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Multi-criteria analysis of the emission of harmful compounds from a marine diesel engine fueled with a mixture of marine fuel and n-butanol

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The article analyses in detail the impact of adding n-butanol to marine fuel on the emission of harmful compounds in diesel engines used in maritime transport. The applied multi-criteria analysis showed that introducing n-butanol as a fuel additive can significantly reduce the emission of substances such as nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2), which consequently reduces the negative impact on the natural environment. In addition, the studies confirm that the mixture does not affect the operational efficiency of engines, which means that it can be used without the need to introduce major changes to the infrastructure or to the vessels themselves. Nevertheless, the authors emphasise that further research is necessary, especially at higher concentrations of n-butanol, to optimise this method in terms of long-term ecological and economic benefits and to ensure its full effectiveness. The conclusions indicate the potential of this technology, but they emphasise that it will be crucial to carry out additional tests to minimise the risk of possible negative side effects.

Key words: *marine diesel engine, emission, engine efficiency, multicriteria analysis*

1. Introduction

Butanol, also known as butyl alcohol, is one of many chemicals that play a key role in today's world in terms of reducing emissions of harmful compounds from marine combustion engines. This organic compound, an alcohol, has many uses and interesting properties that attract the attention of scientists, industrialists, and chemistry enthusiasts. Butanol has long been an important element of the chemical industry and other economic sectors, and also plays an important role in scientific research, especially in the context of alternative energy sources and sustainable development. The paper is a continuation of the team's previous research on the composition of marine fuel n-butanol. In addition to testing exhaust emissions, the team also investigated engine vibration characteristics [1, 5, 13, 14]. Similar studies are being conducted in other facilities around the world. An interesting approach to the topic of blended fuels was presented by Yu et al. [20]. Their work is based on a three-dimensional simulation model of an engine cylinder developed using the commercial simulation software AVL-Fire, with its accuracy validated against experimental data. The impact of diesel/biodiesel/n-butanol fuel blends on engine performance, combustion behavior, and emission characteristics was examined through simulations conducted on the model. The combustion process was analyzed for fuel mixtures containing 0%, 5%, 10%, 15%, and 20% n-butanol at different loads. Despite the engine's brake power decreasing, brake-specific fuel consumption rose, and NO_x emissions increased. Furthermore, across all load conditions, soot and CO emissions were observed to decline as the proportion of n-butanol in the fuel blend increased. The authors presented an interesting approach in the paper [6, 7]. The effect of oxygenated diesel fuel containing n-butanol on the exhaust emissions of passenger cars was described, which was tested on the NEDC transition cycle. The tests carried out showed that a diesel/butanol blend containing 10% n-butanol caused a significant reduction in PM and smoke emissions, had no effect on NO_x and CO_2 emissions, and caused higher CO and HC emissions. Tipanluisa et al. reached similar conclusions [17, 19]. This research explored the use of a single-zone combustion model combined with triple Wiebe functions to evaluate the effects of diesel/n-butanol blends as drop-in fuels for a four-cylinder heavy-duty diesel engine. Commercial diesel fuel served as the baseline for comparison with n-butanol blends containing 5%, 10%, and 20% by volume. The study examined combustion behavior, engine performance, and emission characteristics across various speed and load conditions in accordance with the World Harmonized Steady-State Cycle (WHSC). All n-butanol blends led to a reduction in CO and particulate emissions across all operating conditions. However, emissions of THC and NO_x increased, particularly at full load. Among the tested blends, 10% concentration demonstrated superior engine performance as well as favorable combustion and emission characteristics, highlighting its potential as a promising fuel blend. It should be noted that despite many publications showing that n-butanol mixtures improve combustion processes, also susceptible to changes in ambient temperature. The authors of the publication [4, 5, 8, 9, 18] pointed out that the inclusion of n-butanol as a component of the mixture is beneficial for both efficiency and particulate emissions, but the concentration of the mixture is limited by problems with starting at very low ambient temperatures, which should be carried out on marine combustion engines. The authors [7, 11, 12, 15] of the paper also reach the same conclusions by conducting experiments on a four-stroke, single-cylinder, air-cooled diesel engine due to its transition from neat rapeseed oil biodiesel to fuel blends prepared by mixing in various proportions (by volume) of rapeseed methyl ester and butanol [4]. At full (100%) load conditions, the lowest NO_x emission was obtained with the engine running on a biofuel blend. The lowest level of carbon monoxide emissions (CO) was observed when the engine was running with the most butanol-oxygenated biofuel blend. The highest smoke opacity of the exhaust was obtained when the engine was fueled with neat biodiesel and at full load. However, when examining the concentrations of individual compounds together with the engine parameters, it is difficult to assess the impact of the tested mixture on marine engine work, especially under different loads. Therefore, this opens the way for other multi-criterion tools that can be very helpful in drawing conclusions.

2. Research plan and object

The research on the composition of marine fuel was carried out on the Cegielski-Sulzer 6AL20/24 marine diesel engine [3].

Fig. 1. The marine diesel engine Cegielski-Suzer 6AL20/24 laboratory stand

Engine operating parameters were recorded using an engine monitoring system and the TESTO 350 analyzer [16] was used to measure emissions of harmful compounds. During the measurements, the engine's fuel consumption was also recorded. Technical data were shown in Table 1.

The complete three-valued plan was selected for the experiment, consisting of 1 block and 27 measuring points. The tests were carried out for a mixture of marine fuel and n-butanol at concentrations of 0, 15, and 30 percent.

Table 1. Marine diesel engine Sulzer type 6AL20/24 [3]

Specification	
Piston arrangement	Inline
Cylinder diameter	200 mm
Piston stroke	240 mm
Displacement volume	1 cyl. – 7.54 dm^3
Nominal power	420 kW
Starter	pressure compressed air – 3 MPa
Number of cylinders	6
Number of valves per cylinder	4

The value of the stoichiometric constant of the fuel was calculated based on the equation:

$$L_T = 11.84 \cdot c + 34.214 \cdot h \left[\frac{kg}{kg_{fuel}}\right] \quad (1)$$

The composition of the fuel used on Navy ships is: c = 0.87 and h = 0.13. The following values were adopted for mixture of n–butanol and marine fuel: But15 – c = 0.8367; h = 0.1309; o = 0.0324; But30 – c= 0.8034; h = 0.1318; o = 0,0648. The calculations were made on the basis of a program calculating calorific values and theoretical air demand. The calorific values were adopted based on the previous research conducted and described in the paper [21]. Substituting the theoretical mass air demand into the excess air coefficient formula:

$$\lambda = \frac{L_R}{L_T} \quad (2)$$

After transformation, the determined actual air demand:

$$L_R = \lambda \cdot [11.84 \cdot c + 34.214 \cdot h] \left[\frac{kg}{kg_{fuel}}\right] \quad (3)$$

The excess air coefficient is calculated based on the relationship:

$$\lambda = \frac{C_{CO_2max}}{C_{CO_2}} \quad (4)$$

where: C_{CO_2} – carbon dioxide concentration in exhaust gases [%].

The air flow rate is calculated as:

$$\dot{m}_{air} = G_e \cdot L_R \left[\frac{kg}{s}\right] \quad (5)$$

Exhaust mass flow rate:

$$\dot{m}_{ex} = G_e + \dot{m}_{air} \left[\frac{kg}{s}\right] \quad (6)$$

The next step was calculation emission intensity of individual harmful compounds calculated on the basis of equation:

$$e_j = u \cdot c_j \cdot \dot{m}_{ex} \quad (7)$$

where: $\dot{m}_{ex}$ – exhaust mass flow rate, c_j – concentration of the exhaust component, u – the coefficient depending on the exhaust component: NO_x – 0.001587, CO – 0.000966, CO_2 –15.19.

The relative emission to the registered engine power was calculated:

$$e_m = \frac{e_j}{P_e} \quad (8)$$

Finally, the overall engine efficiency was determined from the data recorded from the engine (from each measurement point).

3. Multi-criteria ranking

3.1. Optimization using multi-criteria methods

Multi-criteria ranking is used to compare many options or solutions, taking into account criteria that are supposed to facilitate decision making. It is useful when a decision has to be made based on various factors. The main assumption is to unify the examined factors and structure the evaluation of various options, which in turn facilitates the analysis. The final result of the analysis depends on the weights that will be assigned to individual criteria. The search for an optimal solution using a single criterion is rather rare, so it is important that the decision maker precisely defines the criteria and their weights.

In multi-criteria optimization problems, there are two groups of solutions [10]:

– dominated: binding criteria that cannot be improved without simultaneously deteriorating the value of the other criteria. There is no clear answer in this group, but a group of favorable solutions can be distinguished
– non-dominated: it is possible to find one solution, but it requires parameterization and application of all criteria. One of the advantages of such a solution is reducing the multi-criteria problem to a single-criteria problem, while the disadvantage is subjectivism in normalization and difficulties in estimating the weights of individual criteria.

In the search for a single solution, the weighted sum method is most often used, where the criteria are combined into one objective function according to a specific formula. Then, the zero unitarization method can be used, which is used to evaluate a finite number of variants to choose from. In this method, all variables are used in evaluating individual criteria and divided into three classes: stimulants (increase in the evaluation of the phenomenon), destimulants (decrease in the evaluation of the phenomenon), and nominants (favorable value). When specifying a variable as a stimulant or a destimulant, the direction of the function (minimum or maximum) is important.

3.2. Zero unitarization method

Fixed reference points should be assumed in the zero unitarization method. For this purpose, the range of the normalized variable was determined [2]:

$$G(X_j) = \max_i x_{ij} - \min_i x_{ij} \quad (9)$$

The following relationship was used to calculate the value of stimulants:

$$z_{ij} = \frac{x_{ij} - \min_i x_{ij}}{G(X_j)} \quad \begin{pmatrix} i = 1, 2, \dots, r \\ j = 1, 2, \dots, s \end{pmatrix}, \; X_j \in S \quad (10)$$

However, determining the value of the destimulant:

$$z_{ij} = \frac{\max_i x_{ij} - x_{ij}}{G(X_j)} \quad \begin{pmatrix} i = 1, 2, \dots, r \\ j = 1, 2, \dots, s \end{pmatrix}, \; X_j \in D \quad (11)$$

It should be noted that in the zero unitarization method, values in the <0;1> range are obtained. The normalization of diagnostic features is the initial stage that allows to obtain a joint multi-criteria assessment of each of the considered objects, which are then summed up to obtain an aggregate (synthetic) variable:

$$Q_i = \sum_{j=1}^{s} z_{ij} \quad (i = 1, 2, \dots, r) \quad (12)$$

Variable Q_i is a synthetic variable that is a large-criteria evaluation of a complex phenomenon characterizing the i-th object. Knowledge of this variable allows for the construction of a ranking, i.e., a system of objects ordered in relation to non-increasing values of Q_i. The objects with the best values are at the beginning, while the objects with the worst values are at the end of the ranking. In order to divide the set of objects into three parts (best, average, worst), the following relation should be used to calculate the limit value of average objects:

$$U = \frac{\max_i Q_i - \min_i Q_i}{3} \quad (13)$$

The following subgroups were obtained in this way:

– best object:

$$Q_i \in < \max_i Q_i - U, \max_i Q_i > \quad (14)$$

– average objects

$$Q_i \in (\max_i Q_i - 2U, \max_i Q_i - U) \quad (15)$$

– worst-case objects:

$$Q_i \in < \min_i Q_i, \max_i Q_i - 2U > \quad (16)$$

Table 2. The Q and UQ coefficient values based on calculations [2]

Rotational speed [1/min]	Load [kNm]	Butanol concentration [%]	Q	UQ
450	0.98	0	2.24	0.55
450	1.9	0	2.42	0.59
450	2.81	0	2.36	0.58
600	0.98	0	1.29	0.32
600	1.9	0	2.57	0.63
600	2.81	0	2.98	0.73
600	4.65	0	3.16	0.77
675	0.98	0	1.91	0.47
675	2.81	0	3.22	0.79
675	4.65	0	3.37	0.83
750	0.98	0	1.87	0.46
750	1.9	0	2.70	0.66
750	2.81	0	3.68	0.91
750	4.65	0	3.87	0.95
450	0.98	15	3.21	0.79
450	1.9	15	2.31	0.57
450	2.81	15	2.28	0.56
600	0.98	15	1.55	0.38
600	1.9	15	2.69	0.66
600	2.81	15	2.96	0.72
600	4.65	15	3.29	0.81
675	0.98	15	1.85	0.45
675	2.81	15	3.24	0.79
675	4.65	15	2.95	0.72
750	0.98	15	1.75	0.43
750	1.9	15	2.66	0.65
750	2.81	15	3.64	0.89
750	4.65	15	3.85	0.94
450	0.98	30	3.86	0.94
450	1.9	30	2.16	0.53
450	2.81	30	2.10	0.52
600	0.98	30	1.58	0.38
600	1.9	30	2.55	0.62
600	2.81	30	3.08	0.75
600	4.65	30	3.05	0.75
675	0.98	30	1.86	0.454
675	2.81	30	3.61	0.89
675	4.65	30	3.39	0.83
750	0.98	30	1.82	0.45
750	1.9	30	2.48	0.61
750	2.81	30	3.78	0.93
750	4.65	30	4.08	1

Based on the results of engine parameters and concentrations of harmful compound emissions: nitrogen oxides, carbon monoxide, and carbon dioxide, the emission of individual harmful compounds was calculated. Then, the values of overall engine efficiency were calculated at the tested measurement points. The values of overall engine efficiency are considered as stimulants, and the emission of individual harmful compounds is assumed as a destimulant. On this basis, the Q coefficient was determined as a result of calculations (Table 2).

From the data obtained: maximum value maxQ = 4.08, average value U = 0.93, and minimum value minQ = 1.29. Dividing into subgroups, the following results are presented:

– best object: $Q_b \in < 3.15,\ 4.08 >$
– average objects $Q_a \in (2.22, 3.15)$
– worst-case objects: $Q_w \in < 1.29, 2.22 >$.

Due to the fact that the determined values do not clearly explain the influence of stimulants and destimulants on Q value, it is necessary to perform a statistical analysis. For this purpose, the unit values are adopted for the next steps (Table 2):

$$UQ = \frac{Q_i}{maxQ} \qquad (17)$$

3.3. Statistical analysis

The statistical analysis of the determined unit values of UQ factor was carried out in the Statistica program [2]. All 42 measurement points were taken into account, appropriately divided by the concentration of n-butanol in ship fuel (14 points each for But0 – 0%, But15 – 15%, and But30 – 30% concentration). Descriptive statistics determined characteristics describing the properties of the distribution of UQ value characteristics. The location of the feature (mean, median, lower and upper quartile), its measures of dispersion (quartile range, variance, standard deviation), measures of asymmetry (skewness), and measures of concentration (Kurtosis) were examined. The results of the statistical analysis were presented in the form of Fig. 2 and Fig. 3 and Table 3 and Table 4.

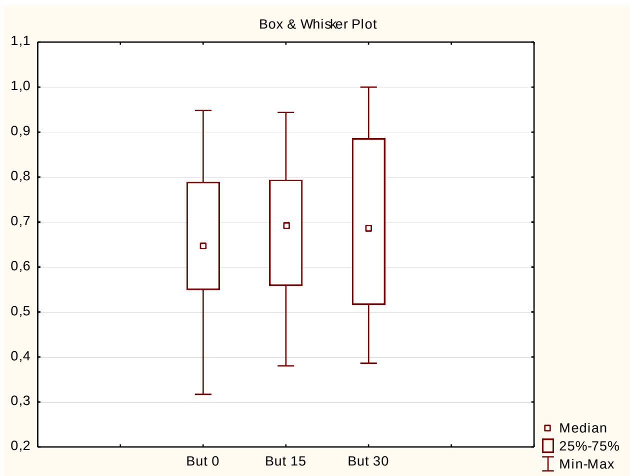

Fig. 2. The box plots represent the median values with upper and lower quartiles of UQ factor

The mean and median values of the UQ factor are close to each other. Mean values increase with increasing n-butanol concentrations. The highest median value of the UQ factor is at a n-butanol concentration of 15%. The median values for concentrations of 15% and 30% in blended fuel are higher than the median value of marine fuel.

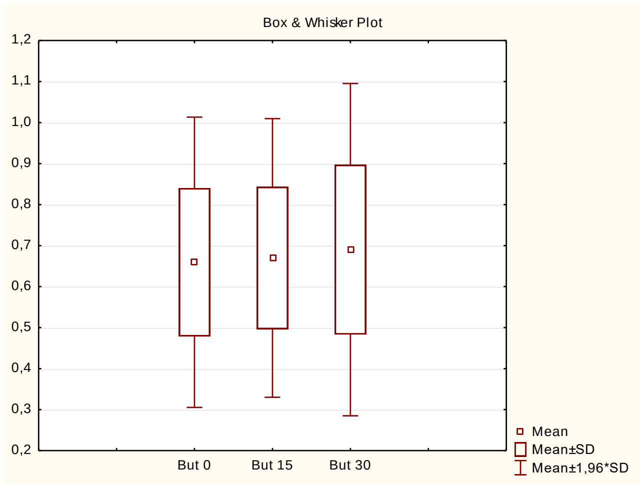

Fig. 3. The box plots represent the mean values with the standard deviation of UQ factor

The set of UQ coefficient values is not very diverse, as evidenced by small variance values. The coefficient of skewness is close to zero for all concentrations. However, at concentrations of 0 and 15, it takes negative values (slight left-side asymmetry), and at a concentration of 30%, it takes a positive value (slight positive asymmetry). Kurtosis values are negative, which indicates a flattened distribution.

Table 3. Descriptive statistics for UQ factor

Variable	Descriptive statistics				
	Valid N	Mean	Median	Minimum	Maximum
But0	14	0.66	0.65	0.32	0.95
But15	14	0.67	0.69	0.38	0.94
But30	14	0.69	0.68	0.39	1.00

The quartile range is similar for marine fuel and 15% n-butanol concentration. For the concentration of 30% butanol is the highest.

Table 4. Descriptive statistics for UQ factor (continued)

Variable	Descriptive statistics						
	Lower quartile	Upper quartile	Quartile range	Variance	Std. dev.	Skewness	Kurtosis
But0	0.55	0.79	0.24	0.033	0.180	–0.159	–0.54
But15	0.56	0.79	0.23	0.03	0.17	–0.21	–0.9
But30	0.52	0.89	0.37	0.04	0.2	0.05	–1.49

The lower quartile for But0 and But15 is 0.55, while for But30 it is 0.51. The upper quartile for But0 and But15 is 0.79, while for But30 it is 0.88. A quartile range of 0.23 (But 0 and 15) indicates that the middle 50% of the data is narrowed to within 0.23 units of the data. This means that the data in this range are relatively close together, suggesting low variability in this central region of the data set. For the concentration value of But30, the quartile range interval with a width of 0.36 units, and the data range is the largest.

The variance for the cases studied ranges from 0.17 to 0.2. This means that the data values are fairly close to the mean, but are not completely clustered at one point. The values in the set do not deviate too far from the mean, but are not clustered very closely together either.

In the case of But0 and But15 concentrations, negative skewness indicates that the data is shifted to the left, with a long left tail and fewer extremely low values. Weak skewness, i.e., the dispersion of data around the mean, is still relatively equal. Such a distribution is characterized by a greater concentration of data to the right of the mean, and the mean is smaller than the median.

Concentration But30 has low positive skewness. This indicates that the distribution is close to symmetric, but with minimal right shift. The mean is only slightly higher than the median, and the right tails are relatively short.

In each analyzed case, negative values of kurtosis were presented. Negative kurtosis (platykurtic) indicates a data distribution that is flat, with short tails and rare outliers. UQ factor data in such a distribution is more evenly distributed, and extreme values are less common. In the context of statistical analysis, this can mean that the data is less "noisy" and does not contain many exceptions, which can simplify analysis.

The UQ factor distribution was presented in graphical (Fig. 4–6) and tabular form (Table 4–6). The histogram distribution was divided into 14 parts.

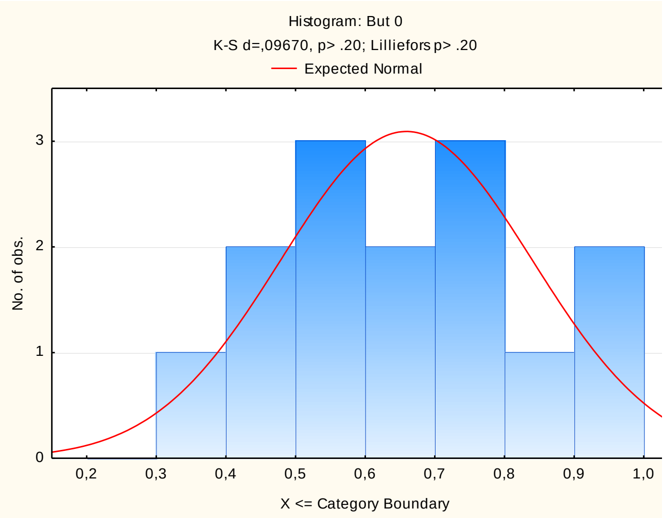

Fig. 4. Histogram UQ factor distribution for concentration But0

The highest UQ factor values for But0 concentration were observed in the ranges from 0.5 to 0.6 and 0.7 to 0.8, while the lowest were in the ranges from 0.3 to 0.4 and from 0.8 to 0.9. A slight fit to the normal distribution can be seen, but it deviates in the range of values from 0.9 to 1.

Table 4. Frequency table UQ factor for concentration But0

Category	Frequency table: But 0; K-S d = 0.09670. p > 0.20; Lilliefors p > 0.20					
	Count	Cumulative count	Percent of valid	Cumul % of valid	% of all cases	Cumulative % of all
0.2 < x ≤ 0.3	0	0	0	0	0	0
0.3 < x ≤ 0.4	1	1	7.14286	7.1429	7.14286	7.1429
0.4 < x ≤ 0.5	2	3	14.28	21.43	14.28	21.43
0.5 < x ≤ 0.6	3	6	21.43	42.8	21.43	42.86
0.6 < x≤ 0.7	2	8	14.28	57.14	14.28	57.143
0.7 < x ≤ 0.8	3	11	21.43	78.57	21.43	78.57
0.8 < x ≤ 0.9	1	12	7.143	85.714	7.143	85.71
0.9 < x ≤ 1.0	2	14	14.28	100.00	14.28	100
Missing	0	14	0		0	100

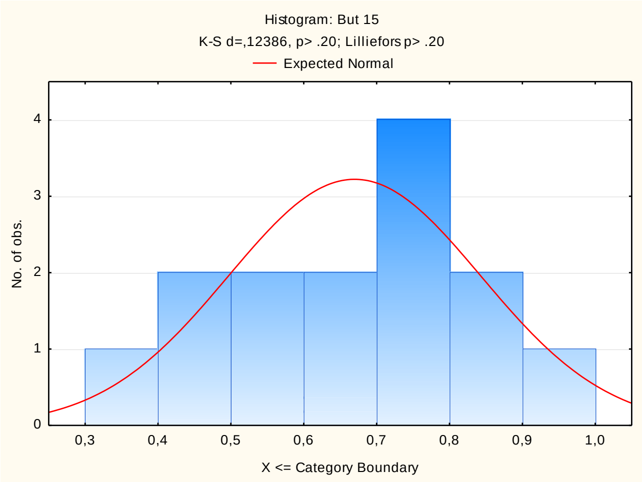

Fig. 5. Histogram UQ factor distribution for concentration But 15

Table 5. Frequency table UQ factor for concentration But 15

Category	Frequency table: But 15; K-S d = 0.12386; p > 0.20; Lilliefors p > 0.20					
	Count	Cumulative count	Percent of valid	Cumul % of valid	% of all cases	Cumulative % of all
0.3 < x ≤ 0.4	1	3	7.143	7.143	7.143	7.14
0.4 < x ≤ 0.5	2	5	14.28	21.43	14.28	21.43
0.5 < x ≤ 0.6	2	7	14.28	35.71	14.28	35.71
0.6 < x≤ 0.7	2	11	14.28	50.00	14.28	50.00
0.7 < x ≤ 0.8	4	13	28.57	78.57	28.57	78.57
0.8 < x ≤ 0.9	2	14	14.28	92.85	14.29	92.85
0.9 < x ≤ 1.0	1	14	7.15	100	7.15	100
Missing	0	1	0.0		0.0	100.0

For the case of But15 concentration, the largest number is located in the range from 0.7 to 0.8 of the UQ factor value. The smallest number is located on the border of the ranges, i.e., in the ranges from 03 to 0.4 and from 0.9 to 1.

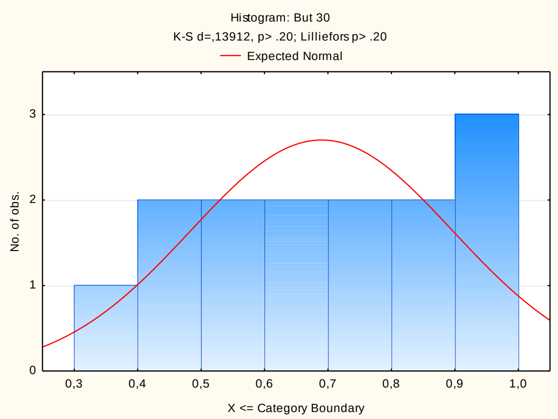

Fig. 6. Histogram UQ factor distribution for concentration But30

Table 6. Frequency table UQ factor for concentration But30

Category	Frequency table: But30; K-S d = 0.13912; p > 0.20; Lilliefors p > 0.20					
	Count	Cumulative count	Percent of valid	Cumul % of valid	% of all cases	Cumulative % of all
0.3 < x ≤ 0.4	1	1	1	7.14	7.14	7.14
0.4 < x ≤ 0.5	2	2	3	14.28	21.42	14.28
0.5 < x ≤ 0.6	2	2	5	14.28	35.71	14.28
0.6 < x≤ 0.7	2	2	7	14.28	50	14.28
0.7 < x ≤ 0.8	2	2	9	14.28	64.28	14.28
0.8 < x ≤ 0.9	2	2	11	14.28	78.57	14.28
0.9 < x ≤ 1.0	3	3	14	21.42	100	21.42
Missing	0	0	14	0		0

UQ factor values distribution for concentration But30 shows the highest number in the range from 0.9 to 1, while the lowest number is in the range from 0.3 to 0.4. In the range from 0.4 to 0.9, the numbers are at a constant level.

4. Summary

The paper presents a comprehensive analysis of the impact of a marine fuel and n-butanol mixture on the emissions of harmful substances from marine diesel engines. Research conducted using multicriteria analysis has shown that such a mixture could become a promising alternative to traditional fuels. The key conclusions can be divided into several main areas:

1. Impact on pollutant emissions. Experimental results show that adding n-butanol to marine fuel leads to a significant reduction in emissions of harmful compounds. The reduction in emissions helps reduce the negative environmental impact of shipping.
2. Operational efficiency of the engines. Despite the introduction of an alternative fuel mixture, the operational efficiency of diesel engines has been maintained. This means that environmental benefits go hand in hand with maintaining efficient performance, which is crucial for practical marine transportation applications.
3. Eco-economic potential. The authors emphasize that fuel blending has the potential to contribute to improved environmental performance by reducing emission harmful compounds from exhaust gases. At the same time, because of the maintained engine performance, its use can also be economically viable. This dual approach – environmental protection combined with operational profitability – is an attractive direction for further research and implementation.
4. Need for further research and optimization. Although the results are promising, the article indicates that the use of a mixture with higher n-butanol concentrations requires further research. Optimization of engine performance and precise determination of fuel mixing conditions are essential to fully realize the eco-economic potential of this technology.

Nomenclature

CO	carbon oxide
CO_2	carbon dioxide
GHG	greenhouse gas
MDF	marine diesel fuel
NO_x	nitrogen oxides
THC	hydrocarbons

Bibliography

[1] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engines. J Eng Gas Turb Power. 2001;123:440-447. https://doi.org/10.1115/1.1364522

[2] Bąk I, Cheba K, Szczecińska B. The statistical analysis of road traffic in cities of Poland. Transp Res Procedia. 2019; 39:14-23. https://doi.org/10.1016/j.trpro.2019.06.003

[3] Instrukcja techniczno-ruchowa silnika okrętowego H. Cegielski-Sulzer typu 6AL20/24. Poznań: Cegielski-Sulzer.

[4] Khan IA, Singh SK, Yadav AK, Ghosh U, Sharma D. Enhancement in the performance of a diesel engine fuelled with Pongamia methyl ester and n-butanol as oxygenated additive. Int J Ambient Energy. 2019;40:842-846. https://doi.org/10.1080/01430750.2018.1437559

[5] Kluczyk M. Influence of butanol-diesel oil fuel blends on marine engine vibration characteristics. Adv Sci Technol Res J. 2024;18(5):372-384. https://doi.org/10.12913/22998624/190834

[6] Kozak M. Exhaust emissions from a diesel passenger car fuelled with a diesel fuel-butanol blend. SAE Technical Paper 2011-28-0017. 2011. https://doi.org/10.4271/2011-28-0017

[7] Kozak M, Merkisz J. Oxygenated diesel fuels and their effect on PM emissions. Appl Sci. 2022;12(15):7709. https://doi.org/10.3390/app12157709

[8] Labeckas G, Slavinskas S, Mickevičius T. Experimental investigation of biodiesel-n-butanol fuels blends on performance and emissions in a diesel engine. Combustion Engines. 2022;188(1):90-95. https://doi.org/10.19206/CE-142030

[9] Lapuerta M, Ramos Á, Barba J, Fernández-Rodríguez D. Cold- and warm-temperature emissions assessment of n-butanol blends in a Euro 6 vehicle. Appl Energy. 2018;218: 173-183. https://doi.org/10.1016/j.apenergy.2018.02.178

[10] Nisbet R, Miner G, Yale K. Handbook of statistical analysis and data mining applications. 2017;1-792.

[11] Rodríguez CG, Lamas MI, Rodríguez JdD, Abbas A. Multi-criteria analysis to determine the most appropriate fuel composition in an ammonia/diesel oil dual fuel engine. J Mar Sci Eng. 2023;11(4):689. https://doi.org/10.3390/jmse11040689

[12] Rodríguez CG, Lamas MI, Rodríguez JdD, Abbas A. Possibilities of ammonia as both fuel and NO_x reductant in marine engines: a numerical study. J Mar Sci Eng. 2022;10(1): 43. https://doi.org/10.3390/jmse10010043

[13] Singh R, Kumar R. Insights into the influence of n-butanol with neat biodiesel and biodiesel diesel blends on diesel engine characteristics: review. Int J Energy Res. 2022;46: 5441-5466. https://doi.org/10.1002/er.7550

[14] Sirman MB, Owens EC, Whitney KA. Emissions comparison of alternative fuels in an advanced automotive diesel engine. SAE Technical Paper. 2000;109:2166-2176. https://doi.org/10.4271/2000-01-2048

[15] Tat ME, Van Gerpen JH. The kinematic viscosity of biodiesel and its blends with diesel fuel. J Am Oil Chem Soc. 1999;76:1511-1513.

[16] Testo 350 Maritime Instruction Manual. Lenzkirch: Testo; 2010.

[17] Tipanluisa L, Thakkar K, Fonseca N, López JM. Investigation of diesel/n-butanol blends as drop-in fuel for heavy-duty diesel engines: combustion, performance, and emissions. Energy Convers Manag. 2022;255:115334. https://doi.org/10.1016/j.enconman.2022.115334

[18] Voniati G, Dimaratos A, Koltsakis G, Ntziachristos L. Ammonia as a marine fuel towards decarbonization: emission control challenges. Sustainability. 2023;15(21):15565. https://doi.org/10.3390/su152115565

[19] Wander PR, Altafini CR, Colombo AL, Perera SC. Durability studies of mono-cylinder compression ignition engines operating with diesel, soy and castor oil methyl esters. Energy. 2011;36:3917-3923. https://doi.org/10.1016/j.energy.2010.10.037

[20] Yu S, Cao C, Lv W. Combustion and emission characteristics investigation of a marine diesel engine powered by diesel/biodiesel/n-butanol blends. Energy Sci Eng. 2022;10(9): 3317-3330. https://doi.org/10.1002/ese3.1220

[21] Zacharewicz M, Socik P, Wirkowski P, Zadrąg R, Bogdanowicz A. Evaluation of the impact of supplying a marine diesel engine with a mixture of diesel oil and n-butanol on its efficiency and emission of toxic compounds. Combustion Engines. 2023;195(4):40-47. https://doi.org/10.19206/CE-169484

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