16)$$

– Root mean squared error

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}. \quad (2.17)$$

– Mean absolute error

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\, y_i - \hat{y}_i|. \quad (2.18)$$

– Mean absolute percentage error

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left\|\frac{y_i - \hat{y}_i}{y_i}\right\|. \quad (2.19)$$

The statistical indicators presented above provide an objective evaluation of modelling errors and the model's suitability for analysing the impact of biofuels on engine parameters.

2.9. Conclusions of the Second Chapter

The research in the Second Chapter was devoted to the selection of the most suitable biofuel blends, the development of their research methodology and the justification of the application of a mathematical model based on the regression trees method. The obtained conclusions allow for the precise definition of further experimental and modelling steps to evaluate the influence of fuel blends on the operating parameters of a compression ignition engine.

1. Physical, chemical and combustion characteristics of the chosen fuel blends, e.g., hydrotreated vegetable oils (HVO), non-edible fats derived

from animals, and fatty acid methyl esters (FAME), were assessed. According to the research, the properties of these fuel blends differ from those of conventional diesel, and their impact on engine operation could rely on the mixture composition and injection technique.

2. A methodology for fuel blend research was developed, which defines the stages of experimental tests, measurement equipment and data analysis methods. The methodology ensures that it will be possible to reliably determine the influence of fuel on changes in cylinder pressure, thermal energy conversion, fuel consumption and exhaust emissions.
3. The regression trees method was applied to create a mathematical model that would allow the prediction of the impact of fuel mixtures on engine operating parameters and emission levels. Application of the method will help identify the most significant factors affecting engine efficiency and pollution and form a structural model of the influence of fuel mixtures.
4. The mathematical model, based on the regression trees method, allows for predicting the impact of fuel mixture properties on engine operating processes without the need to conduct large-scale experimental tests. This allows for reducing the costs of experimental research and optimising the selection of fuel mixtures even before their physical testing.

3

Numerical and Experimental Research of the Biodiesel Blends

This chapter delineates an experimental investigation into biodiesel blends and their implications for the combustion process, energy efficiency, and ecological impact of a compression ignition engine. The research seeks to identify a suitable alternative to traditional diesel fuel by evaluating various fuel combinations that include hydrotreated vegetable oils (HVO), fatty acid methyl esters (FAME), and non-food fats derived from animals.

Supported by AVL BOOST simulations, the chapter offers an in-cylinder pressure analysis performed using experimental data to evaluate the impact of various fuel mixes on combustion dynamics. The efficiency of key performance indicators, including brake thermal efficiency (*BTE*), brake-specific fuel consumption (*BSFC*), and emissions of CO, HC, and NO_x is investigated to evaluate diverse biodiesel blends. The collected data offer insightful analysis of how best to maximise fuel compositions for lower emissions and higher engine efficiency. Two articles by the author have been published on the topic of the chapter (Shepel et al., 2021, 2022).

3.1. Numerical Analysis of In-cylinder Pressure and Combustion Parameters Using Software for the Numerical Analysis of the Combustion Process

During the simulation at a brake mean effective pressure (*BMEP*) of 0.4 MPa, the start of fuel injection timing (SOI) was kept constant at 5 CAD for all fuel types. The start of combustion (SOC) and ignition delay (ID) for each fuel type are shown in Figure 3.1. The engine crankshaft speed was set at 2,000 rpm, with the variable parameters being engine load and fuel type.

3.1.1. Numerical Simulation and Analysis of Engine Work Cycle as a Fuel Using Hydrotreated Vegetable Oil and Fatty Acid Methyl Ester Fuel Blends

During the simulation at a brake mean effective pressure (*BMEP*) of 0.4 MPa, the start of fuel injection timing (SOI) was kept constant at 5 CAD for all fuel types. The start of combustion (SOC) and ignition delay (ID) for each fuel type are shown in Figure 3.1. The engine crankshaft speed was set at 2,000 rpm, with the variable parameters being engine load and fuel type.

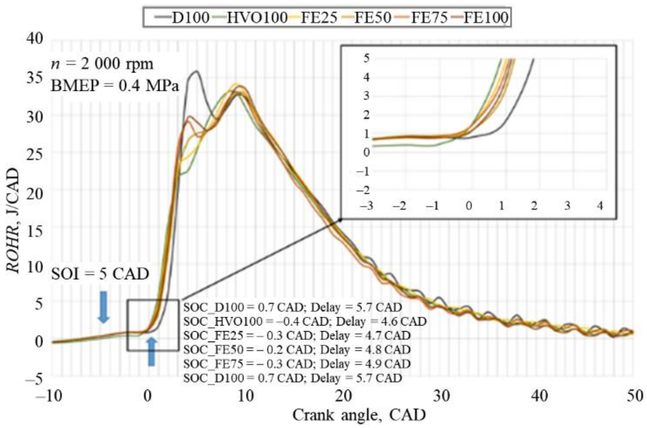

Fig. 3.1. Heat release rate in the cylinder depending on the CAD

Upon comparing various fuel mixtures, it was observed that HVO (hydrotreated vegetable oil) had an earlier start of combustion than the other fuels, even with the same injection timing. This indicates that HVO has the shortest ignition delay period. The experimental data showed that the ignition delay for HVO and its mixtures was shorter than that of diesel, which can be attributed to their higher cetane number, helping to reduce the ignition delay (Uyumaz, 2018).

At 4 CAD, the heat release rate for HVO was approximately 34% lower than that for D100 (pure diesel), indicating a reduction in the peak heat release rate compared to diesel fuel. Diesel fuel, on the other hand, exhibited a longer ignition delay due to its higher viscosity, which results in slower evaporation and atomisation processes, thus increasing the ignition delay.

The ignition delay was also found to depend on the number of carbon atoms in the molecules of the fuel blends. For example, the experimental mixture with FE100 (pure duck fat) had fewer carbon atoms than diesel, resulting in a shorter ignition delay. The heat release rate at 4 CAD was approximately 29% lower for FE25, 23% for FE50, 15% for FE75, and 14% for FE100 compared to pure diesel. This is further evidenced by the lowest maximum combustion rates observed during rapid combustion for these mixtures.

As the ester concentration in the mixture increased, there was a noticeable trend of decreasing maximum combustion rates during fast combustion. The oxygen content in the biodiesel mixtures improved the fuel–air mixing rate in the cylinder compared to diesel fuel, contributing to an extended combustion duration. Additionally, biodiesel's slower vaporisation compared to diesel fuel resulted in a smaller premixed combustion phase, which correlates with the viscosity and density of the fuels. Furthermore, the cetane number of the fuel influenced the SOC timing (Othman et al., 2017).

The lower viscosity of HVO compared to diesel fuel contributes to improved mixing characteristics during the premixed phase. This allows HVO to evaporate more quickly and mix with the ambient air more effectively than diesel fuel. Additionally, as a straight-chain paraffinic hydrocarbon, HVO is more easily degraded than diesel fuel, facilitating better atomisation, vaporisation, and mixing with the air in the combustion chamber (Kegl, 2006). A similar trend was observed in blends containing HVO. When analysing the third combustion phase (diffuse combustion), it was evident that HVO100 reached its peak heat release earlier than other fuels, which can be attributed to the earlier start of combustion. Diesel fuel, in contrast, exhibited the lowest maximum combustion rate during the mixing-controlled combustion phase, as a larger proportion of the fuel burned during the first combustion phase (Marasri et al., 2019).

At 9 CAD, the heat release rate for HVO was approximately 1% higher than for D100 (pure diesel). Furthermore, for ester mixtures, the heat release was ~3% higher for FE100 compared to diesel fuel, and the trend was ~4% for FE25, ~1% for FE50, and ~1% for FE75.

Temperature rise trends (Fig. 3.2) closely followed those of pressure rise. Diesel fuel reached the highest temperature rise at 53 K/deg at 4 CAD, which occurred later than for other fuels. HVO showed a temperature rise of 40 K/deg, approximately 24% lower than diesel, with ester mixtures showing similar trends ranging from 15% lower for FE100 (4 CAD) to 29% lower for FE50 (8 CAD). The later start of combustion explains the reduced temperature rise, but the more intense combustion during the premixed phase leads to a higher rate of nitrogen oxide formation in the cylinder. Consequently, all fuel mixtures produced lower nitrogen oxide rates during the premixed phase compared to diesel. In the third combustion phase, the diffuse heat release was almost identical across all fuel mixtures.

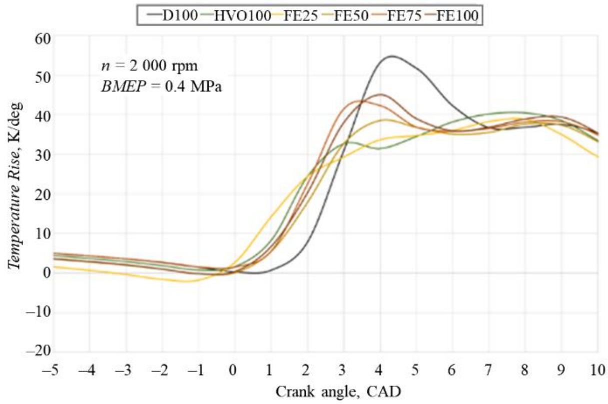

Fig. 3.2. Dependence of the temperature rise in the cylinder on the crank angle degree

The pressure rise graph revealed a pattern similar to that of the temperature rise. The start of combustion and the subsequent sharp rise in pressure were visible. When using pure HVO, the pressure rise was about 47% lower at 3 CAD compared to diesel fuel, while for FE100, it was approximately 25% lower at the same point. For other ester blends, such as FE25 (2 CAD) and FE50 (3 CAD), the pressure rise was about 38% lower compared to diesel. For FE75, the pressure rise was about 22% lower at 3 CAD compared to diesel. These results confirm that the maximum pressure rise occurs during the premixed combustion phase, which is typical of diesel fuel due to its longer ignition delay and the accumulation of more fuel in the cylinder (Kumar & Jaikumar, 2014). From a practical perspective, the highest peak pressure rise correlates with the highest shock loads on the cylinder-piston group and the highest noise levels, which is characteristic of diesel fuel.

As seen in Figure 3.3, the pressure differences between the mixtures ranged from 0.02% to 1.4%. HVO showed a decrease of ~0.3% at 10 CAD compared to diesel fuel at 9 CAD, while for FE25, FE50, FE75, and FE100, the differences were ~0.7% at 9 CAD, 1% at 10 CAD, 0.02% at 10 CAD, and 1.4% at 10 CAD, respectively.

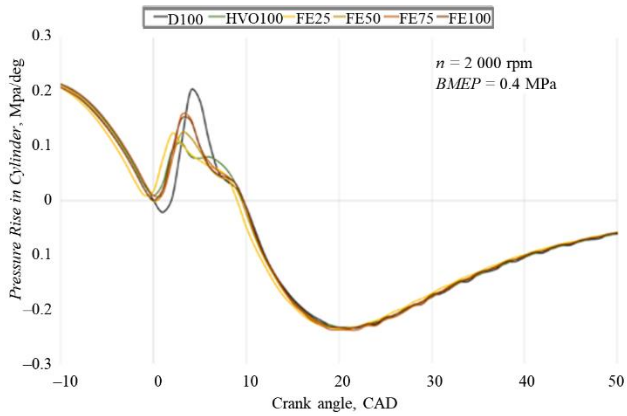

Fig. 3.3. Pressure rise in the cylinder depending on the CAD

During the experiment, it was noted that temperature and pressure were very similar during the compression stroke for all fuels. However, after the start of combustion, the pressure and temperature were differentiated between −0.4 and 0.7 CAD. The pressure graph provides valuable insight, including the rate of diffuse heat release, which is essential for understanding the combustion characteristics of each fuel.

The combustion process is influenced by the structure and size of fuel droplets, the molecular composition of hydrocarbons, the types of hydrocarbon compounds, and the intermolecular bonds (Topare et al., 2022). These fuel characteristics significantly impact both the qualitative and quantitative aspects of combustion, as well as the oxidation reactions of hydrocarbon compounds within the combustion zone (Jayaprabakar & Karthikeyan, 2016).

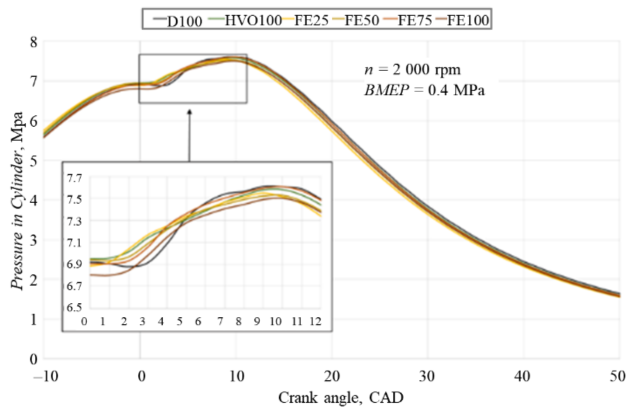

Fig. 3.4. Pressure rise in the cylinder depending on the CAD

Figure 3.4 shows that, as pressure increases between mixtures, the difference observed ranged from 0.02% to 1.4%. For HVO, the decrease was around 0.3% at 10 CAD compared to fossil fuel (9 CAD), while for FE25, FE50, FE75, and FE100, the differences were 0.7% (9 CAD), 1% (10 CAD), 0.02% (10 CAD), and 1.4% (10 CAD), respectively.

During the experiment, it was observed that temperature and pressure during the compression stroke were similar for all fuels. However, after the start of combustion, they began to differ between - 0.4 and 0.7 CAD. The pressure graph provides crucial information from which other key parameters, including the rate of diffuse heat release, can be calculated.

3.1.2. Numerical Simulation and Analysis of Engine Work Cycle as a Fuel Using Hydrotreated Vegetable Oil and Duck Fat Fuel Blends

The start of combustion (SOC) and ignition delay (ID) for various fuels at an engine load of *BMEP* = 0.8 MPa are shown in Figure 3.4. The experimental data reveal that the start of injection (SOI) is constant at 7 CAD before the top dead centre (bTDC) for all fuels. The ignition delay phase for the different fuels increases in the following order: HVO100, F25, F50, F75, F100, and D100. The shorter ignition delay phase observed for biofuel mixtures compared to diesel is attributed to their higher cetane number (Syed et al., 2017). Additionally, Sivalakshmi and Balusamy (2012) explained that low molecular weight gaseous compounds derived from biodiesel during injection into the engine cylinder at high temperatures tend to ignite sooner, thereby reducing the ignition delay and accelerating the onset of biofuel combustion.

At a high engine load (*BMEP* = 0.8 MPa), the amount of fuel consumed follows the order HVO100, D100, F25, F50, F75, and F100. This trend is due to the lower calorific value of the mixtures compared to diesel (Table 2.1 (b)). The increase in fuel mass leads to a higher temperature rise in the combustion chamber, as shown in Figure 3.5. The addition of animal fat to the HVO increases the mass of fuel injected, which in turn delays ignition due to the greater heat required for the evaporation of fuel droplets.

Furthermore, biofuels with shorter ignition delays burn less fuel during the premixed combustion phase and more during the mixing-controlled combustion phase. This shift is particularly noticeable for HVO compared to diesel fuel, as a shorter ignition delay reduces the amount of fuel burned during the premixed combustion phase, thereby increasing the proportion burned in the diffusion combustion phase. A key factor influencing these differences is the viscosity of the fuels.

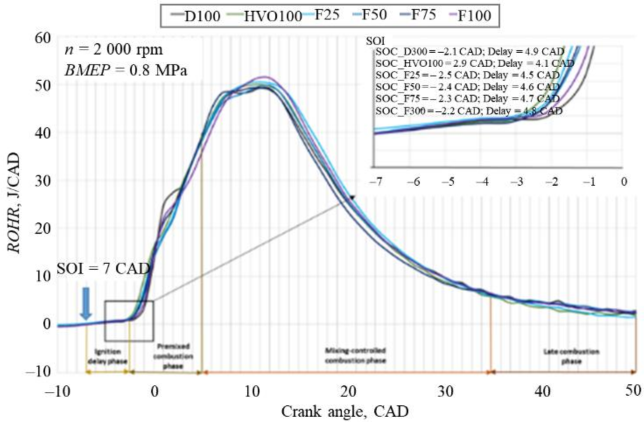

Fig. 3.5. Heat release rate in the cylinder depending on the CAD

As shown in Table 2.1, the viscosity of HVO is 20% lower than that of diesel fuel. Adding duck fat to the fuel mixture significantly increases the fuel viscosity, which, in turn, lengthens the ignition delay. Thus, a clear correlation between fuel viscosity and ignition delay is observed. According to the data in Figure 3.6, the first peak in the rate of heat release (ROHR), corresponding to the premixed combustion phase, is about 20–25% lower for HVO compared to diesel fuel, and this peak occurs 1 degree earlier. This can be explained by the reduced ignition delay phase, which results in a smaller amount of fuel entering the cylinder during that period. The addition of duck fat to the fuel increases the ignition delay phase and intensifies combustion during the premixed phase, leading to an increase in the fuel burned during this stage.

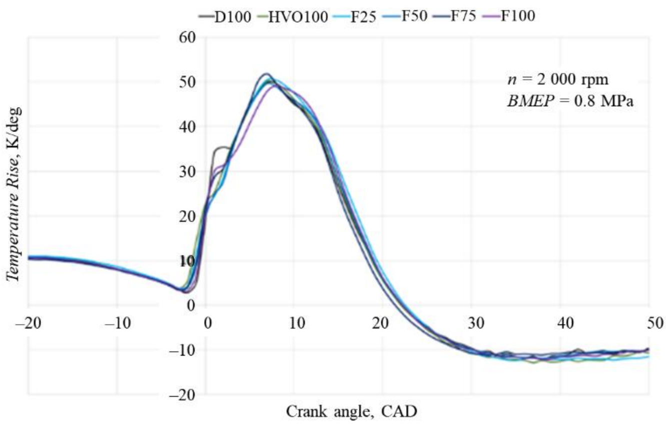

Fig. 3.6. Dependence of the temperature rise in the cylinder on the CAD

The increase in fat content causes a higher ROHR in the mixing-controlled combustion phase. For instance, for the F100 mixture, the maximum ROHR during this phase is the highest, indicating a stronger combustion intensity. As the percentage of fat increases, the ignition delay phase grows longer, resulting in a higher peak rate of heat release. This trend is particularly evident with the F100 mixture, where the ignition delay phase is longer than for HVO or other mixtures.

The lower ignition delay phase observed for pure HVO and mixtures with pure fat, compared to diesel, may be attributed to the higher cetane number of HVO (Singer et al., 2015). A higher cetane number, associated with longer unbranched carbon chains, leads to shorter ignition times and lower levels of "harmful" aromatic hydrocarbons (Rimkus et al., 2021). During the combustion phase at 2 CAD, the heat release rate for HVO is approximately 21% lower than for D100. Additionally, the ignition delay phase is influenced by the viscosity and density of the test mixture samples. Since HVO has a lower viscosity than diesel fuel, it facilitates better mixing in the premix phase. The paraffinic hydrocarbons in HVO also decompose and evaporate faster, improving the mixing with ambient air compared to diesel fuel.

The addition of fat to the HVO mixture increases the viscosity, which results in a longer ignition delay phase and a higher ROHR during the premixed combustion phase. This effect becomes more pronounced with higher fat concentrations in the fuel. The differences in heat release rates are evident when comparing the variance in ROHR for the various mixtures: F25 shows a 24% difference, F50 shows 26%, F75 shows 14%, and F100 shows 10% compared to diesel fuel.

In the mixing-controlled combustion phase, the maximum heat release rate for D100 (at 10–12 CAD) is approximately 1.2% lower than for HVO100 (at 11 CAD). When comparing the pure fat mixtures, the maximum heat release for F100 is about 4.5% higher than for fossil fuel, while for F25, F50, and F75, the differences are 2.5%, 0.7%, and 0.8%, respectively.

The maximum temperature rise in the premixed combustion phase (Fig. 3.6) is observed for diesel fuel at around 34 K/deg. Compared to diesel, HVO has a temperature rise that is 26% lower. The temperature rises for HVO mixtures with pure fat follow a similar trend, with F25, F50, F75, and F100 showing smaller temperature increases compared to diesel by 28%, 27%, 16%, and 12%, respectively. This difference is likely due to factors such as higher viscosity, delayed combustion start, extended fuel injection, higher injection pressure, and lower heating value. The more intense combustion in the premixed phase also influences the formation of nitrogen oxides (NO_x), with higher NOx formation rates observed for diesel compared to other mixtures.

As shown in Figure 3.7, when testing diesel fuel, the pressure rise at 2 CAD (premixed combustion phase) is about 28% higher than for HVO. Similar results are seen for other blends, with F25, F50, F75, and F100 showing reductions in pressure rise of about 20%, 34%, 26%, and 14%, respectively, compared to diesel fuel. This pressure rise correlates with ROHR and the temperature rise in the cylinder. During the mixing-controlled combustion phase, the lowest pressure rise is observed with the pure fat mixture F100, which is likely due to the decreased fuel injection rate caused by the high viscosity of the fuel.

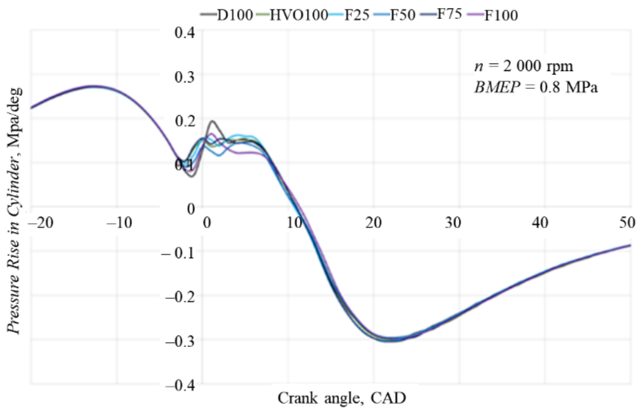

Fig. 3.7. Pressure rise in the cylinder depending on the CAD

Figure 3.8 shows the pressure in the cylinder at *BMEP* = 0.8 MPa, where no significant pressure differences are observed between the fuel mixtures. This is because the start of fuel injection is the same for all fuels (SOI = 7 BTDC), and there are no substantial differences in fuel properties or engine load.

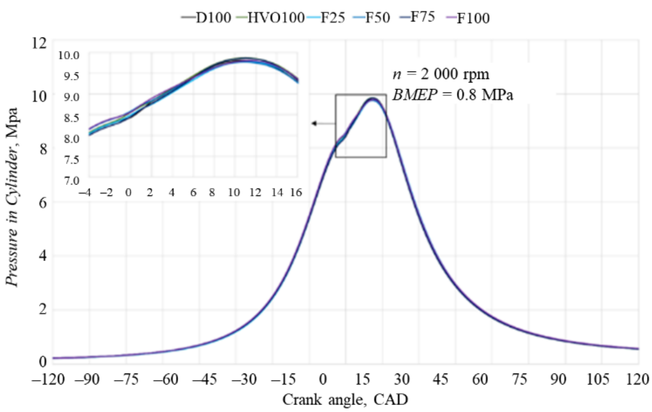

Fig. 3.8. Pressure in the cylinder depending on the CAD23

However, after analysing the combustion process using these pressures, more noticeable differences were observed in various combustion indicators (Fig. 3.5–3.7) when the different fuel mixtures were used. Diesel fuel resulted in the highest maximum cylinder pressures, which were associated with the longest ignition delay phase, as well as the highest maximum ROHR, temperature rise, and pressure rise during the premixed combustion phase. The use of HVO and fat mixtures led to a slight reduction in the maximum cylinder pressure.

3.2. Ecological Indicators Fuel Blends of Hydrotreated Vegetable Oil and Fatty Acid Methyl Esters and Duck Fat

Carbon dioxide (CO_2) emissions decreased for all fuel types as the load increased, as shown in Figure 3.9. At medium load (*BMEP* = 0.4 MPa), the CO_2 emissions of blends containing FE75 and FE100 were approximately 2% and 3% higher, respectively, compared to diesel. These higher CO_2 emissions in the mixtures are attributed to the greater oxygen and carbon content of the tested fuels, in contrast to pure diesel fuel (Fig. 3.9 (a)).

For HVO100, carbon dioxide (CO_2) emissions were approximately 5% lower than those of diesel fuel. Additionally, CO_2 emissions for FE25 and FE50 blends were reduced by around 4% and 2%, respectively. This reduction in CO_2 emissions is largely attributed to the higher hydrogen-to-carbon (H/C) ratio of these fuels, which promotes more complete combustion (Table 2.2). HVO, with its higher H/C ratio (0.1520% / 0.8480%), exhibited the most significant reduction in CO_2 emissions compared to the mixtures and diesel fuel.

Specific CO_2 emissions, as shown in Figure 3.9, decreased for all fuel samples as the load increased. At a *BMEP* of 0.8 MPa, CO_2 emissions for HVO were approximately 4.6% lower than those for fossil fuels. A CO_2 reduction was also observed for F25 and F50, with emissions decreasing by 3.2% and 1.7%, respectively. However, for F75 and F100, CO_2 emissions were 0.9% and 2.1% higher on average compared to diesel fuel. These higher CO_2 emissions in the mixtures are attributed to their higher carbon and oxygen content, as well as increased fuel consumption.

During testing, it was found that blends with a smaller carbon-to-hydrogen (C/H) ratio contributed the most to CO_2 reduction (Table 2.2). HVO, with its lower C/H ratio (5.7%), exhibited the greatest reduction in CO_2 emissions compared to the mixtures and diesel fuel. A decrease in CO_2 emissions was also associated with lower fuel consumption. The slower combustion process in blends such as F25 and F50, likely due to insufficient air in the mixture, further reduced CO_2

production compared to D100, F75, and F100. The combustion rate had little effect on CO_2 emissions, as factors such as specific fuel consumption and the carbon content of the fuel were more significant.

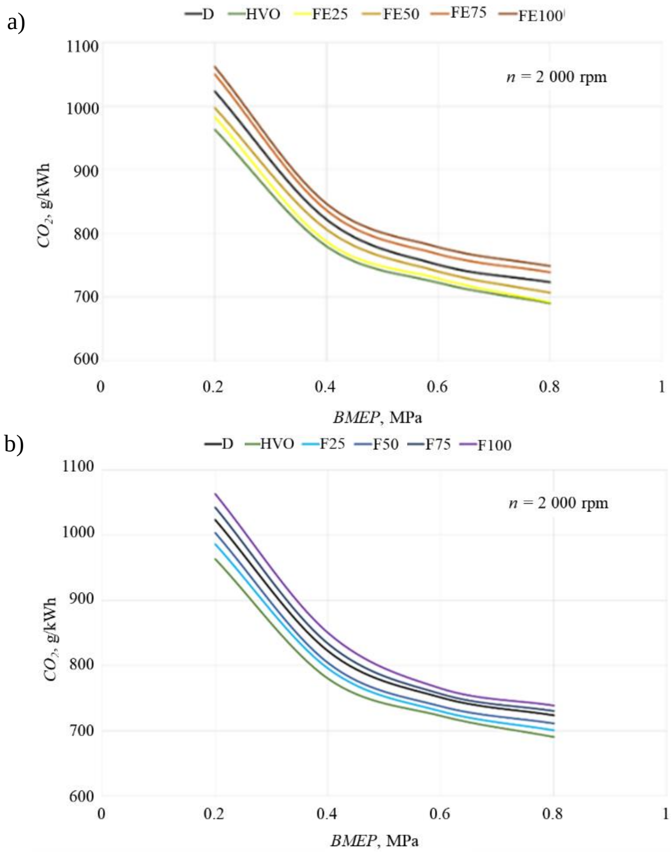

Fig. 3.9. Dependence of carbon dioxide emissions on the load

The level of specific CO_2 emissions from diesel exhaust gases (Fig. 3.9) at the same load is directly proportional to both specific fuel consumption and the carbon content of the fuel. As seen in Table 2, increasing the fat concentration (duck fat) in the fuel mixture decreased the carbon content of the fuel but also lowered the specific heat of combustion. This reduction in the specific heat of combustion resulted in an increase in specific fuel consumption. Thus, the effect of these factors on CO_2 emissions is opposing. The final impact of the fuel on CO_2 emissions depends on which of these two factors – carbon content or fuel consumption – dominates.

For F75 and F100 fuels, the increase in specific fuel consumption (by an average of 12–18%) outweighed the 7–9% reduction in carbon content, resulting in an increase in specific CO_2 emissions compared to diesel fuel across all engine loads. In contrast, for HVO, F25, and F50 fuels, the decrease in carbon content (by 7%, 5%, and 3%, respectively) was the dominant factor, leading to a reduction in specific CO_2 emissions across the entire load range.

During combustion, the fuel is initially converted into CO and then oxidised to CO_2. This oxidation process can be accelerated by the presence of hydrogen-containing substances, such as water. Ester blends are oxygenated fuels, and the additional oxygen molecules help achieve more complete combustion, resulting in lower CO emissions (Satputaley et al., 2017; Behçet et al., 2015; Singh et al., 2015). Higher cylinder temperatures and adequate oxygen content in the fuel also aid in reducing CO emissions. As shown in Figure 3.10a, CO emissions for HVO100 at medium load were approximately 5% lower than for D100 but 15% higher than for FE100. The lower CO emissions for HVO are attributed to its reduced ignition delay, which extends combustion time and promotes more complete oxidation of CO. Diesel fuel, with its higher C/H ratio, results in higher CO emissions than HVO and the mixtures.

Forester blends, CO emissions were also higher compared to fossil fuel. Specifically, for FE25, FE50, and FE75, CO emissions were approximately 6%, 7%, and 8% higher, respectively.

As the concentration of fat (duck fat) in the mixture increases, the viscosity of the fuel rises while the specific net calorific value decreases (Table 2.1 (b)). This decrease in calorific value leads to an increase in fuel supply per cycle, which in turn raises the maximum fuel injection pressure. This increase in injection pressure reduces the average diameter of the fuel droplets, improving the distribution of fuel throughout the combustion chamber. This improved fuel distribution helps reduce local oxygen deficiencies, promoting more complete combustion and reducing CO emissions. However, if the fuel viscosity increases too much, this benefit may diminish, and pollutant emissions could rise instead.

At low load (*BMEP* = 0.2 MPa), CO emissions for F100 were approximately 160% higher compared to fossil diesel fuel (Fig. 3.10 (b)). This suggests incomplete combustion of the pure fat-based fuel. The low cycle rate results in lower pressure, which leads to the formation of larger, high-density fuel droplets with greater viscosity, causing inefficient combustion. A similar trend was observed for all HVO and fat blends. As the load increased to *BMEP* = 0.4 MPa, the maximum difference in CO emissions between F100 and diesel fuel was reduced to about 63%. At higher loads (*BMEP* = 0.6 MPa and *BMEP* = 0.8 MPa), CO emissions for all fuel mixtures became comparable.

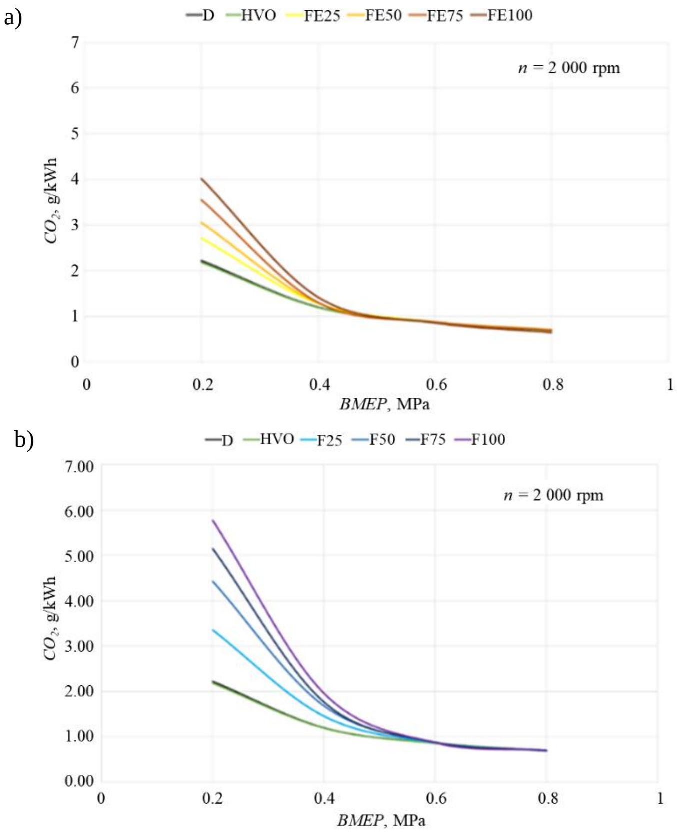

Fig. 3.10. Dependence of carbon monoxide emissions on the load

At *BMEP* = 0.4 MPa, a noticeable reduction in HC emissions was observed. The emission trends for mixtures with intermediate ester concentrations were found to lie between those of HVO100 and diesel fuel. This can be explained by the increase in combustion temperature and improved fuel atomisation as load increases, which enhances fuel combustion efficiency. Additionally, the presence of fatty acids in the mixtures may promote more complete combustion, as the oxygen molecules in the fuel droplets aid in the combustion process. Some unburned hydrocarbons may still be produced due to poor air-fuel mixing or incomplete combustion before or during the combustion process. Satputaley et al. (2017) noted that higher cetane numbers, such as those found in methyl ester, lead to a decrease in HC emissions compared to diesel fuel under all load conditions.

As shown in Figure 3.11, all fuel mixtures exhibited lower HC emissions than diesel fuel. For instance, FE100 had HC emissions around 14% lower than D100, while HVO showed a 37% reduction. Similar trends were observed for the other mixtures. FE25 had HC emissions approximately 33% lower, FE50 had 30% lower emissions, and FE75 had 25% lower emissions compared to diesel fuel. Conversely, oxygen-free diesel exhibited the highest levels of hydrocarbon emissions.

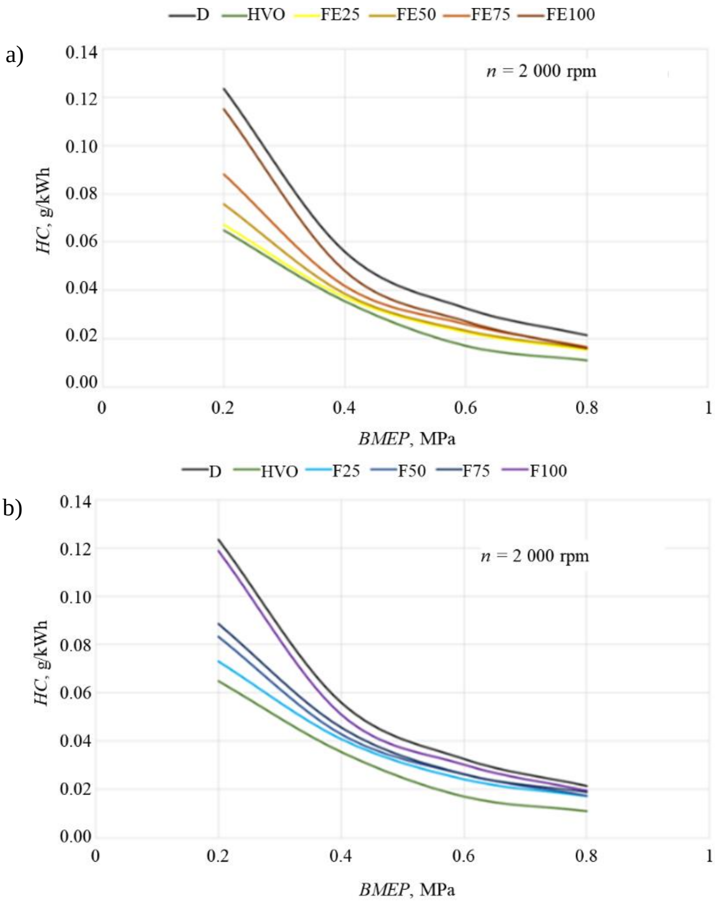

Fig. 3.11. Dependence of hydrocarbon emissions on the load

As shown in Figure 3.11, at all loads, the fuel mixtures exhibit lower HC emissions compared to mineral diesel fuel, with HVO showing the lowest levels. The high cetane number of HVO, and consequently the blends containing HVO, reduces hydrocarbon exhaust emissions compared to diesel fuel (Bello et al., 2012). This is primarily due to the low aromatic compound content in these fuel mixtures. Additionally, it is important to note that fuel mixtures containing duck fat have some oxygen within their structure, which improves the combustion process and further reduces HC emissions when these blends are used.

For example, at *BMEP* = 0.2 MPa, F100 has approximately 4% lower HC emissions compared to diesel (D), while HVO reduces HC emissions by around 47% compared to D. At higher loads, a similar trend was observed across all fuel samples. On average, HC values for mixtures such as F25, F50, F75, and F100 were lower than those for fossil diesel fuel, with reductions of approximately 28%, 23%, 19%, and 7%, respectively. HC emissions from HVO at higher engine loads were about 45% lower compared to diesel. This can be attributed to the previously discussed effects of fuel quality on atomisation and combustion processes. Fuels with lower cetane numbers take longer to ignite, which results in higher HC emissions (Martinka et al., 2019).

Experimental research indicates that lower carbon content in fuel leads to reduced smoke emissions (Gumus & Kasifoglu, 2010). As the ignition delay decreases, combustion begins earlier, leading to a reduction in harmful substances such as smoke, which is associated with a higher cetane number. Smoke emissions from D100 and HVO100 were higher compared to ester blends, as shown in Figure 3.11. This is because oxygenated fuels, such as the ester blends, contribute to the oxidation of soot. Behçet et al. (2015) found that smoke levels were high for diesel fuel but decreased significantly for biodiesel. Furthermore, earlier soot formation in diesel fuel correlates with the presence of aromatic and cycloalkane compounds that promote soot precursor formation.

For HVO, an average reduction in smoke emissions of approximately 18% was observed compared to diesel fuel. HVO is a paraffinic fuel with a higher H/C ratio (Table 2.1). This fuel does not contain aromatic hydrocarbons, sulphur, or other mineral impurities that contribute to soot formation (Rimkus et al., 2015). Similarly, the ester blends also showed lower smoke emissions compared to diesel. For example, FE25 had a 47% reduction, FE50 showed a 55% reduction, FE75 had a 58% reduction, and FE100 exhibited a 62% reduction in smoke emissions compared to diesel.

Smoke is produced by the partial combustion of fuel. The lower smoke levels in HVO, as seen in Figure 3.12, can be explained by its lower C/H ratio (17% less than diesel) and the absence of components such as sulphur and aromatic hydrocarbons, which are known to contribute to soot formation (Knothe et al., 2005). As mentioned earlier, the duck fat-based mixtures (Table 2.1 (b)) contain oxygen molecules that aid in the combustion process. Blends of HVO and pure fat consistently show lower smoke emissions compared to diesel fuel across all tested loads. On average, F25 showed a 51% reduction, F50 had a 54% reduction, F75 showed a 56% reduction, and F100 exhibited a 59% reduction in smoke emissions. The presence of excess oxygen in the mixtures with pure fat leads to more complete combustion, resulting in lower smoke emissions under all engine load conditions.

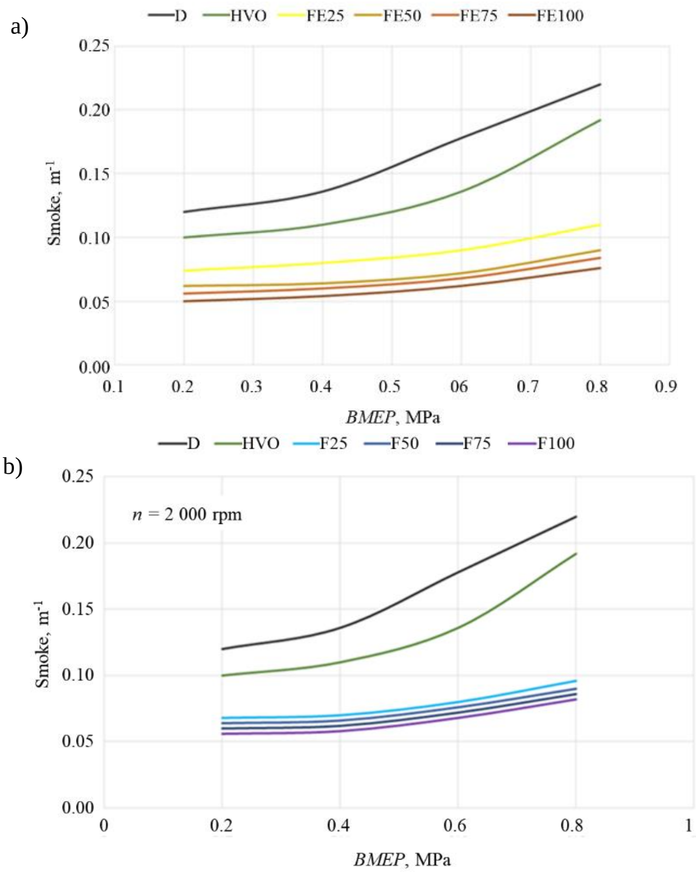

Fig. 3.12. Dependence of smoke emissions on the load

NO_x emissions increased with rising load across all fuel samples, with diesel fuel exhibiting the highest levels. On average, the difference in NO_x emissions between D100 and HVO100 was approximately 19%, while the difference between D100 and FE100 was around 10% (Fig. 3.13).

At a medium load (*BMEP* = 0.4 MPa), nitrogen oxide emissions were reduced by about 12% for FE25, 10% for FE50, 10% for FE75, and 10% for FE100, while HVO showed a reduction of around 20% compared to D100.

The increase in combustion chamber temperature, which occurs with higher loads, directly contributes to higher NO_x emissions. Several researches have highlighted the effect of biodiesel on NO_x emissions due to its oxygen content. This additional oxygen promotes better fuel oxidation during combustion, leading to higher temperatures and, consequently, higher NO_x levels.

HVO showed a more favourable impact on NO_x emissions compared to ester/diesel mixtures. The varying effects on NO_x emissions can be attributed to the combined influence of ignition delay, fuel injection quantity, and the distribution of injection quantities between pilot and main injections. Additionally, the lower iodine number and oxygen content in ester-based mixtures contribute to a 20% reduction in NO_x emissions compared to diesel.

As shown in Figure 3.13, NO_x emissions increased with load for all tested fuels, primarily due to the higher combustion temperatures. Diesel fuel (D100) exhibited the highest NO_x emissions, with the difference between D100 and HVO100 averaging around 18% and the difference between D100 and F100 being approximately 5%. At higher loads *(BMEP* = 0.8 MPa), NO_x emissions were reduced by 17.6% for HVO, 9.1% for F25, 7.2% for F50, 5.4% for F75, and 3% for F100, all compared to D100. This indicates that NOx emissions from conventional diesel fuel were the highest across all load conditions.

a)

b)

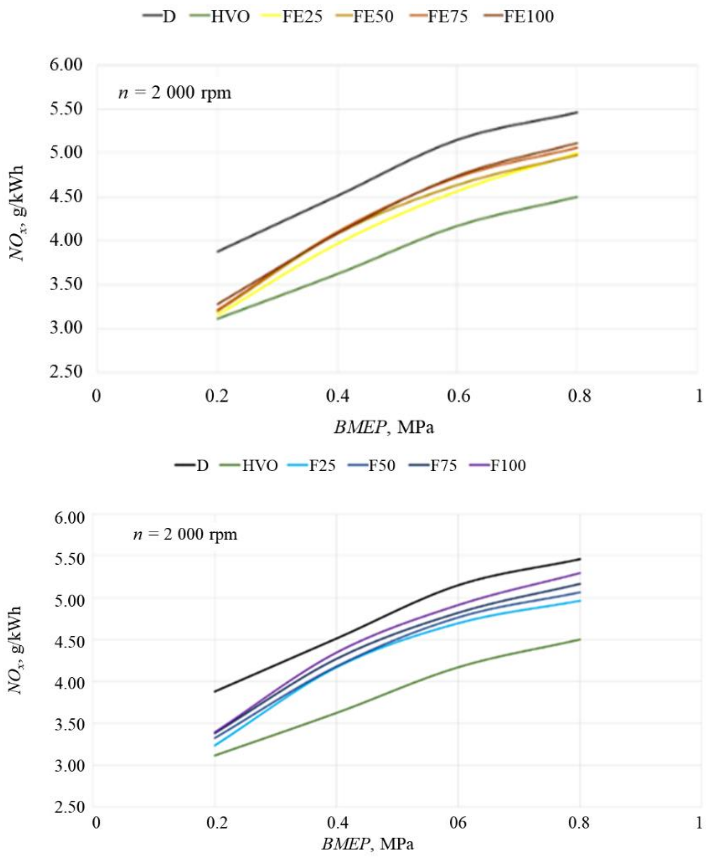

Fig. 3.13. Dependence of nitrogen oxide emissions on the load

NO_x emissions are lowest with HVO, which has the highest cetane number (CN) among all the samples. The varying effects on NO_x emissions may result from the combined influence of ignition delay, fuel injection quantity, and the distribution of injection quantities between pilot and main injections (Rao et al., 2013). Ignition quality is strongly linked to the cetane number, with a higher CN indicating a shorter ignition delay. This leads to less fuel energy (ROHR) during the premix stage and, consequently, lower NO_x emissions.

The increase in NO_x emissions for HVO-fat mixtures can likely be attributed to the presence of oxygen molecules in the fuel. Additionally, the rise in NOx emissions may be explained by the higher iodine value of the mixtures. Since the iodine number is associated with cetane number, as well as fuel density and compressibility, it can affect combustion characteristics (Duda et al., 2018). Therefore, the use of pure fat mixtures enhances fuel oxidation during combustion, resulting in higher local temperatures and a subsequent increase in nitrogen oxide emissions.

3.3. Comparison Energy Indicators Fuel Blends of Hydrotreated Vegetable Oil, Fatty Acid Methyl Esters and Duck Fat

At medium load, the brake-specific fuel consumption (*BSFC*) for D100 was lower than that of all the fuel mixtures, but it was about 3% higher than for HVO. As shown in Figure 3.14, as the ester content in the fuel mixtures increased, the fuel consumption also increased. For example, FE100 exhibited a ~13% higher fuel consumption compared to fossil diesel. When comparing D100 with the other blends, the fuel consumption increased by ~1% for FE25, ~5% for FE50, and ~9% for FE75, in comparison with diesel fuel. This increase in fuel consumption affects the combustion process. Engine operation with ester blends resulted in higher *BSFC* values compared to both diesel and HVO across all load conditions. The tendency towards higher *BSFC* values is often linked to the lower calorific value of the test fuels, which requires more fuel to maintain the same power output (Dimitriadis et al., 2020). Diesel fuel, with 0% oxygen, showed the lowest *BSFC* compared to the biofuel mixtures. The lower specific heating value of the tested fuels (Table 2.1 (b)) has been cited as the reason for the increase in *BSFC* values (Alptekin et al., 2015). However, it is important to note that HVO exhibited the highest fuel consumption rate due to its higher hydrogen content, which results in a higher calorific value per mass (Fig. 3.14).

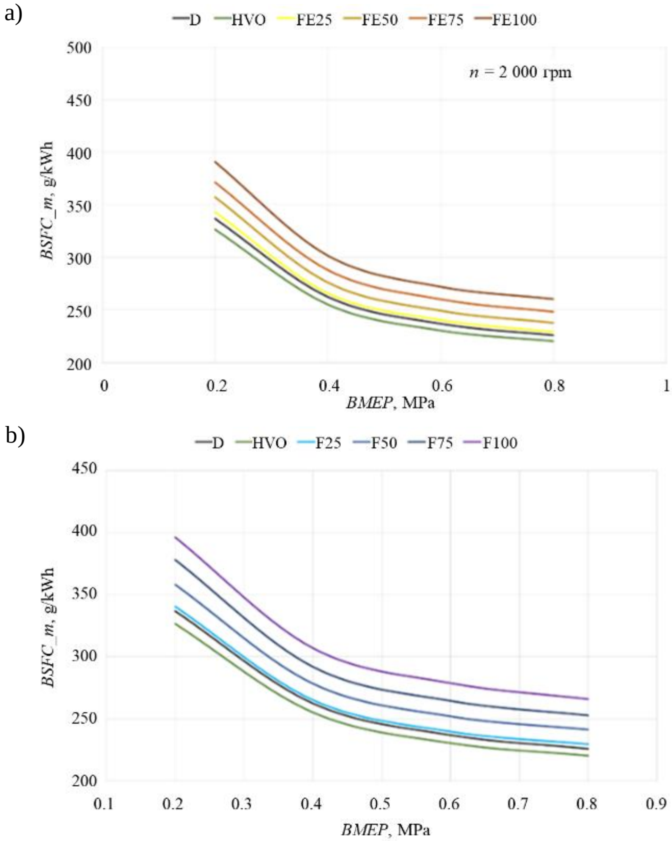

Fig. 3.14. Dependence of BSFC_m, g/kWh on the load

This relationship can be explained by the impact of intake pressure on the brake mean effective pressure (*BMEP*). Engine performance at low loads is influenced by altitude, as the intake manifold pressure directly affects the amount of air mass entering the cylinder (Ghazikhani et al., 2013).

As presented in Figure 3.14b, the *BSFC* for all duck fat blends at high load was higher compared to pure diesel. However, the *BSFC* for HVO was about 2.4% lower than that of pure diesel. As the percentage of pure fat in the samples increased, fuel consumption also increased, with F100 showing a ~17.7% higher fuel consumption compared to diesel fuel. When comparing fossil diesel fuel with other HVO mixtures containing pure fat, the increase in *BSFC* was observed for F25 (~1.6%), F50 (~6.8%), and F75 (~11.8%). Since the calorific value of fat is lower, the engine requires more fuel to maintain a constant speed at a certain load, which results in increased fuel consumption (Rimkus et al., 2015). One reason for the increase in *BSFC* with a higher percentage of pure fat could be its higher density compared to fossil fuels (Abdulkadir et al., 2014).

Figure 3.15 illustrates that brake thermal efficiency (*BTE*) increases for all fuels as the load increases, which is linked to the rise in power output. Furthermore, fuels with a higher specific heat of combustion (the amount of heat released during complete combustion) tend to have lower fuel consumption (Jayaprabakar & Karthikeyan, 2016). All fuel mixtures show lower *BTE* values compared to pure fuels, with HVO exhibiting the highest *BTE*, followed by diesel fuel. The difference between these two types of fuels is approximately 0.5%, primarily due to the specific heat of combustion.

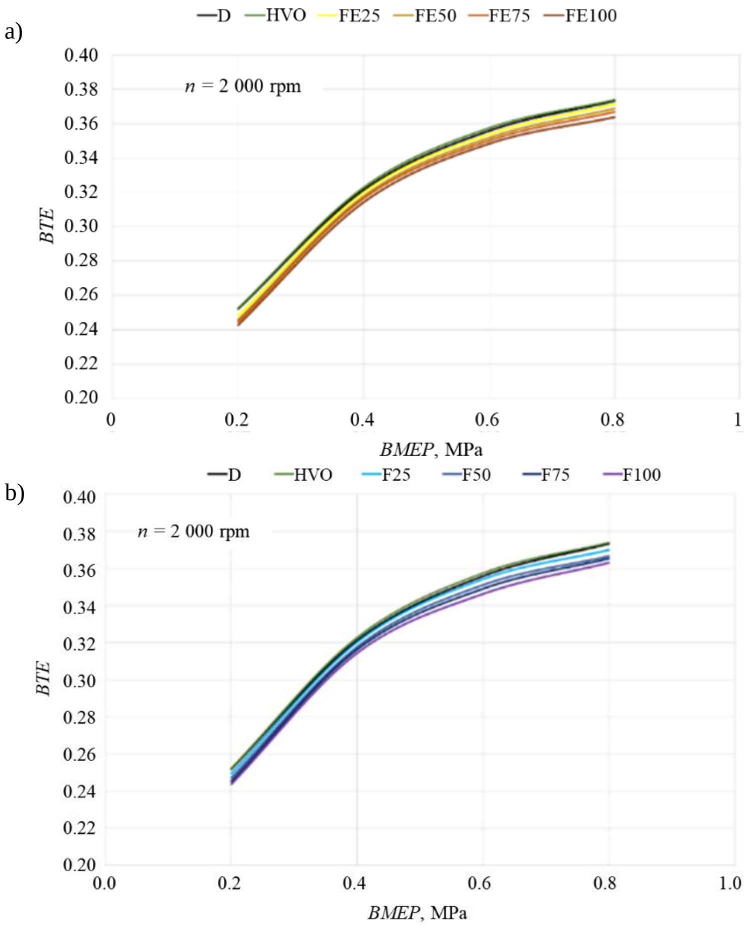

Fig. 3.15. Dependence of BTE on the load

At medium load (*BMEP* = 0.4 MPa), the ester mixtures show an average reduction in *BTE* of around 0.3% when compared to diesel fuel. The lower *BTE* for these mixtures can be attributed to their reduced heating value and increased fuel consumption relative to diesel. This decrease in *BTE* may also result from the reduced heat absorption for higher power outputs at a given load. As the proportion of biodiesel in the mixtures increases, the *BTE* further decreases, primarily due to the poor atomisation of the mixtures caused by their higher viscosity. Fuels with a greater ester content generate less torque because they release less energy due to their lower heating value (Can, 2014; Nantha Gopal et al., 2014). Additionally, the lower *BTE* can be linked to the higher brake-specific fuel consumption (*BSFC*). Moreover, the increase in oxygen content with a higher ester blend percentage (Table 2.1 (b)) further reduces the heating value, which subsequently lowers the *BTE*.

Figure 3.15 shows that *BTE* increases for all fuel samples as the load rises due to the improved ratio of indicated power to internal mechanical losses in the engine. As the load increases, the quality of the mixture formation and combustion processes improves, resulting in a higher combustion temperature (Levine et al., 2014), which in turn enhances the *BTE*. The difference between the fuel samples is approximately 0.14%, which is directly linked to the lower heating value (LHV) and combustion process characteristics.

HVO fuel contains approximately 2.4% more energy per kilogram, and its cyclic fuel mass is about 2.4% less compared to diesel. HVO fuels also have shorter injection and combustion durations. Lower cooling and exhaust heat losses further contribute to the higher *BTE* of HVO compared to diesel fuel.

A clear trend in Figure 3.15 indicates that as the percentage of pure fat in the blends increases, the *BTE* tends to decrease. At a load of *BMEP* = 0.8 MPa, F100 exhibits an average *BTE* reduction of about 2.7% compared to diesel fuel. Brake thermal efficiency is heavily influenced by combustion efficiency. The increased oxygen content in the fuel with the addition of duck fat reduces the LHV, necessitating longer fuel injection durations. This results in a decrease in *BTE* due to poor atomisation, which is a consequence of the high viscosity of the fat. Longer combustion durations lead to more energy being transferred to the cooling system and exhaust, further lowering the *BTE*. While the increased oxygen content accelerates combustion, its effect on *BTE* reduction is relatively small.

3.4. Conclusions of the Third Chapter

The Third Chapter focused on experimental research of biofuel blends evaluating their effects on the combustion process, energy and environmental indicators of a compression ignition engine. AVL BOOST simulations were conducted additionally, which allowed for examining closely how fuel mixtures affect cylinder pressure dynamics and combustion efficiency.

1. Experimental tests verified that combustion and cylinder pressure variations are much influenced by biofuel combinations. A longer ignition delay, shown by FAME-based fuel blends, produced a higher pressure rise rate and extended combustion duration. HVO-based blends guaranteed a tighter and smoother diesel-like combustion process.
2. The results of the AVL BOOST simulation confirmed that the composition of fuel blends directly determines the maximum pressure value in the combustion chamber. FAME-containing fuels generated a higher pressure peak than HVO blends, which may affect the loads on the engine's mechanical components.
3. Fuel injection, vaporisation, and combustion homogeneity of biofuel blends were much influenced by their viscosity and chemical composition. Greater FAME's higher viscosity produced less-than-ideal fuel atomisation and increased the likelihood of locally rich mixes, therefore maybe causing incomplete combustion and higher NO_x emissions.
4. The utilisation of fuel blends with elevated concentrations of FAME resulted in a diminished energy conversion efficiency (*BTE*), whereas HVO blends enhanced the combustion characteristics of the fuel. The enhanced ignition properties of HVO facilitated a more efficient combustion process, thereby ensuring a superior level of thermal energy conversion.
5. Using FAME-based blends resulted in increased fuel consumption (*BSFC*), which is linked to their lower calorific value. HVO blends enable fuel consumption to be more closely matched to diesel, allowing for greater use in the transportation industry.
6. Experimental findings show that using biofuel blends can significantly reduce CO and HC emissions compared to using regular diesel. Higher oxygen content in fuel mixes is associated with this effect, which improves the combustion process and reduces the production of incomplete combustion products.
7. The fuel mix composition affects NO_x emissions, with higher FAME percentages often increasing NO_x concentrations in exhaust streams. This relates to the features of FAME fuels, which define the longer combustion time and greater combustion temperature.
8. Combining lower CO and HC emissions with controlled NO_x levels proved superior with HVO-based fuels. This suggests that one can maximise the effect of fuel mixes on engine efficiency and environmental performance by choosing their ratios in line.

4

Data-driven Modelling of Engine Performance and Emissions Using Regression Trees

This chapter focuses on the application of machine learning techniques, particularly regression trees, to model and predict engine performance and emissions when using various biodiesel blends. The motivation behind this approach lies in the need to effectively analyse large datasets generated from experimental research, which include complex interactions between fuel composition, combustion characteristics, and emission levels. Traditional statistical methods often fail to capture the non-linear dependencies between these parameters, making machine learning-based approaches a valuable tool in transport engineering research.

The regression trees method was selected as a key analytical tool due to its ability to handle multi-variable dependencies while maintaining interpretability. The structure of decision trees allows for a hierarchical analysis of the impact of diverse biofuel blends on key engine performance indicators such as brake thermal efficiency (*BTE*), brake-specific fuel consumption (*BSFC*), and emissions of CO, CO_2, NO_x, HC, and smoke. One of the key advantages of this approach is the ability to identify and quantify the most influential parameters affecting engine performance and emissions. By segmenting the dataset into diverse operating regimes, the model can pinpoint specific conditions under which alternative fuel blends outperform conventional diesel in terms of energy efficiency and ecological benefits.

4.1. Application of Regression Trees in the Assessment of Biodiesel Blends’ Impact on Engine Performance and Emissions

The decision trees suffer from high variance. A set of decision trees is usually defined to decrease the variance and improve the predictions. Bagging (Hastie et al., 2009) is one of the possible techniques to create decision trees based on several bootstrapped training sets. Each decision tree is trained on a subset of the data set, which is chosen randomly with replacement. The variance is reduced by aggregating a set of predictions obtained from an ensemble of trees.

Another extension of the bagging method to create the ensemble of trees is called Random Forest (Breiman, 2001). A training set is defined for each tree, where the set of features is randomly chosen from a full set of features. This technique allows for avoiding the problem of selecting the dominant predictor in the split of entire space into regions. The forecast obtained from Random Forest based on regression trees is defined as the average of the predictions from trees. On the one hand, predictions from trees with randomly selected features are less correlated; on the other hand, the average of predictions obtained from regression trees is less variable.

The presented regression tree model analyses the trends in carbon monoxide (CO) emissions depending on the excess air ratio (λ) and the type of fuel used (Fig. 4.1). The structural branching of the model allows for the identification of the main factors influencing CO emissions and their distribution depending on the operating modes. When analysing the left branch, it is observed that when the excess air ratio $\lambda < 2.8$, the lowest amount of CO is formed (0.78), which means that the combustion process is the most efficient since with a lower excess air, better fuel oxidation is ensured. Such a trend accounts for 51% of all cases in the data set, which indicates that this situation is the most common. At excess air ratios greater than 2.8, CO emissions increase, but different fuel types result in diverse CO levels, e.g., blends containing HVO and FAME (F25, FE25, FE50, and FE75) emit lower CO than blends containing F50, F75, and FE100.

Meanwhile, the right-hand branch reveals that when $\lambda \geq 3.8$, fuel type becomes an important factor. When blends such as D100, F25, FE25, FE50, FE75 and HVO are used, CO emissions increase to 2.2, which accounts for 17% of the total data. Meanwhile, F50, F75 and FE100 fuel blends emit even more CO, but their final emission value depends on the excess air ratio. If $\lambda < 4.4$, CO emissions reach 3.3, and if λ ≥ 4.4, the value increases to 4.5. This indicates that an excess of air during combustion diminishes efficiency, leading to unburned fuel that exacerbates CO emissions. In conclusion, minimal CO emissions occur when λ is below 2.8, signifying optimal fuel combustion. As the excess air ratio increases, CO emissions increase, especially when certain biofuel blends are used (F50, F75, and FE100), and the highest CO emissions are achieved at the highest λ (≥4.4). This allows for the conclusion that controlling the excess air ratio and selecting the right fuel blends are essential factors in reducing CO emissions in compression-ignition engines.

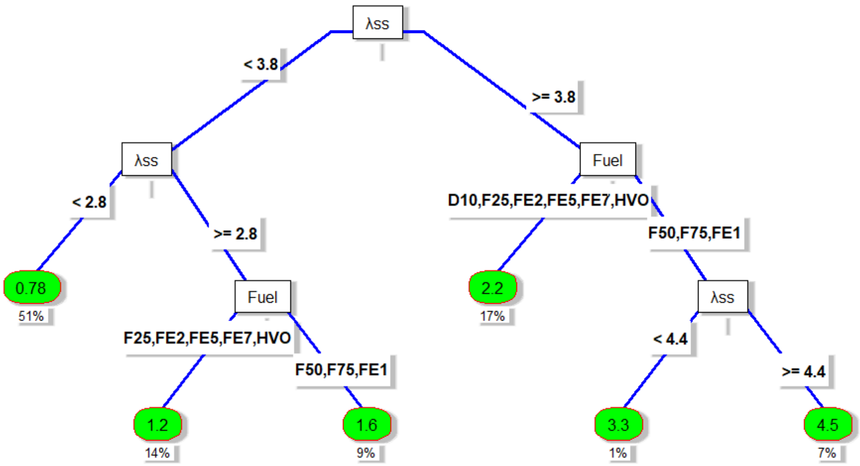

Fig. 4.1. Dependence of CO on engine parameters

The presented regression tree model analyses the trends in carbon dioxide (CO_2) emissions depending on the excess air ratio (λ) and the type of fuel mixture (Fig. 4.2). The model helps to identify the main factors influencing the distribution of CO_2 emissions and allows us to understand how the fuel composition and combustion conditions affect the amount of CO_2 emissions. When analysing the left branch, it is noted that at an excess air ratio (λ) < 2.8, the lowest amount of CO_2 emissions (728) is recorded. This indicates that under these conditions, the most efficient fuel combustion occurs, during which less fuel is consumed for excess oxidation, and the combustion reaction proceeds evenly. This situation accounts for 51% of all measurements; therefore, it can be stated that this is the most common engine operating mode. When the excess air ratio increases to 2.8 ≤ λ < 3.8, the CO_2 emissions increase slightly to 798, which accounts for 23% of the total data set. This increase can be explained by a higher fuel consumption for a corresponding energy output.

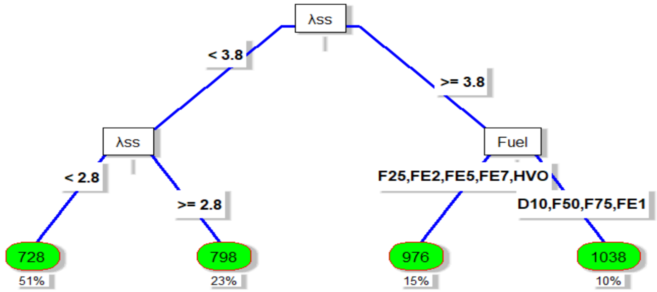

Fig. 4.2. Dependence of CO_2 on engine parameters

Turning now to the suitable branch, which has an excess air ratio of λ > 3.8, displays high CO_2 emissions; the composition of the fuel mixture becomes important in this regard. Fuel mixtures containing F25, FE25, FE50, FE75 and HVO emit an average of 976 ppm CO_2, which accounts for 15% of all measurements. Meanwhile, fuel mixtures D10, F50, F75 and FE100 cause even higher CO_2 emissions – 1038 ppm, which indicates that these mixtures require a higher amount of fuel to achieve the same engine power, which leads to increased emissions. This situation accounts for 10% of all measurements.

In summary, the lowest CO_2 emissions are observed when the air excess ratio is less than 2.8, as this is the condition that ensures the most efficient fuel consumption. The level of CO_2 emissions increases with increasing air excess ratio and depends on the composition of the fuel mixture. Mixtures with higher FAME and HVO content have average emissions, while mixtures with D100, F50 and FE100 produce the highest CO_2 content.

These results indicate that the composition of fuel mixtures and the control of the air excess ratio are essential factors in reducing CO_2 emissions and optimising the combustion process in compression-ignition engines.

Depending on the surplus air ratio (λ), the composition of the fuel mixture and the engine running conditions, the provided regression tree model analyses the trends of unburned hydrocarbon (HC) emissions (Fig. 4.3). The model allows for identifying the main factors determining the distribution of HC emissions and helps to understand under what conditions this pollution indicator can be reduced. When analysing the left branch, when the excess air ratio (λ) < 3.8, it is seen that HC emissions are the lowest. In this case, the variable Me (most likely indicating the engine operating mode or mixture composition) has an additional significance. If Me ≥ 75, the HC emission level reaches only 0.021, which accounts for 51% of all measurements, indicating that such conditions are optimal for reducing unburned hydrocarbons. Meanwhile, if Me < 75, the HC content increases to 0.042, which accounts for 23% of all measurements. This trend shows that at low excess air ratio, engine operating parameters and fuel injection strategy become significant factors in reducing HC emissions.

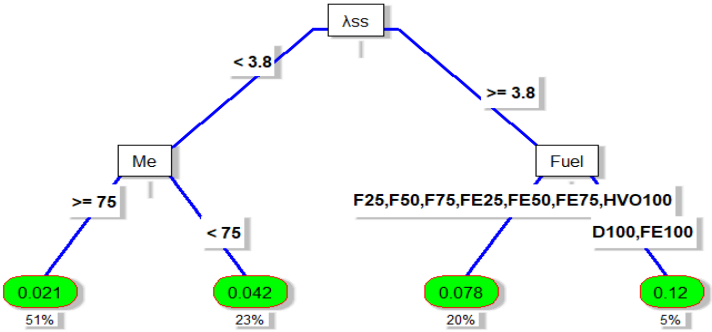

Fig. 4.3. Dependence of HC on engine parameters

Moving to the right branch, where $\lambda \geq 3.8$, the composition of the fuel mixture becomes a decisive factor. Using F25, F50, F75, FE25, FE50, FE75 and HVO100 fuel mixtures, the average HC emissions increase to 0.078, which accounts for 20% of all measurements. This indicates that higher excess air can cause incomplete fuel oxidation, which leads to an increase in the amount of unburned hydrocarbons.

Meanwhile, when using D100 and FE100 fuel mixtures, HC emissions reach the highest level of 0.12, but this situation accounts for only 5% of all measurements. This suggests that the use of certain biofuels in a wide range of excess air can worsen the combustion process and lead to higher HC emissions.

Considering the surplus air ratio (λ), fuel mixture composition, and various engine running factors, the proposed regression tree model examines the trends in nitrogen oxide (NO_x) emissions (Fig. 4.4). The model facilitates the identification of the main elements influencing NO_x generation in the engine running compression-ignition.

Examining the left branch finds that the average NO_x emission value is lowest (3.2) when $\lambda \geq 2.8$. This suggests that the reduced generation of nitrogen oxides under such combustion conditions is probably related to the lower combustion temperature. Moreover, the kind of fuel affects the emissions; NO_x concentration rises to 3.7 when using D100 and HVO100 mixes and rises to 4.1 when using the F25, F50, F75, FE100, FE25, FE50, and FE75 mixtures. Longer combustion duration and higher combustion temperature of blends with FAME suggest that their use may help to produce more NO_x.

The right branch shows that when $\lambda < 2.8$, NO_x emissions become significantly higher. For $\lambda \geq 2.2$, when using blends containing HVO100 and FAME, emissions reach 4.8, which accounts for 24% of all observations. This can be attributed to higher combustion temperature and a more intensive oxidation process. At even lower λ (<2.2), NO_x emissions increase even more: when using D100, F25, F50, F75, FE100, FE25, FE50, and FE75, they reach 5.1. This means that the lower excess air ratio, together with the higher FAME content of biodiesel blends, promotes an increase in NO_x emissions due to higher combustion intensity.

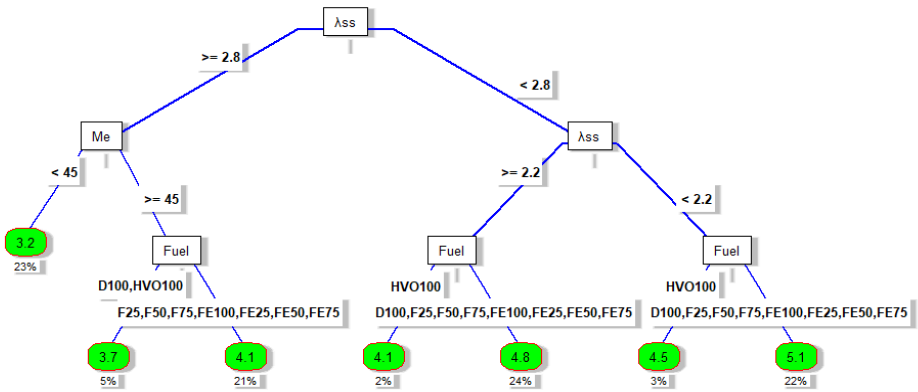

Fig. 4.4. Dependence of NO_x on engine parameters

In summary, it can be stated that the lowest NO_x emissions are achieved when the excess air ratio is higher than 2.8, but their level still depends on the fuel mixture composition. The highest emissions occur at low λ (<2.2) and when using FAME-based blends. This confirms that NO_x emission reduction can be achieved by optimising the excess air ratio and selecting appropriate biofuel blends.

Figure 4.5 for the given regression tree model analysis of the smoke trends based on the fuel mixture composition and surplus air ratio (λ). One of the most significant pollution issues related to a diesel engine is particle emissions, influenced by several fuel types and combustion circumstances; the model helps to understand this.

Analysing the left branch, which uses F25, F50, F75, FE100, FE25, FE50, and FE75 fuel mixtures, it is seen that the excess air ratio (λ) is an important factor regulating smoke. If $\lambda \geq 2.5$, the lowest smoke values are recorded when using F50, F75, FE100, FE50, and FE75, the average smoke value is 0.06, and in the case of F25 and FE25 mixtures, it is 0.074. If $\lambda < 2.5$, the smoke indices increase: the same fuel mixtures reach values of 0.075–0.092, which indicates that a lower excess air leads to less efficient fuel combustion and greater soot formation.

The right branch analyses D100 and HVO100 fuel mixtures. It is observed that when $\lambda \geq 2.3$, the smoke is lower (0.11), but when $\lambda < 2.3$, the value increases to 0.21, which indicates a significant increase in particulate emissions. In addition, the smoke level depends on the type of fuel: when using HVO100, the smoke is lower (0.13), and when using D100, it is higher (0.18).

In summary, it can be stated that the lowest smoke is achieved at $\lambda \geq 2.5$ and when using F50, F75, FE100, FE50 and FE75 fuel mixtures, which ensure better combustion and less soot formation. The highest smoke emission is recorded at $\lambda < 2.3$, especially when using D100 fuel. These results show that control of the excess air ratio and properly selected fuel mixtures can effectively reduce smoke emissions, and HVO-containing fuel mixtures are more effective in reducing soot emissions than conventional diesel.

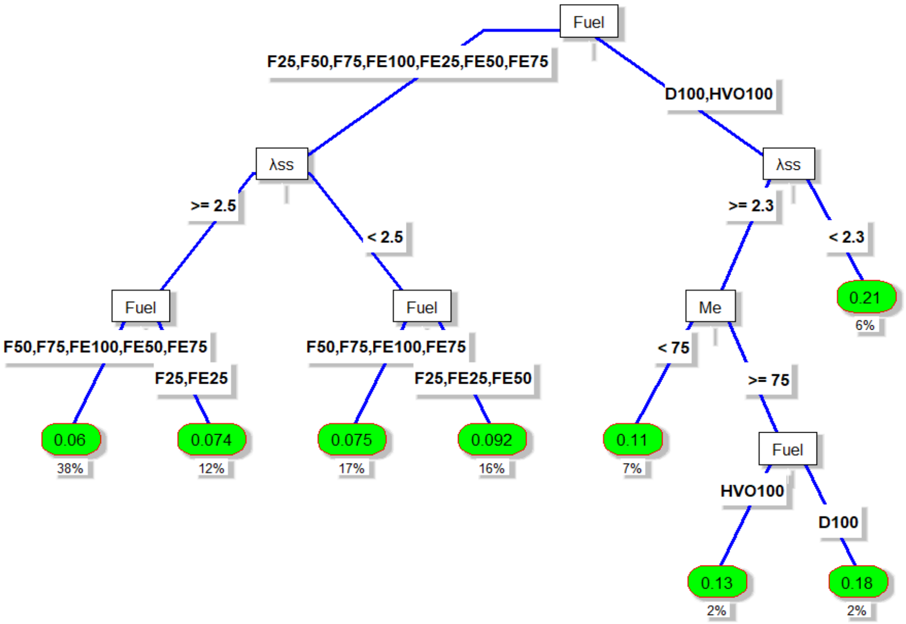

Fig. 4.5. Dependence of smoke on engine parameters

The presented regression tree model examines brake-specific fuel consumption (*BSFC*) based on excess air ratio (λ), fuel mixture composition, and other engine running variables. Figure 4.6 shows *BSFC* – an important energy indicator displaying the fuel consumption for a particular engine power. This model helps to identify the impact of fuel mixtures and operating conditions on fuel consumption. When analysing the left branch, when $\lambda < 3.8$, it is observed that fuel consumption is the lowest, especially when additional operating parameters (Me) are ≥ 75. In this case, when using D100, F25, F50, FE25, FE50, and HVO100, *BSFC* is 235 g/kWh, and when using F75, FE100, and FE75, this indicator is slightly higher, e.g., 256 g/kWh. When Me < 75, fuel consumption increases slightly: F25 and HVO100 fuel mixtures reach 254 g/kWh, while F50, F75, FE100, FE25, FE50, and FE75 mixtures consume more fuel, e.g., 282 g/kWh.

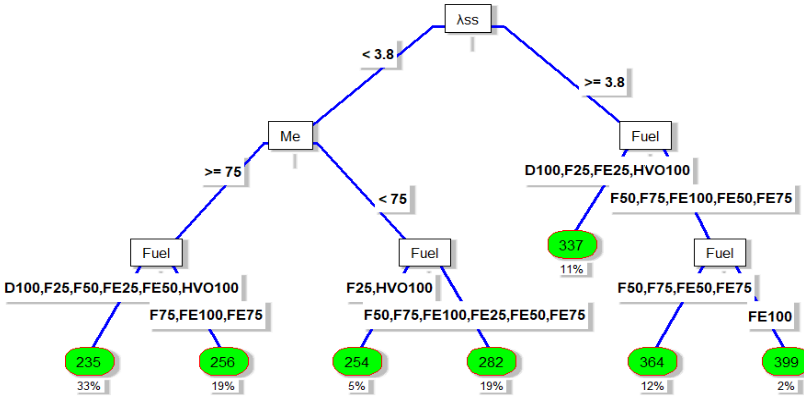

Fig. 4.6. Dependence of BSFC on engine parameters

In the right branch, when λ ≥ 3.8, fuel consumption is higher, and the fuel composition becomes the determining factor. Mixtures D100, F25, FE25, and HVO100 cause BSFC to increase to 337 g/kWh, which indicates lower energy efficiency due to higher excess air coefficient, which can cause excessive cooling of the mixture and less efficient combustion. Fuel consumption increases even more when using F50, F75, FE100, FE50, and FE75; depending on their combination, BSFC can reach 364 or even 399 g/kWh, which means significantly lower fuel energy efficiency.

In summary, it can be stated that the lowest fuel consumption is achieved at λ < 3.8 and using D100, F25, F50, FE25, FE50 and HVO100 fuels, since under such conditions, the combustion process is most efficient. The highest fuel consumption is observed at λ ≥ 3.8, especially when using blends with higher FAME concentrations, such as FE100. This indicates that the oxygen content and lower calorific value of biofuels can affect higher fuel consumption. It is necessary to optimise fuel blends and engine operating parameters, especially the excess air ratio, to reduce BSFC.

Figure 4.7 for the given regression tree model analysis of the relationship of brake thermal efficiency (*BTE*) on the excess air coefficient (λ) and extra engine running parameters (Me). This indication closely relates to the engine's energy efficiency since *BTE* shows how much chemical energy of the fuel is turned into useful mechanical power.

Analysing the left branch, where the excess air coefficient (λ) ≥ 3.8, it is seen that the engine efficiency is the lowest, e.g., *BTE* reaches only 0.25. This shows that excessive excess air reduces combustion efficiency due to lower temperature and slower flame propagation, which reduces the engine's mechanical efficiency.

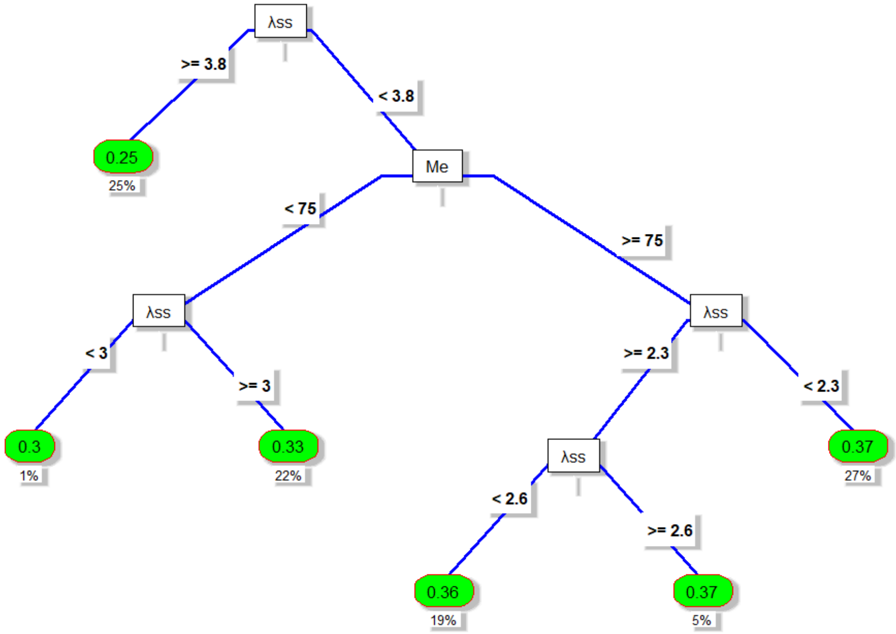

Fig. 4.7. Dependence of BTE on engine parameters

When λ < 3.8, the efficiency depends on the engine operating parameter Me. For Me < 75, the *BTE* is slightly higher but still relatively low – from 0.3 to 0.33, depending on the value of λ (lower *BTE* at λ < 3 and slightly higher at λ ≥ 3). This allows for the conclusion that the efficiency partially increases with lower excess air, but the combustion conditions are still not optimal.

In the right branch, when Me ≥ 75, the *BTE* indicators become higher. For the excess air coefficient λ ≥ 2.3, the efficiency depends on additional values of λ: for 2.3 ≤ λ < 2.6, the *BTE* reaches 0.36, and for λ ≥ 2.6, 0.37 is reached. The highest BTE is observed when λ < 2.3: the efficiency reaches 0.37, which is the highest value in this model (27% of all observations).

In summary, the thermal efficiency of the brakes is highest when the excess air ratio is less than 2.3, and the engine is operating in the optimal mode (Me ≥ 75). This indicates that under such conditions, the best fuel combustion and the highest energy conversion into mechanical power are ensured. The efficiency decreases with increasing λ, especially when λ ≥ 3.8 when the lowest *BTE* (0.25) is reached, which indicates inefficient combustion and high heat losses. To achieve the highest engine performance, it is necessary to control the excess air ratio and optimise the engine operating parameters to maintain the *BTE* at the highest level.

Using regression tree (Tree) and Random Forest (Random Forest) approaches, the pseudo-R-squared (pseudo-R^2) values shown in Table 4.1 allow for the evaluation of the accuracy of regression models in projecting diverse engine performance and emissions metrics. Higher pseudo-R^2 values show that the model fits real data better; that is, the value is closer to 1; hence, the model reflects real data more precisely.

Table 4.1. The values of pseudo R-squared

Parameter	Tree	Random Forest
Smoke	0.948	0.982
BSFC	0.971	0.990
BTE	0.989	0.998
CO	0.958	0.965
CO_2	0.960	0.987
HC	0.951	0.983
NO_x	0.960	0.990

Examining the results shows that for all values of the parameters under investigation, the Random Forest approach regularly has better pseudo-R^2 values than regression trees. This indicates that the Random Forest model has higher prediction accuracy, as it is able to better assess complex data relationships and reduce the problem of excess variance, which often occurs when using a single regression tree.

When evaluating individual indicators, it is observed that both regression trees and Random Forest models predict engine efficiency indicators best (*BTE* – 0.989 and 0.998), which indicates that the analysis of fuel consumption and energy efficiency is most reliable using these methods. High values are also observed in emission modelling: CO, CO_2 , HC and NO_x values exceed 0.95 in both regression trees and Random Forest methods, which indicates good accuracy of emission models.

However, there are some differences between the methods. The smoke model shows the most improvement when applying Random Forest; the pseudo-R^2 value rises from 0.948 to 0.982, so indicating that the Random Forest method greatly boosts the accuracy of the smoke prediction. Likewise, the Random Forest approach (0.990) fits the *BSFC* model better than a single regression tree (0.9971), therefore indicating that the fuel consumption prediction is more dependable, utilising a more complicated methodology. Ultimately, especially in cases when the accuracy of the analysis is crucial to lower model variance and maximise combustion processes, it can be said that the Random Forest method is more accurate than a single regression tree in forecasting engine performance and emissions. Both approaches, however, produce high pseudo-R^2 values (>0.94), suggesting that they are fit for simulating the effect of substitute fuels on engine performance.

4.2. Conclusions of the Fourth Chapter

The Fourth Chapter examined the mathematical modelling of engine operating parameters and emissions using regression trees and Random Forest methods. The research in this chapter allowed for determining the influence of biodiesel blends on the performance characteristics of compression ignition engines, optimising the composition of fuel blends, and assessing the accuracy of prediction models. Main conclusions:

1. Regression trees and Random Forest methods were applied to predict engine operating parameters and emissions, showing a high pseudo-R^2 coefficient value (>0.94), which indicates the high prediction accuracy of models. The Random Forests method turned out to be more accurate than regression trees, especially in predicting smoke and brake-specific fuel consumption (*BSFC*) indicators.
2. According to the modelling, energy indicators and emission levels depend much on the composition of fuel mixes. Whereas HVO-based blends allow for a better balance between NO_x and smoke, FAME-based blends raised nitrogen oxide (NO_x) emissions.
3. While with a greater excess air ratio ($\lambda \geq 3.8$), efficiency reduces, and a smaller excess air ratio ($\lambda < 2.3$) guarantees better fuel energy usage. Lower combustion temperature and heat losses, as well as poorer combustion conditions, are related to this. Higher *BSFC* in fuel blends derived from higher FAME concentration was correlated with their lower calorific value. HVO-based fuels, in the meantime, allow for almost consistent diesel-based fuel use.
4. Using biodiesel blends greatly lowered CO and HC emissions as compared to standard diesel, which is linked with higher oxygen content in the fuel composition, thereby enabling more effective fuel combustion and decreased incomplete combustion products.
5. At $\lambda = 2.5$, the smoke of FAME blends was higher than that of HVO blends; while using D100, the smoke was highest depending most on the surplus air ratio and fuel composition. This indicates that with proper selection of fuel blends, particulate emissions can be reduced.

6. The regression tree method allowed for the identification of the main factors influencing engine operating parameters, while Random Forest models reduced the variance of the models, allowing for more stable and accurate prediction results.
7. The obtained results confirmed that mathematical modelling can be effectively used to assess the impact of fuel blends on engine performance, allowing for the optimisation of fuel composition before conducting experimental research. This allows for reducing the costs of experimental research and accelerating the selection of the most suitable biodiesel blends.

These findings suggest that regression methods can be successfully applied to predict engine performance, and properly tuned biodiesel blends can improve environmental performance and maintain acceptable energy efficiency.

General Conclusions

A comprehensive evaluation of the effects of biodiesel blends on the performance and emissions of a compression ignition engine was made possible by the dissertation's integration of numerical models with real data. The main points covered here offer a brief synopsis:

1. Experimentally prepared biofuel blends consisting of HVO, FAME and animal fat met the essential physical and chemical parameters set by EN 590 and EN 14214 standards, except for pure fat (F100), which was found to have excessive viscosity and poor low-temperature performance. The best diesel-like parameters were demonstrated by blends FE25–FE50 and F25.
2. Engine operation experiments showed that HVO-containing fuels provide shorter ignition delay, smoother pressure rise and smaller temperature spikes in the cylinder compared to FAME or pure fat. These fuels also reduced the likelihood of shock loads and noise. FAME blends, on the contrary, were characterised by longer ignition delays and higher pressure spikes.
3. Experiments showed that HVO blends had the highest *BTE*, even exceeding the values of standard diesel, and their *BSFC* was the lowest. FAME and fat-containing blends had lower efficiency and higher costs due to

higher viscosity and lower calorific value. *BTE* and *BSFC* indicators significantly depended on the blend composition and engine load.

4. HVO blends significantly reduced CO, HC and particulate emissions (up to 45% compared to diesel) while maintaining lower smoke over the entire load range. Meanwhile, NO_x emissions of FAME blends increased on average by up to 12%, although other emissions (CO, HC) decreased. Higher λ values reduced smoke but increased CO emissions if the blend had a significant viscosity effect.
5. Regression tree and Random Forest models, developed based on experimental data, were characterised by high prediction accuracy – pseudo-R^2 > 0.94 for all modelled output parameters. In the Random Forest model, λ (42%) and fuel type (33%) had the greatest influence. Solution analysis revealed that the most important factors for NO_x emission reduction are appropriate excess air and HVO dominance in the mixture. The models allow for a quick assessment of the effect of various parameter combinations without additional experiments.

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Summary in Lithuanian

Įvadas

Problemos formulavimas

Energetikos ir transporto sektoriai vis didesnį dėmesį skiria iškastinių degalų ištekliams ir jų poveikiui aplinkai. Intensyvus naftos produktų vartojimas prisideda prie klimato kaitos, todėl tampa būtina ieškoti alternatyvių degalų, galinčių užtikrinti energijos efektyvumą ir kartu sumažinti kenksmingų emisijų kiekį.

Atsižvelgiant į šias problemas, Europos Sąjunga (ES) ir kitos tarptautinės organizacijos skatina pereiti prie atsinaujinančių energijos šaltinių, o biodyzelinas tampa viena iš perspektyviausių alternatyvų. Biodyzelinas, gaminamas iš augalinių aliejų arba gyvūninės kilmės riebalų, išsiskiria geresnėmis aplinkosauginėmis savybėmis, tačiau jo poveikis variklio darbui ir išmetamųjų dujų sudėčiai vis dar kelia mokslinių diskusijų. Nepaisant biodyzelino pranašumų, tokių kaip mažesnės CO_2 emisijos ir geresnės tepimo savybės, jo fizikinės ir cheminės savybės, įskaitant degimo charakteristikas, lieka nepakankamai ištirtos, ypač maišant jį su pirmosios ir antrosios kartos biodegalais. Tačiau šių biodegalų derinių poveikis variklio energiniams ir ekologiniams rodikliams dar nėra pakankamai išanalizuotas.

Išnagrinėjus alternatyvių degalų, skirtų dyzeliniams varikliams, literatūrines apžvalgas, nustatyta, kad trūksta informacijos apie biodyzelino mišinius, sudarytus iš antrosios kartos biodegalų: HVO ir riebalų rūgščių metilo esterių. Ši spraga paskatino atlikti tyrimus, siekiant įvertinti šių mišinių degimo, energinius ir ekologinius parametrus. Fizinės ir cheminės šių mišinių savybės buvo nagrinėjamos siekiant išsamiai įvertinti jų potencialą naudoti dyzeliniuose varikliuose pagal taikomus standartus.

Darbo aktualumas

Transporto sektorius aktyviai ieško tvaresnių alternatyvų, motyvuojančių aplinkosaugos iššūkių ir būtinybės sumažinti priklausomybę nuo iškastinio kuro. Biodegalų naudojimas padeda sušvelninti transporto sektoriaus poveikį aplinkai ir kartu užtikrinti degalų tiekimo saugumą, laikantis Europos Sąjungos ir pasaulinių aplinkosaugos iniciatyvų nustatytos politikos. Biodyzelinas, gaunamas tiek iš augalinių, tiek iš gyvūninių riebalų, išsiskiria kaip patraukli alternatyva tradiciniam dyzelinui dėl savo biologinio skaidumo, atsinaujinančių savybių ir sumažinto išmetamųjų teršalų kiekio. Tačiau įprastiniai pirmosios kartos biodyzelinai, gaunami iš vartojamųjų augalinių aliejų, susiduria su etiniais ir finansiniais sunkumais dėl konkurencijos dėl žemės ūkio žaliavų. Kaip tvaresnis pakaitalas iškyla antros kartos biodyzelinai, įskaitant hidrinimu valytus augalinius aliejus (HVO) ir riebalų rūgščių metilo esterius (RRME), gautus iš atliekų arba nemaistinių riebalų. Šie pokyčiai galėtų padėti kurti žiedinę ekonomiką ir sumažinti poveikį maisto grandinei.

Nors biodyzelinas turi privalumų, įvairių biodegalų ir jų derinių poveikis uždegimo suspaudimu variklių eksploatacinėms charakteristikoms vis dar nėra tinkamai ištirtas. Visų pirma, trūksta duomenų apie skirtingų pirmos ir antros kartos biodyzelino mišinių proporcijų poveikį degimo procesui, variklio efektyvumui ir išmetamųjų teršalų sudėčiai.

Šios disertacijos aktualumas grindžiamas poreikiu išsamiai išanalizuoti gyvūninės kilmės ne maisto riebalų ir pirmos bei antros kartos biodyzelino mišinių naudojimo uždegimo suspaudimu varikliuose perspektyvas. Eksperimentiniai tyrimai leis nustatyti optimalius degalų mišinius, kurie užtikrintų geriausią ekologinių ir energetinių rodiklių pusiausvyrą. Gauti rezultatai prisidės prie efektyvesnio alternatyvių biodegalų taikymo transporto sektoriuje, mažinant neigiamą poveikį aplinkai ir didinant atsinaujinančių energijos šaltinių naudojimo galimybes. Disertacijos išvados gali būti reikšmingos tiek mokslinių tyrimų plėtrai, tiek praktiniam biodegalų naudojimui.

Tyrimo objektas

Tyrimo objektas – mišinių, kurių sudėtyje yra atsinaujinančių komponentų, skirtų naudoti suspaudimo uždegimo varikliuose, degimo procesas.

Darbo tikslas

Disertacijos tikslas – nustatyti gyvūninės kilmės nemaistinių riebalų bei pirmosios ir antrosios kartos biodyzelino degalų mišinių poveikį slėginio uždegimo variklio ekologiniams ir energiniams rodikliams, siekiant įvertinti jų tinkamumą kaip alternatyvą įprastam dyzelinui.

Darbo uždaviniai

Siekiant įgyvendinti užsibrėžtą tikslą, buvo sprendžiami šie uždaviniai:

1. Paruošti ir išanalizuoti biodegalų mišinius, sudarytus iš nemaistinės gyvūninės kilmės riebalų bei pirmosios ir antrosios kartos biodyzelino, įvertinant jų fizines ir chemines savybes.

2. Atlikti eksperimentinius tyrimus, siekiant nustatyti gyvūninių riebalų ir pirmos bei antros kartos biodegalų mišinių poveikį slėginio uždegimo variklio darbo parametrams, įskaitant degimo proceso eigą, slėgio pokyčius cilindre ir uždegimo vėlavimą.
3. Išanalizuoti variklio energetinį efektyvumą naudojant įvairius biodegalų mišinius, įvertinant degalų sąnaudas, terminį naudingumo koeficientą ir šiluminės energijos konversiją esant skirtingoms variklio apkrovoms ir darbo sąlygoms.
4. Įvertinti biodegalų mišinių ekologinį poveikį, analizuojant išmetamųjų dujų (CO_2, CO, NO_x, HC ir dūmų) kiekį ir nustatant jų atitiktį aplinkosaugos standartams.
5. Sukurti matematinį modelį, skirtą analizuoti degalų mišinių degimo procesus slėginio uždegimo varikliuose ir prognozuoti jų poveikį variklio efektyvumui bei emisijoms.

Tyrimų metodika

Eksperimentiniai tyrimai buvo atliekami dviem etapais:

- Olštyno Mechatronikos ir IT mokymo katedroje buvo paruošti degalų mišiniai.
- Vilniaus Gedimino technikos universiteto (VILNIUS TECH) Transporto inžinerijos fakulteto laboratorijoje buvo išbandyti degalai keturių cilindrų vidaus degimo variklyje su tiesiogine degalų įpurškimo sistema.
- Eksperimentiniams bandymams buvo atrinkti devyni skirtingos sudėties degalų mišiniai, kurių veiksmingumas buvo lyginamas su įprastu dyzelinu. Degalų degimo procesai buvo toliau analizuojami naudojant AVL BOOST programinę įrangą.

Darbo mokslinis naujumas

Šios disertacijos rengimo metu Transporto inžinerijos mokslui buvo gauti šie nauji rezultatai:

1. Sukurtas naujas hibridinis eksperimentinis-skaitmeninis metodas, skirtas degalų mišinių poveikiui variklio veikimui įvertinti, integruojant slėgio bangų analizę, AVL BOOST modeliavimą ir biologinės kilmės degalų fizikines bei chemines savybes, kurios anksčiau nebuvo taikytos gyvūninių riebalų ir HAA/RRME mišinių tyrimuose.
2. Pirmą kartą eksperimentiškai nustatytas optimalių HAA ir gyvūninių riebalų proporcijų poveikis degimo uždelsimui, šilumos išsiskyrimo greičiui ir NO_x emisijoms esant skirtingoms variklio apkrovoms – tai suteikia naujų žinių apie šių degalų mišinių degimo dinamiką.
3. Sukurti regresinio medžio pagrindu sukurti prognozavimo modeliai, kurie numato išmetamųjų teršalų lygius ir variklio efektyvumo rodiklius >0,94 pseudo-R^2 tikslumu pagal degalų sudėtį, oro perteklių (λ) ir apkrovą – tai originalus duomenų analizės sprendimas biodegalų tyrimuose.

Darbo rezultatų praktinė reikšmė

1. Nustatyti optimalūs biodegalų mišiniai, tinkami naudoti suspaudimo uždegimo varikliuose siekiant sumažinti emisijas ir išlaikyti variklio efektyvumą.

2. Eksperimentiniai duomenys ir analizės metodai gali būti taikomi transporto inžinerijoje ir biodegalų pramonėje, kuriant naujus degalus ir optimizuojant jų naudojimą.
3. Tyrimo rezultatai prisideda prie ES ekologinių reikalavimų įgyvendinimo, skatinant atsinaujinančių energijos išteklių naudojimą ir mažinant priklausomybę nuo iškastinių degalų.
4. Tyrimo išvados gali būti taikomos variklių gamintojams ir degalų tiekimo sektoriui, siekiant geriau suderinti biodegalų savybes su šiuolaikinių dyzelinių variklių technologijomis.

Ginamieji teiginiai

1. Biodegalų mišinių sudėtis daro reikšmingą įtaką slėginio uždegimo variklio degimo procesui, emisijų lygiui ir energiniams rodikliams, lyginant su įprastu dyzelinu.
2. Antrosios kartos biodyzelino ir gyvūninės kilmės riebalų mišiniai sumažina CO, HC ir kietųjų dalelių emisijas, tačiau jų poveikis NO_x emisijoms priklauso nuo degalų sudėties ir variklio darbo sąlygų.
3. Eksperimentiniai tyrimai patvirtina, kad tinkamai parinkti biodegalų mišiniai naudojami dyzeliniuose varikliuose be reikšmingų konstrukcinių pakeitimų, išlaikant jų eksploatacines savybes.
4. Matematinis modeliavimas leidžia tiksliai prognozuoti degalų mišinių poveikį variklio darbo parametrams ir emisijoms, sudarant prielaidas optimizuoti degalų sudėtį pagal aplinkosauginius ir energinius kriterijus.

Darbo rezultatų aprobavimas

Disertacijos tema buvo paskelbti 5 moksliniai straipsniai: 2 – recenzuojamuose mokslo žurnaluose, įtrauktuose į *Web of Science* duomenų bazę; 2 –*Web of Science* konferencijų leidiniuose; 1 – kituose recenzuojamuose mokslo leidiniuose.

Tyrimo rezultatai buvo pristatyti trijose tarptautinėse mokslinėse konferencijose Lietuvoje ir užsienyje:

- „TRANSBATICA XI: Transporto mokslas ir technologijos“, 2019 m., Vilnius, Lietuva.
- 17-oji tarptautinė jaunųjų mokslininkų konferencija energetikos ir gamtos mokslų klausimais „CYSENI 2021“: 2021 m. gegužės 24–28 d., Kaunas, Lietuva.
- „VII Jaunųjų mokslininkų akademija“, 2023 m. lapkričio 13–15 d., Lesna, Lenkija.

Disertacijos struktūra

Disertacija susideda iš įvado, keturių skyrių, išvadų, santraukos lietuvių kalba ir literatūros sąrašo. Bendra darbo apimtis – 84 puslapiai, įskaitant: 19 sunumeruotų formulių, 38 paveikslus, 8 lenteles. Disertacijoje naudota 127 literatūros šaltiniai.

Padėka

Noriu padėkoti savo vadovui doc. Dr. Jonui Matijošiui už pagalbą visuose disertacijos etapuose. Noriu padėkoti prof. dr. Alfredui Rimkui už kantrybę, dėmesį ir pagalbą apdorojant AVL BOOST modeliavimo programos medžiagas degimo procesui tirti.

Nuoširdžiai dėkoju prof. Sławomirui Wierzbickui ir doc. Prof. Kamil Duda už neįkainojamą pagalbą man stažuojantis Varmijos ir Mozūrų universitete Olštyne.

1. Biodyzelino savybių ir jo naudojimo suspaudimo uždegimo varikliuose apžvalga

Atsinaujinančių energijos šaltinių plėtra vis dažniau pripažįstama kaip vienas iš pagrindinių transporto sektoriaus tikslų, siekiant sumažinti priklausomybę nuo iškastinio kuro ir mažinti šiltnamio efektą sukeliančių dujų emisijas. Europos Sąjunga ir įvairios tarptautinės organizacijos yra įdiegusios griežtus standartus, siekdamos sumažinti transporto priemonių išmetamų teršalų kiekį ir skatinti alternatyvių degalų, įskaitant biodyzeliną, naudojimą (Potrč ir kt., 2021).

Iš įvairių organinių žaliavų gaunami biodegalai gali būti potenciali dyzelino alternatyva, tačiau jų charakteristikos ir poveikis variklio darbui tebėra mokslinių diskusijų objektas (Chong ir kt., 2021). Biodyzelinas yra skystieji degalai, gaunamas cheminės transesterifikacijos būdu iš augalinių aliejų arba gyvūninių riebalų. Degimo metu išmetamas anglies dioksidas (CO_2) yra natūraliai susijęs su anglies ciklu, todėl biodyzelino naudojimas gali reikšmingai sumažinti šiltnamio efektą sukeliančių dujų emisijas (Banković-Ilič ir kt., 2014).

Be to, biodegalai pasižymi geresnėmis tepimo savybėmis nei įprastas dyzelinas, todėl gali sumažinti variklio komponentų susidėvėjimą (Mahlia ir kt., 2020; Athar & Zaidi, 2020). Tačiau pirmosios kartos biodyzelinas gali konkuruoti su maisto gamyba, nes jo gamybai naudojami valgomieji augaliniai aliejai, o tai kelia žaliavų tiekimo iššūkių (Bessou ir kt., 2011).

Antrosios kartos biodegalai, įskaitant hidroapdorotus augalinius aliejus (HVO) ir riebalų rūgščių metilo esterius (FAME), yra gaminamas iš atliekų arba ne maistinių žaliavų, tokių kaip panaudoti maistiniai aliejai ir gyvūninės kilmės riebalai (Othman ir kt., 2017). Transporto sektoriuje biodegalai gali būti naudojamas gryna forma arba maišomas su įprastu dyzelinu, atsižvelgiant į jo fizines ir chemines savybes (Candeia ir kt., 2009).

Moksliniai tyrimai rodo, kad HVO ir FAME mišinių naudojimas kartu su dyzelinu gali užtikrinti panašų variklio efektyvumą, tačiau jų poveikis išmetamųjų dujų sudėčiai skiriasi. Pavyzdžiui, FAME pasižymi didesniu rūgštingumu ir higroskopiškumu, kas gali turėti neigiamą poveikį degalų tiekimo sistemoms (Suarez-Bertoa ir kt., 2019). Priešingai, HVO yra labiau suderinamas su šiuolaikinių dyzelinių variklių eksploatacinėmis savybėmis, nes pasižymi didesniu cetano skaičiumi ir mažesniu tankiu.

Nors biodegalai turi nemažai privalumų, jo diegimas transporto sektoriuje susiduria su įvairiais technologiniais iššūkiais. Pirma, kadangi biodegalai gali turėti skirtingą cheminę sudėtį nei įprastas dyzelinas, būtina išsamiai ištirti jo poveikį degimo trukmei, maksimaliam cilindro slėgiui ir energijos konversijos efektyvumui (Heywood, 2018). Be to, svarbu analizuoti degalų mišinių poveikį emisijų lygiui, ypač azoto oksidų (NO_x) susidarymui, kuris kai kurių biodegalų mišinių atveju gali padidėti (Yesilyurt ir kt., 2020).

Šios disertacijos kontekste ypač svarbu ištirti gyvūninės kilmės nemaistinių riebalų bei pirmosios ir antrosios kartos biodyzelino mišinių savybes ir jų suderinamumą su slėginio uždegimo varikliais. Kadangi gyvūninės kilmės riebalai turi didesnį klampumą ir mažesnį oksidacinį stabilumą nei tradiciniai augaliniai aliejai, būtina detaliai ištirti jų poveikį degalų tiekimo sistemos veikimui ir išmetamųjų dujų sudėčiai (Kirubakaran & Selvan, 2018).

Eksperimentiniai tyrimai gali padėti nustatyti optimalias degalų mišinių proporcijas, leidžiančias užtikrinti gerą variklio efektyvumą ir mažesnę aplinkos taršą (Knothe ir kt., 2005). Biodyzelino savybės ir jo poveikis suspaudimo uždegimo variklių veikimui priklauso nuo naudojamų žaliavų fizikinių ir cheminių parametrų. Pagrindinės biodyzelino gamybai naudojamos medžiagos yra augaliniai aliejai ir gyvūninės kilmės riebalai, kuriuose trigliceridai yra pagrindiniai komponentai. Degalų klampumas, oksidacinis stabilumas, uždegimo charakteristikos ir degimo procesas priklauso nuo trigliceridų struktūros bei riebalų rūgščių sudėties (Ramos ir kt., 2019).

Transesterifikacija yra pagrindinis biodyzelino gamybos procesas, kurio metu trigliceridai paverčiami riebalų rūgščių metilo esteriais. Ši reakcija vyksta tarp trigliceridų ir alkoholio (dažniausiai metanolio arba etanolio), naudojant šarminius, rūgštinius arba fermentinius katalizatorius (Zahan & Kano, 2019). Efektyvi transesterifikacija leidžia sumažinti nepageidaujamų šalutinių produktų kiekį ir užtikrina aukštą metilo esterių išeigą.

2. Eksperimentinių tyrimų metodologija ir biodyzelino mišinių matematinis modeliavimas naudojant regresinius medžius

Eksperimentiniai tyrimai buvo atlikti Vilniaus Gedimino technikos universiteto Transporto inžinerijos fakulteto laboratorijoje (Lietuva). Tyrimui buvo naudojamas keturių cilindrų vidaus degimo variklis, turintis tiesioginę degalų įpurškimo sistemą.

Variklio bandymai, skirti įvertinti analizuojamų degalų mišinių eksploatacines savybes, buvo atlikti esant nustatytoms variklio darbo sąlygoms, kai sukimosi dažnis siekė n = 2 000 min^{-1}.

Pagrindiniai variklio parametrai (žr. 1S lentelę) apėmė 1 900 cm³ darbinio tūrio vidaus degimo variklį su turboripūtimu ir elektroniniu degalų įpurškimo siurbliu. Degalų įpurškimo pradžia (SOI) buvo valdoma variklio elektroninio valdymo bloko (ECU) pagal vienkartinio įpurškimo procedūrą.

1S lentelė. Pagrindiniai variklio parametrai

Apibūdinimas	Parametras
Variklis	1.9 L Turbodyzelinis tiesioginio įpurškimo
Cilindrų skaičius	4
Suslėgimo laipsnis	19.5
Eiga	95.5 mm
Skersmuo	79.5 mm
Maksimali galia	66 kW esant 4 000 min^{-1}
Maksimalus sukimo momentas	182 Nm esant 2 000–2 500 min^{-1}

Degimo procesų analizei, naudojant įvairius biodegalų mišinius slėginio uždegimo variklyje, buvo taikoma AVL BOOST programinė įranga. Į AVL BURN moduliui pateiktus duomenis įėjo šie variklio parametrai: cilindro skersmuo, stūmoklio eiga, suspaudimo laipsnis, degimo kameros tūris, švaistiklio ilgis, darbo taktų skaičius, įsiurbimo ir išmetimo kolektorių tūriai, variklio sūkių dažnis, efektyvusis vidutinis slėgis (BMEP), degimo pradžios kampas (SOC), degimo trukmė (CD), degalų masės srautas (mv), degalų mažiausia šiluminė vertė (LHV).

Esant 2 000 min^{-1}. variklio sukimosi dažniui, bandymai buvo atliekami su šiomis apkrovomis: 30 Nm, 60 Nm, 90 Nm ir 120 Nm. Variklio apkrovos ir degalų įpurškimo pradžios reikšmės pateiktos 2S lentelėje.

Pagrindinės biodegalų charakteristikos daugumoje šalių yra reglamentuojamos pagal priimtus nacionalinius standartus. Šiame tyrime dyzeliniams varikliams skirtų degalų mišinių savybės buvo vertinamos pagal tris Europos Sąjungos degalų standartus: EN 590 – standartas, taikomas dyzelinui, skirtam dyzeliniams varikliams; EN 14214 – standartas, apibrėžiantis riebalų rūgščių metilo esterių (FAME) reikalavimus ir bandymo metodus dyzeliniams varikliams.

2S lentelė. Variklio apkrova ir degalų įpurškimo pradžia

Matavimo taškai	1	2	3	4
Variklio sūkiai *n*, min^{-1}	2000	2000	2000	2000
Variklio sukimo momentas M_B, Nm	30	60	90	120
BMEP, MPa	0.2	0.4	0.6	0.8
SOI, CAD	–4	–5	–6	–7

Įvairių degalų fizikinių ir cheminių savybių palyginimas pateiktas 3S lentelėje.

3S lentelė. Degalų fizikinių ir cheminių savybių palyginimas

Degalai	Tankis (kg/m^3) esant 15°C	Klampumas (mm^2/s) esant 40°C	Pliūpsnio temperatūra °C	Sieros kiekis mg/kg	Vandens kiekis mg/kg	Bendras užterštumas [mg/kg]	Oksida-cijos sta-bilumas [h]	Rūgšties skaičius [mg KOH/g]	Šaltojo filtro užsikimšimo taškas °C
1	2	3	4	5	6	7	8	9	10
Leidžiama vertė pagal kokybės standartą EN 590									
	820–845	2–4,5	≥55	≤10	≤200	≤24	≥20	–	–
Leidžiama vertė pagal kokybės standartą EN 14214									
	860–900	3,5–5	≥101	≤10	≤500	≤24	≥8	≤0,5	–
Leidžiama vertė pagal brošiūros informaciją Neste Renewable Diesel for HVO									
	770–790	2-4	≥61	≤5	≤200	≤10	–	–	–
D100	823	3.5	45	7.35	85	20	17	–	10
HVO	776	2,9	79	4,16	20	5,52	≥6	0,04	–20
FE25	800	3,2	84	4,12	120	7,05	1,82	0,03	–7
FE50	824	3,4	87	4,27	150	12,35	1,79	0,05	–3
FE75	849	3,9	93	4,37	400	16,04	0,18	0,09	1
FE100	873	4,3	102	5,41	460	19,78	0,18	0,08	4
F25	800	4,7	86	4,52	690	43,27	1,35	0,1	6
F50	831	9,8	97	4,87	770	neįmanoma patikrinti šio pavyzdžio	0,70	0,3	10
F75	867	18,8	115	5,21	925		0,44	0,5	17
F100	908	34,8	197	5,31	1450		0,44	0,7	24

Degalai	Vandenilio kiekis %	Anglies kiekis %	Deguonies kiekis %	C/H	Žemutinis šilumingumas [MJ/kg]	Cetaninis skaičius
D100	0.130	0.870	0.000	6.69	42.70	45
FE25	0.1460	0.8233	0.0308	5.6	42.30	69.95
FE50	0.1400	0.7985	0.0615	5.7	41.05	64.52
FE75	0.1340	0.7738	0.0923	5.8	39.53	59.41

3S lentelės pabaiga

1	2	3	4	5	6	7	8	9	10
FE100	0.1280	0.7490	0.1230	5.8		38.00		58	
F25	0.146	0.827	0.027	5.64		42.40		72.04	
F50	0.141	0.804	0.055	5.70		40.70		67.19	
F75	0.136	0.782	0.082	5.77		39.00		62.34	
F100	0.130	0.760	0.110	5.85		37.30		57.49	
HVO100	0.152	0.848	0.00	5.58		43.70		76.89	

Antrajame skyriuje atliktas tyrimas buvo skirtas tinkamiausių biodegalų mišinių parinkimui, jų tyrimo metodikos sukūrimui bei matematinio modelio, pagrįsto regresinių medžių metodu, taikymo pagrindimui.

Gautos išvados leidžia tiksliai nustatyti tolesnius eksperimentinių ir modeliavimo tyrimų etapus, siekiant įvertinti degalų mišinių poveikį slėginio uždegimo variklio darbo parametrams.

3. Skaitinis ir eksperimentinis biodegalų mišinių tyrimas

Variklio darbo ciklas buvo modeliuojamas naudojant AVL BOOST skaitmeninio modeliavimo programinę įrangą, kuri modeliuoja termodinaminius procesus degimo metu cilindre. Šis modeliavimas pagrįstas termodinamikos dėsniais (Bellér ir kt., 2021). Degimo procesas buvo analizuojamas naudojant AVL BOOST BURN įrankį, siekiant palyginti skirtingų degalų našumą panašiomis sąlygomis.

Skaitinis variklio darbo ciklo modeliavimas ir analizė, naudojant Hidrinti augaliniai aliejai ir riebalų rūgščių metilo esteris degalų mišinius

Esant šiai apkrovai (*BMEP* = 0,4 MPa), bandymų metu visiems degalams degalo įpurškimo pradžios momentas (SOI) buvo nustatytas pastovus – 5° alkūninio veleno pasisukimo kampo (CAD).

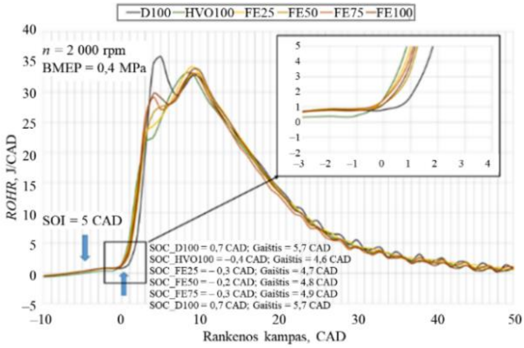
Degimo pradžios momentas (SOC) ir uždegimo vėlinimo trukmė (ID) priklausomai nuo degalų tipo pateikti 1S paveiksle.

Lyginant skirtingus degalų mišinius, pastebėta, kad HVO degimas prasideda anksčiau nei kitų degalų, esant vienodam degalų padavimo pradžios momentui. Tai rodo, kad HVO turi trumpiausią uždegimo vėlinimo trukmę, palyginti su kitais kuro tipais.

Esant *BMEP* = 0,4 MPa apkrovai, bandymų metu visiems degalams įpurškimo pradžia (SOI) buvo pastovi – 5 CAD. Degimo pradžios momentas (SOC) ir uždegimo vėlinimas (ID), priklausomai nuo degalų rūšies, pateikti 1S paveiksle.

Eksperimentiniai tyrimai parodė, kad HVO ir jo mišiniai pasižymi trumpesniu uždegimo vėlinimu nei dyzelinas, o tai siejama su aukštesniu cetano skaičiumi (Uyumaz, 2018). Esant 4 CAD, HVO šilumos išsiskyrimo greitis buvo ~34 % mažesnis nei D100. Tai rodo, kad HVO pasižymi mažesniu šilumos išsiskyrimo piko greičiu, palyginti su dyzelinu. Dyzelinas turi ilgesnį uždegimo vėlinimą dėl didesnio klampumo, kuris lėtina degalų garavimą ir suskaidymą į mažesnes daleles, taip pailginant uždegimo vėlinimą. Uždegimo vėlinimo trukmė taip pat priklauso nuo anglies atomų skaičiaus degalų mišinio molekulėse.

Palyginus FE100 ir dyzeliną, FE100 turi mažiau anglies, todėl jo uždegimo vėlinimas trumpesnis. Šilumos išsiskyrimo greitis esant 4 CAD, palyginti su mineraliniu dyzelinu: FE25 – mažesnis ~29 %, FE50 – mažesnis ~23 %, FE75 – mažesnis ~15 %, FE100 – mažesnis ~14 %.



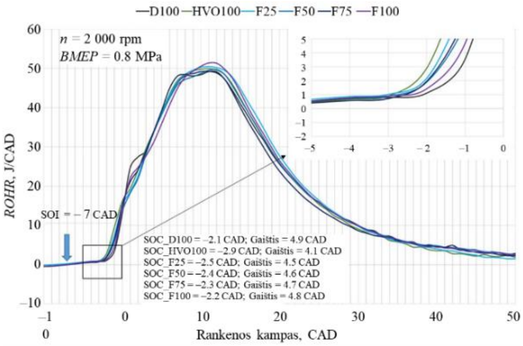
1S pav. Šilumos išsiskyrimo greitis cilindre priklausomai nuo alkūninio veleno pasisukimo kampo (CAD) naudojant HVO ir FAME degalų mišinius

Tai patvirtina ir žemesnis maksimalus degimo greitis greitojo degimo fazėje. Didinant esterių koncentraciją degalų mišinyje, pastebima maksimalaus degimo greičio mažėjimo tendencija per greitąją uždegimo fazę. HVO mažesnis klampumas, palyginti su dyzelinu, pagerina degalų mišinio su oru formavimosi charakteristikas pirminėje degimo fazėje. Tai reiškia, kad HVO garuoja greičiau ir todėl greičiau susimaišo su aplinkiniu oru nei dyzelinas. Tą pačią tendenciją pastebėjome ir HVO mišiniuose. Analizuojant trečiąją degimo fazę (difuzinį degimą), pastebėta, kad HVO100 pasiekia savo degimo piką anksčiau nei kiti degalai. Tai paaiškinama ankstesne degimo pradžia. Tuo tarpu dyzelinas pasižymi mažiausiu maksimaliu degimo greičiu difuzinio degimo fazėje, nes pirmojo degimo etapo metu sudega didesnė kuro dalis (Marasri ir kt., 2019). Esant 9 CAD, HVO šilumos išsiskyrimo greitis buvo ~1 % didesnis nei D100. FE100 šilumos išsiskyrimo greitis buvo ~3 % didesnis nei mineralinio dyzelino. FE25, FE50 ir FE75 šilumos išsiskyrimo tendencijos buvo atitinkamai ~4 %, 1 % ir 1 %.

Skaitinis variklio darbo ciklo modeliavimas ir analizė, naudojant hidrintus augalinius aliejus ir anties riebalų degalų mišinius

Degimo pradžia (SOC) ir uždegimo vėlinimo trukmė (ID) skirtingiems degalams esant BMEP = 0,8 MPa pateikti 2S paveiksle. Eksperimentinių duomenų analizė parodė, kad visų degalų įpurškimo pradžia (SOI) buvo 7 CAD prieš VMT (bTDC). Skirtingų degalų uždegimo vėlinimo trukmė didėjo tokia tvarka: HVO100 → F25 → F50 → F75 → F100 → D100. Trumpesnį biodegalų mišinių uždegimo vėlinimą, palyginti su dyzelinu, lemia jų didesnis cetano skaičius. Be to, nustatyta, kad biodyzelino injekcijos metu aukštoje temperatūroje susidarę mažos molekulinės masės dujiniai junginiai gali užsidegti anksčiau, taip sutrumpindami uždegimo vėlinimo fazę ir pagreitindami degimo proceso pradžią.

Didėjant variklio apkrovai (BMEP = 0,8 MPa), degalų suvartojimas augo tokia tvarka: HVO100 → D100 → F25 → F50 → F75 → F100. Taip yra dėl to, kad biodegalų mišinių kaloringumas yra mažesnis nei dyzelino (1S lentelė). Dėl to didėja įpurškiamų degalų masė, o tai savo ruožtu kelia temperatūrą degimo kameroje (2S paveikslas). Anties riebalų priedas prie HVO padidina įpurškiamų degalų masę, todėl ilgėja uždegimo vėlinimas. Taip yra dėl didesnio šilumos suvartojimo degalų lašelių garavimui.



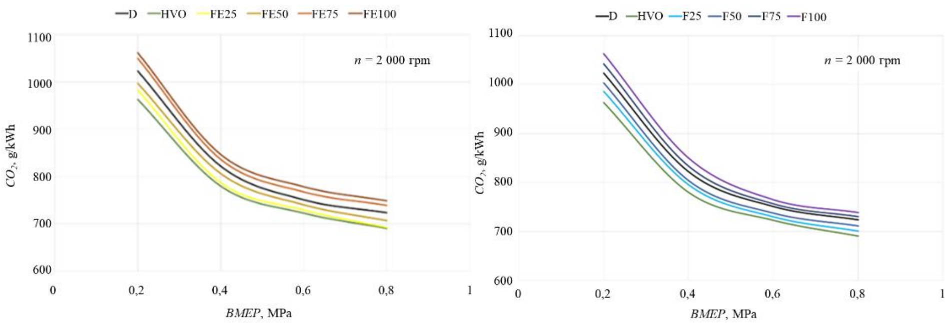
2S pav. Šilumos išsiskyrimo greitis cilindre priklausomai nuo alkūninio veleno pasisukimo kampo (CAD) naudojant HVO ir anties riebalų degalų mišinius

Kadangi HVO pasižymi trumpesne uždegimo vėlinimo faze, mažesnė degalų dalis sudega premiksinio degimo fazėje, o daugiau – maišymosi kontroliuojamo degimo fazėje. HVO uždegimo vėlinimo fazės sumažėjimas, palyginti su mineraliniu dyzelinu, lemia mažesnę degalų dalį, degančią blyksnio laikotarpiu (premiksiniame degime), todėl difuzinio degimo fazėje sudega didesnė degalų dalis. Vienas iš svarbiausių šių skirtumų degimo procese veiksnių yra degalų klampumas. Remiantis 1S lentele, HVO klampumas yra ~20 % mažesnis nei dyzelino. Anties riebalų priedas į degalų mišinį ženkliai padidina klampumą ir uždegimo vėlinimą. Taigi, pastebima aiški koreliacija tarp degalų klampumo ir uždegimo vėlinimo fazės. 2S paveiksle matyti, kad HVO pirmojo ROHR (šilumos išsiskyrimo greičio) piko vertė priešmišininio degimo fazėje yra 20–25 % mažesnė nei dyzelino, be to, šis pikas pasiekiamas 1 laipsniu anksčiau. Šis dėsningumas paaiškinamas sutrumpėjusia uždegimo vėlinimo faze ir dėl to mažesniu degalų kiekiu, patenkančiu į cilindrą per šį laikotarpį. Anties riebalų priedas į degalus padidina uždegimo vėlinimo fazę ir didina degimo proceso intensyvumą premiksinio degimo fazėje.

Ekologiniai rodikliai: hidroapdoroto augalinio aliejaus, riebalų rūgščių metilo esterių ir anties riebalų degalų mišiniai

Anglies dioksido (CO_2) emisijos mažėjo visų degalų tipų atveju, didėjant variklio apkrovai, kaip parodyta 3S a, b paveiksluose.

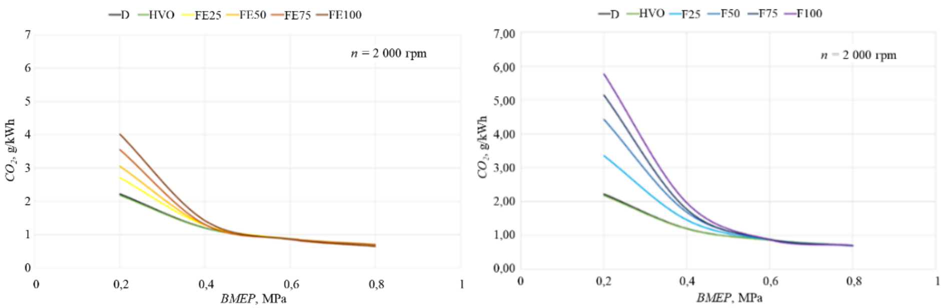
Be to, šiame eksperimente nustatyta, kad degalų mišiniai, kurių vandenilio ir anglies (H/C) santykis yra didesnis, labiausiai prisideda prie CO_2 emisijų mažinimo, nes jų degimas yra efektyvesnis (1S lentelė). HVO pasižymi aukštesniu vandenilio ir anglies santykiu (0,1520 / 0,8480 %), todėl šio degalų tipo CO_2 emisijos buvo mažiausios, palyginti su kitais tirtais mišiniais ir dyzelinu.



(a) (b)

3S pav. Anglies dioksido (CO_2) emisijų priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišinius

4S a paveiksle pateikti CO emisijų duomenys HVO100 esant vidutinei variklio apkrovai: CO emisijos HVO100 buvo ~5 % mažesnės nei D100 ir CO emisijos HVO100 buvo ~15 % didesnės nei FE100. Kaip matyti iš 4S pav., HVO emisijos buvo mažesnės dėl trumpesnės uždegimo vėlinimo fazės, kas lėmė ilgesnį degimo laiką ir efektyvesnį CO oksidacijos procesą. Dyzelinas parodė mažesnes CO emisijas nei kiti tirti degalų mišiniai, o tai aiškinama aukštu anglies ir vandenilio (C/H) santykiu dyzelino sudėtyje.

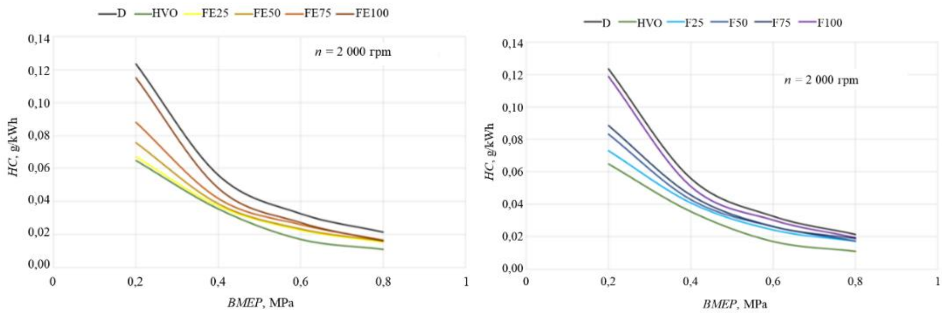


(a) (b)

4S pav. Anglies monoksido (CO) emisijų priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišiniu

Tiriamų esterių turinčių degalų mišinių atveju CO emisijos buvo didesnės nei iškastinio dyzelino, tačiau skirtingų mišinių reikšmės skyrėsi: FE25 – CO emisijos buvo ~6 % didesnės, FE50 – CO emisijos buvo ~7 % didesnės, FE75 – CO emisijos buvo ~8 % didesnės. Vandenilį turintys junginiai, tokie kaip molekulinis vandenilis, pagreitina oksidacijos procesą (El-Shafay ir kt., 2022). Be to, gryni riebaliniai degalų mišiniai yra deguonies turintys degalai, o papildomas deguonies atomas pagerina degalų sudegimą, todėl CO emisijos mažėja.

Didėjant anties riebalų koncentracijai degalų mišinyje, pastebėtos šios tendencijos: Didėjo degalų klampumas ir mažėjo grynasis specifinis kaloringumas (1S lentelė). Esant žemai apkrovai (*BMEP* = 0,2 MPa), F100 CO emisijos buvo ~160 % didesnės nei iškastinio dyzelino (5S b pav.). Tai rodo, kad gryni riebaliniai degalai neužsidega pilnai, nes esant mažam variklio ciklui, slėgis taip pat yra žemas. Dėl to susidaro dideli aukšto tankio ir didelės klampos degalų lašeliai, kurie sudega prasčiau. Ta pati tendencija pastebėta visiems HVO ir riebalų mišiniams. Didinant apkrovą iki *BMEP* = 0,4 MPa, didžiausias CO emisijų skirtumas tarp F100 ir dyzelino buvo ~63 %.



(a) (b)

5S pav. Angliavandenilių (CH) emisijų priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišinius

Esant *BMEP* = 0,4 MPa, buvo stebimas aiškus CH emisijų mažėjimas. Taip pat pastebėta, kad mišinių su vidutine esterių koncentracija emisijų kreivės buvo tarpinėje padėtyje tarp HVO100 ir dyzelino.

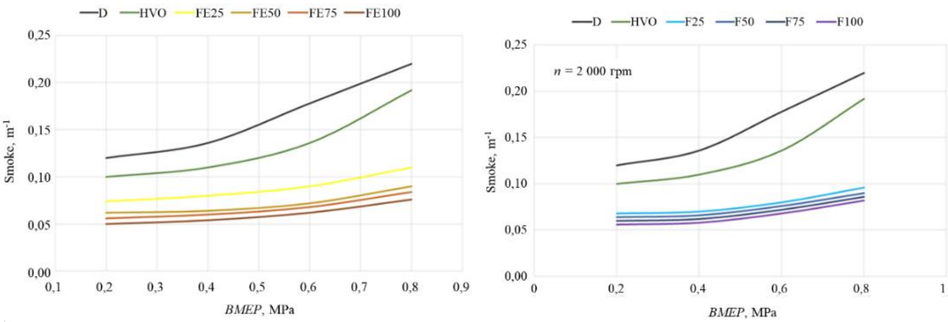
Kaip matyti iš 5S pav., visose apkrovos režimuose degalų mišiniai išskyrė mažiau CH emisijų nei mineralinis dyzelinas, o HVO emisijų reikšmės buvo mažiausios. Visi analizuoti degalų mišiniai parodė mažesnes CH emisijas nei dyzelinas, kaip matyti iš 5S paveikslo: FE100 HC emisijos buvo ~14 % mažesnės nei D100, HVO HC emisijos buvo ~37 % mažesnės nei D100 (5S a pav.). Vidutinės CH emisijų mažėjimo tendencijos kitoms mišinių proporcijoms buvo tokios: FE25 – ~33 % mažiau nei dyzelinas, FE50 – ~30 % mažiau nei dyzelinas, FE75 – ~25 % mažiau nei dyzelinas. Oru nepraturtintas (deguonies neturintis) dyzelinas parodė didžiausias CH emisijas. Vidutiniškai F25, F50, F75 ir F100 mišinių CH emisijos buvo mažesnės nei dyzelino atitinkamai: F25 – ~28 %, F50 – ~23 %, F75 – ~19 %, F100 – ~7 % (5S b paveikslas). Esant didesnėms variklio apkrovoms, HVO HC emisijos buvo ~45 % mažesnės nei dyzelino.

Dūmai susidaro dėl dalinio degalų sudegimo. Pagal 6S pav., HVO dūmingumo lygis vidutiniškai buvo ~18 % mažesnis nei dyzelino. Taip pat visi biodegalų mišiniai turėjo mažesnius dūmingumo rodiklius nei dyzelinas: FE25 – ~47 % mažiau dūmų, FE50 – ~55 % mažiau dūmų, FE75 – ~58 % mažiau dūmų, FE100 – ~62 % mažiau dūmų (6S a paveikslas). Dūmingumo mažėjimas pastebėtas visose apkrovos režimuose, kas siejama su didesniu degalų deguonies kiekiu bei mažesniu C/H santykiu (1S lentelė).

Mišiniai su HVO ir grynaisiais riebalais taip pat parodė mažesnį dūmingumą nei dyzelinas. Vidutinės dūmingumo reikšmės visose apkrovos režimuose: F25 – ~51 % mažiau nei dyzelinas, F50 – ~54 % mažiau nei dyzelinas, F75 – ~56 % mažiau nei dyzelinas, F100 – ~59 % mažiau nei dyzelinas (6S b pav.).

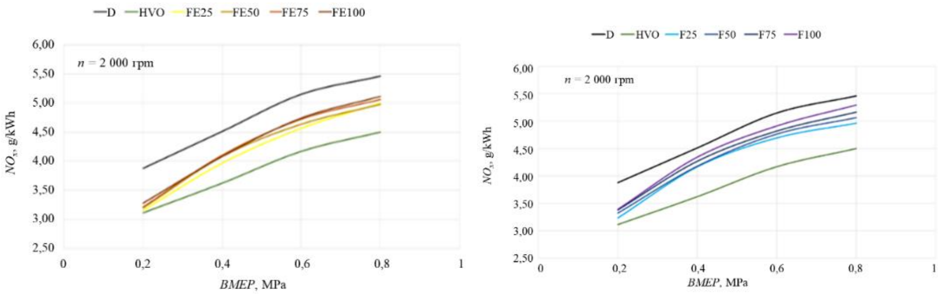
7S a pav. matyti, kad visų tirtų degalų mišinių NO_x emisijos didėjo didėjant variklio apkrovai. Taip yra dėl aukštesnės degimo temperatūros, kuri skatina azoto oksidų susidarymą. Iš visų tirtų degalų didžiausias NO_x emisijų kiekis buvo užfiksuotas naudojant

D100. Vidutiniai NO_x emisijų skirtumai tarp skirtingų degalų mišinių ir dyzelino (D100) įvairiose apkrovos režimuose buvo tokie: HVO100 – NO_x emisijos vidutiniškai buvo ~18 % mažesnės nei D100, F100 – NO_x emisijos buvo vidutiniškai ~5 % mažesnės nei D100.



(a) (b)

6S pav. Dūmingumo emisijų priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišinius



(a) (b)

7S pav. Azoto oksidų (NOx) emisijų priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišinius

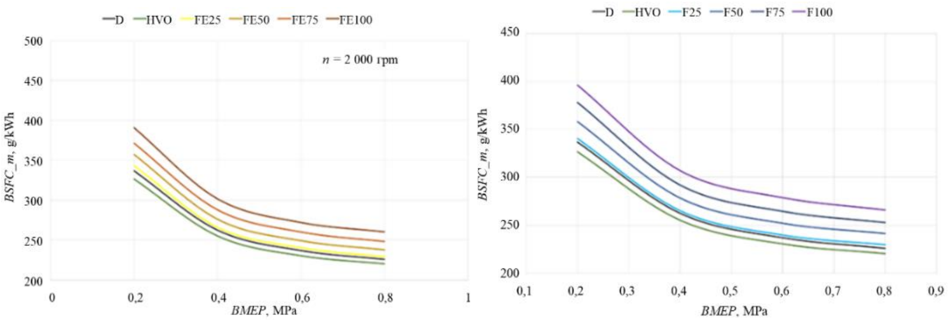
Vidutinės apkrovos režime (*BMEP* = 0,4 MPa) NO_x emisijos sumažėjo: FE25 – ~12 %, FE50 – ~10 %, FE75 – ~10 %, FE100 – ~10 %, HVO100 – ~20 %, palyginti su D100.

Esant aukštai apkrovai (*BMEP* = 0,8 MPa), NO_x emisijų sumažėjimas, lyginant su D100, buvo toks: HVO100 – ~17,6 %, F25 – ~9,1 %, F50 – ~7,2 %, F75 – ~5,4 %, F100 – ~3 % (7S b pav.). Riebalų pagrindu pagaminti degalų mišiniai pagerino degalų oksidaciją degimo proceso metu, o tai vietiniu mastu padidino temperatūrą degimo kameroje ir todėl padidino azoto oksidų (NO_x) emisijas.

Energinių rodiklių palyginimas: hidroapdoroto augalinio aliejaus, riebalų rūgščių metilo esterių ir anties riebalų degalų mišiniai

Vidutinės apkrovos režime (*BMEP* = 0,4 MPa) lyginamosios degalų sąnaudos buvo mažiausios naudojant D100, tačiau tuo pačiu metu jos buvo didesnės nei HVO (8S pav.). Pastebėta aiški tendencija: didėjant esterių koncentracijai degalų mišinyje, didėjo degalų sąnaudos, kaip pavaizduota 8S a pav. Palyginus FE100 su iškastiniu dyzelinu, FE100 degalų sąnaudos buvo ~13 % didesnės. Lyginant D100 su kitais mišinių variantais, degalų sąnaudos padidėjo: FE25 – ~1 %, FE50 – ~5 %, FE75 – ~9 %. Šis degalų sąnaudų padidėjimas turėjo įtakos degimo procesui, nes biodegalai turi mažesnį kaloringumą nei mineraliniai degalai, todėl norint pasiekti tą pačią galią, sunaudojamas didesnis degalų kiekis.

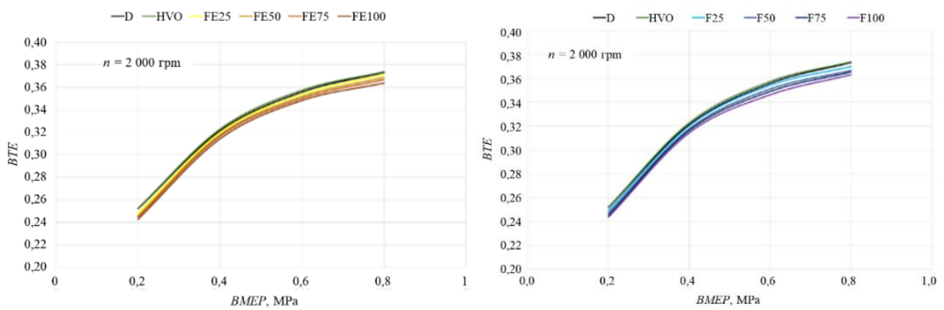
Kaip matyti iš 8S b pav., visų anties riebalų mišinių lyginamosios degalų sąnaudos (*BSFC*, g/kWh) esant didelėms apkrovoms buvo didesnės nei gryno dyzelino. Tačiau HVO BSFC buvo ~2,4 % mažesnės nei gryno dyzelino, kas rodo jo geresnį energinį efektyvumą. Pastebėta tendencija, kad didėjant grynųjų riebalų koncentracijai mišinyje, degalų sąnaudos taip pat didėjo: F100 *BSFC* buvo ~17,7 % didesnės nei dyzelino. Lyginant iškastinį dyzeliną su kitais HVO ir grynųjų riebalų mišiniais, nustatyta tokia *BSFC* didėjimo tvarka: F25 – ~1,6 % didesnės, F50 – ~6,8 % didesnės, F75 – ~11,8 % didesnės. Šis degalų sąnaudų didėjimas aiškinamas tuo, kad riebalų pagrindu pagaminti degalai turi mažesnį kaloringumą nei mineraliniai degalai, todėl varikliui reikia sunaudoti didesnį degalų kiekį norint pasiekti tą patį darbą.



(a) (b)

8S pav. Degalų sąnaudų (BSFC_m) priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišinius

9S a pav. matyti, kad didėjant apkrovai, visų degalų mišinių terminis efektyvumas (*BTE*) didėjo, nes padidėjo iš variklio išgaunama galia. Tačiau visų biodegalų mišinių *BTE* reikšmės buvo mažesnės nei dyzelino, išskyrus HVO, kuris parodė aukščiausią *BTE* tarp visų mišinių, tačiau vis tiek šiek tiek žemesnį nei grynas dyzelinas.



(a) (b)

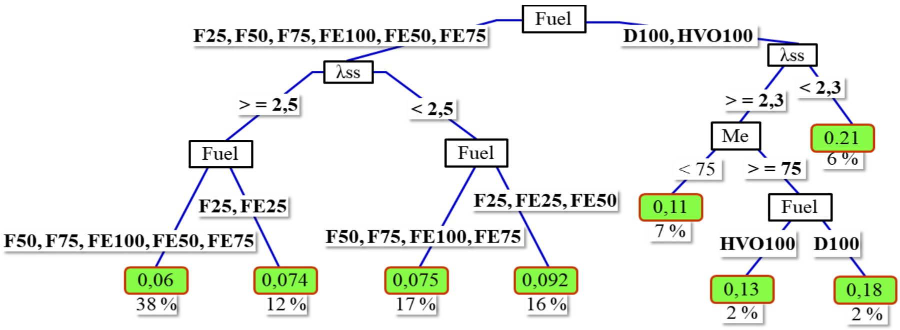
9S pav. Terminio efektyvumo (BTE) priklausomybė nuo apkrovos: (a) – naudojant HVO ir FAME degalų mišinius ir (b) – naudojant HVO ir anties riebalų degalų mišinius

Didėjant biodegalų koncentracijai mišinyje, *BTE* reikšmės mažėjo, nes dėl didesnio klampumo pablogėjo degalų purškimas ir garavimas. Didesnė esterio dalis mišinyje lėmė mažesnį variklio sukimo momentą, nes dėl mažesnės šiluminės vertės buvo išskiriama mažiau energijos. HVO pasižymėjo trumpesne įpurškimo trukme ir trumpesne degimo trukme, kas lėmė efektyvesnį kuro sudegimą. Mažesni aušinimo ir išmetamųjų dujų šilumos nuostoliai padidino HVO BTE, palyginti su dyzelinu.

Aiški tendencija (9S b pav.): didėjant grynųjų riebalų kiekiui mišiniuose, *BTE* mažėjo. Esant *BMEP* = 0,8 MPa, F100 *BTE* buvo vidutiniškai ~2,7 % mažesnis nei dyzelino.

4. Duomenimis grįstas variklio darbo ir emisijų modeliavimas naudojant regresinius medžius

Sprendimų medžiai dažnai pasižymi didele dispersija, tačiau jų tikslumą galima pagerinti apibrėžiant sprendimų medžių rinkinį. Bagging (Bootstrap Aggregating) – tai metodas, pagrįstas atsitiktinai atrinktais mokymo duomenų rinkiniais, kai kiekvienas medis treniruojamas naudojant atskirą atsitiktinį duomenų poskyrį. Atsitiktinių miškų (Random Forest) metodas – tai bagging technikos plėtinys, kai kiekvienam medžiui parenkamas atsitiktinis požymių rinkinys. Tai sumažina dominuojančio kintamojo atrankos problemą ir pagerina modelio stabilumą. Vidutinis ansamblinių metodų prognozių rezultatas yra mažiau koreliuotas ir mažiau kintantis, todėl sprendimų priėmimas tampa patikimesnis.

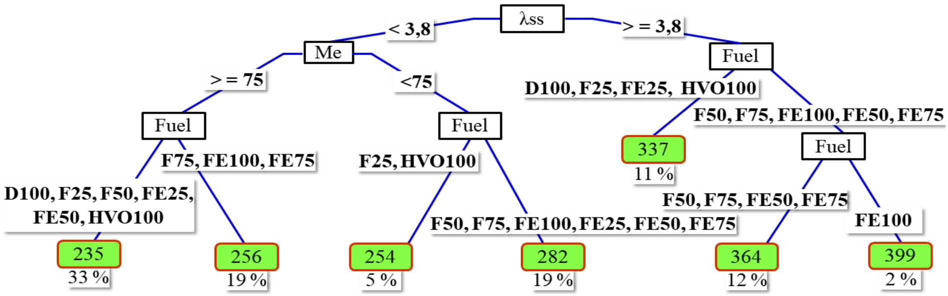


10S pav. Dūmingumo priklausomybė nuo variklio parametrų

Regresiniai medžiai yra galingas įrankis dyzelinių variklių darbo charakteristikoms analizuoti, ypač vertinant dūmingumo (10S pav.) tendencijas, lyginamąsias degalų sąnaudas (*BSFC*_m) (11S pav.) ir terminį efektyvumą (*BTE*) (12S pav.). Šie modeliai padeda suprasti, kaip skirtingi degalų tipai ir degimo sąlygos veikia emisijas.

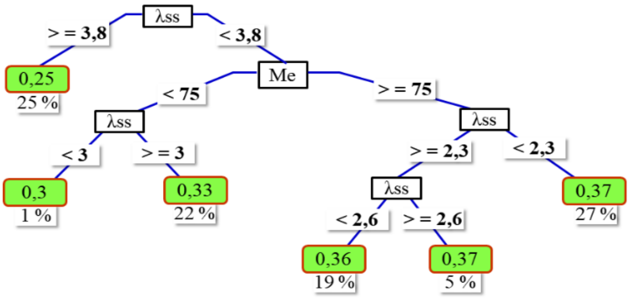
Regresinis modelis (10S pav.) atskleidė, kad: Mažiausios dūmingumo reikšmės buvo pasiektos, kai $\lambda \geq 2,5$, ypač naudojant mišinius F50, F75, FE100, FE25, FE50, FE75. Kai $\lambda < 2,5$, dūmingumo rodikliai didėjo, o tai rodo neefektyvesnį degalų degimą ir didesnę suodžių susidarymo tendenciją.

Regresinis modelis (11S pav.) įvertino *BSFC* priklausomybę nuo perteklinio oro koeficiento (λ), degalų mišinio sudėties ir kitų variklio darbo parametrų. Kai $\lambda < 3,8$, degalų sąnaudos buvo mažiausios, ypač kai Me (papildomi darbo parametrai) ≥ 75. Kai $\lambda \geq 3,8$, degalų sąnaudos padidėjo, o pagrindiniu lemiamu veiksniu tapo degalų sudėtis. Šiuo atveju: D100, F25, FE25 ir HVO100 padidino *BSFC* iki 337 g/kWh, o tai rodo mažesnį energinį efektyvumą dėl didelio perteklinio oro koeficiento. F50, F75, FE100, FE50 ir FE75 dar labiau padidino degalų sąnaudas, kas rodo reikšmingai mažesnį degalų energijos efektyvumą.



11S pav. Lyginamųjų degalų sąnaudų priklausomybė nuo variklio parametrų

Modelis (12S pav.) taip pat analizavo *BTE* priklausomybę nuo perteklinio oro koeficiento (λ) ir papildomų variklio darbo parametrų (Me). Kai λ ≥ 3,8, variklio efektyvumas buvo mažiausias, o *BTE* siekė tik 0,25. Efektyvumas didėjo mažėjant pertekliniam orui, tačiau degimo sąlygos vis dar nebuvo optimalios. Kai Me ≥ 75, *BTE* rodikliai tapo didesni, o aukščiausia *BTE* reikšmė buvo užfiksuota, kai λ < 2,3.



12S pav. Terminio naudingumo koeficiento priklausomybė nuo variklio parametrų

Didžiausias stabdymo terminis efektyvumas (*BTE*) buvo pasiektas, kai perteklinio oro santykis (λ) buvo mažesnis nei 2,3, o variklis dirbo optimaliu režimu (Me ≥ 75). Didėjant λ, efektyvumas mažėjo, ypač kai buvo pasiekta mažiausia *BTE* reikšmė (0,25), kas rodo neefektyvų degimą ir didelius šilumos nuostolius. Norint pasiekti didžiausią variklio našumą, būtina kontroliuoti perteklinio oro koeficientą ir optimizuoti variklio darbo parametrus.

Tyrimui buvo pritaikyti du pagrindiniai modeliai (4S lentelė): Regresiniai medžiai ir Atsitiktiniai miškai (Random Forest). Pseudo-R^2 reikšmės parodė, kad: Didėjant pseudo-R^2, modelis geriau atitiko realius duomenis. Atsitiktinių miškų metodas nuosekliai turėjo didesnes pseudo-R^2 reikšmes nei regresiniai medžiai, kas rodo tikslesnes prognozes.

Abu modeliai tiksliausiai prognozavo variklio efektyvumo rodiklius, todėl jie buvo patikimiausi degalų sąnaudų ir energinio efektyvumo analizei. Tačiau: Dūmingumo modelis parodė didžiausią pagerėjimą taikant atsitiktinių miškų metodą, kuris užtikrino aukštesnę pseudo-R^2 reikšmę. Atsitiktinių miškų metodas buvo tikslesnis nei pavienis regresinis medis, kai reikėjo modeliuoti variklio darbo parametrus ir emisijas.

4S lentelė. Pseudo-R^2 reikšmės

	Regresiniai medžiai	Atsitiktiniai miškai
Dūmingumas	0,948	0,982
BSFC	0,971	0,990
BTE	0,989	0,998
CO	0,958	0,965
CO_2	0,960	0,987
CH	0,951	0,983
NO_x	0,960	0,990

Apskritai, abu metodai davė aukštas pseudo-R^2 reikšmes, todėl jie tinkami modeliuoti biodegalų poveikį variklio darbui.

Bendrosios išvados

Šiame darbe skaitiniai modeliai buvo integruoti su eksperimentiniais duomenimis, leidžiant išsamiai įvertinti biodizelino mišinių poveikį slėginio uždegimo variklio darbo parametrams ir emisijoms. Pagrindinės tyrimo išvados:

1. Eksperimentiškai paruošti biodegalų mišiniai, sudaryti iš HVO, FAME ir gyvulinių riebalų, atitiko pagrindinius EN 590 ir EN 14214 standartų nustatytus fizinius ir cheminius parametrus, išskyrus grynus riebalus (F100), kuriems būdingas per didelis klampumas ir prastos eksploatacinės savybės žemoje temperatūroje. Geriausius dyzelinui artimus parametrus parodė FE25–FE50 ir F25 mišiniai.
2. Variklio darbo eksperimentai parodė, kad HVO turintys degalai užtikrina trumpesnį uždegimo vėlavimą, tolygesnį slėgio kilimą bei mažesnius temperatūros šuolius variklio cilindre, palyginti su FAME ar grynais riebalais. Šie degalai taip pat sumažino smūginių apkrovų ir triukšmo tikimybę. Priešingai, FAME mišiniai pasižymėjo ilgesniu uždegimo vėlavimu ir didesniais slėgio šuoliais.
3. Eksperimentai parodė, kad HVO mišiniai turėjo didžiausią terminį naudingumo koeficientą (BTE), viršijantį net standartinio dyzelino rodiklius, o jų specifinės degalų sąnaudos (BSFC) buvo mažiausios. FAME ir riebalų mišiniai buvo mažiau efektyvūs ir turėjo didesnes degalų sąnaudas dėl didesnio klampumo ir mažesnės šiluminės vertės. BTE ir BSFC rodikliai reikšmingai priklausė nuo mišinio sudėties ir variklio apkrovos.
4. HVO mišiniai reikšmingai sumažino CO, HC ir kietųjų dalelių emisijas (iki 45 % palyginti su dyzelinu) bei išlaikė mažesnį dūmingumą visame apkrovos diapazone. Tuo tarpu FAME mišinių NO_x emisijos vidutiniškai padidėjo iki 12 %, nors kitos emisijos (CO, HC) sumažėjo. Didesnės λ reikšmės sumažino dūmingumą, tačiau, esant dideliam klampumo poveikiui, padidino CO emisijas.
5. Remiantis eksperimentiniais duomenimis sukurti regresinių medžių ir atsitiktinių miškų modeliai pasižymėjo dideliu prognozavimo tikslumu – pseudo-$R^2 > 0,94$ visiems modeliuojamiems išėjimo parametrams. Atsitiktinių miškų modelyje didžiausią įtaką turėjo λ (42 %) ir degalų tipas (33 %). Sprendimų analizė parodė, kad svarbiausi veiksniai NO_x emisijai mažinti yra tinkamas oro perteklius ir HVO dominavimas mišinyje. Modeliai leidžia greitai įvertinti įvairių parametrų derinių poveikį be papildomų eksperimentų.

Oleksandra SHEPEL

RESEARCH ON ENERGETIC AND ECOLOGICAL INDICATORS OF A COMPRESSION IGNITION ENGINE FUELLED BY ANIMAL NON-EDIBLE FATS AND BIOFUEL BLENDS

Doctoral Dissertation

Technological Sciences,
Transport Engineering (T 003)

GYVULINIAIS NEMAISTINIAIS RIEBALAIS IR BIODEGALŲ MIŠINIAIS VAROMO SLĖGINIO UŽDEGIMO VARIKLIO ENERGINIŲ IR EKOLOGINIŲ RODIKLIŲ TYRIMAS

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