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DOI: 10.15199/40.2024.3.1

Risks caused by microbiologically influenced corrosion in diesel fuel storage tanks

Zagrożenia spowodowane korozją mikrobiologiczną w zbiornikach magazynowych oleju napędowego

Microbiologically influenced corrosion (MIC) poses serious problems for the petrochemical and refinery industries. Particularly favourable conditions for MIC arise in storage tanks and transmission pipelines for mixtures of diesel oil with the addition of a biocomponent (in Poland 7%). The best conditions for the development of MIC occur at the fuel-water interface, where microorganisms are provided with a source of food and water, the presence of which is one of the basic conditions for the development of microorganisms. The development of microbiological deposits leads to the formation of sludge, causing fuel deterioration and corrosion that occurs under the resulting biomass.

Studies have shown that biodiesel, alone as a substitute and as an additive to traditional fuels, increases the corrosion rate of carbon steel used in pipelines, storage tanks and other fuel infrastructure. Therefore, there is an increasing demand for research on methods of protecting steel surfaces in these conditions. The phenomena causing the corrosion of tanks and directions of research related to the protection against corrosion of infrastructure will be discussed.

Keywords: microbiologically influenced corrosion, MIC, fuel storage tanks, biofilm, microorganisms

Korozja powodowana przez mikroorganizmy (ang. microbiologically influenced corrosion*, MIC) stwarza poważne problemy w przemyśle petrochemicznym i rafineryjnym. Szczególnie korzystne warunki do rozwoju MIC powstają w zbiornikach magazynowych i rurociągach przesyłowych mieszanek oleju napędowego z dodatkiem biokomponentu (w Polsce: 7%). Najlepsze występują na granicy faz paliwo-woda, gdzie mikroorganizmy mają zapewnione źródło pożywienia i wody, co jest jednym z podstawowych warunków ich rozwoju. Tworzenie się osadów mikrobiologicznych prowadzi do powstawania szlamów, powodujących pogorszenie jakości paliwa i korozję, która zachodzi pod powstałą biomasą.*

Badania wykazały, że biodiesel, samodzielnie jako substytut i jako dodatek do tradycyjnych paliw, przyspiesza korozję stali węglowej stosowanej w rurociągach, zbiornikach magazynowych i innej infrastrukturze paliwowej. Wzrasta zatem zapotrzebowanie na badania nad sposobami zabezpieczania powierzchni stalowych w tych warunkach. Omówione zostaną zjawiska powodujące korozję zbiorników oraz kierunki badań związane z ochroną przed korozją infrastruktury paliwowej.

Słowa kluczowe: korozja wzbudzona przez mikroorganizmy, MIC, zbiorniki magazynowe paliw, biofilm, mikroorganizmy

1. Introduction

Microbiologically influenced corrosion is a concern for many industries, especially the petrochemical industry and logistics infrastructure in particular, namely fuel storage tanks and pipelines [1–4]. The switch to biofuels as an alternative to traditional fossil fuels, in addition to the undeniable advantages such as their renewability and biodegradability, poses problems related to the lower corrosion resistance of the engineering materials used in the infrastructure [5, 6]. This is particularly true of carbon steel, the most commonly used material for this purpose. In addition, fuel degradation is more rapid and the resulting microbial contaminants further degrade the properties of the fuel, especially during long-term storage. This can cause damage to distribution equipment

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■ Received / Otrzymano: 22.09.2023. Accepted / Przyjęto: 10.11.2023

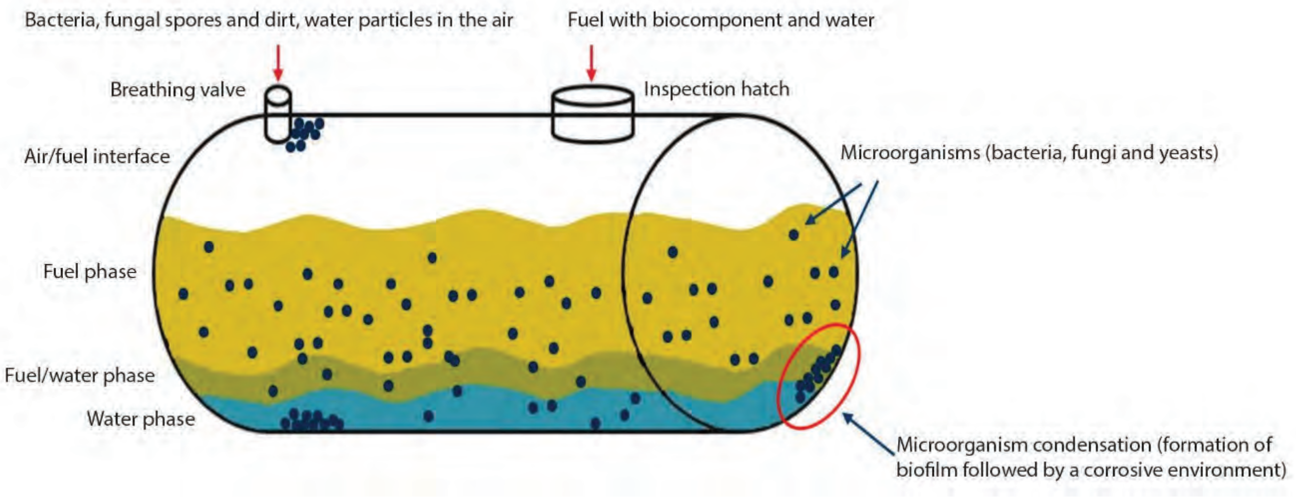

Fig. 1. Location of microorganisms in a fuel tank
Source: own work based on [14].

Rys. 1. Umiejscowienie drobnoustrojów w zbiorniku paliwa
Źródło: opracowanie własne na podstawie [14].

and vehicle engines [7, 8]. All fuels are affected by these phenomena, but the greatest problems are observed with diesel fuel. As it is currently not possible to replace diesel with biodiesel, biocomponents (biodiesel) can be added to fossil diesel in quantities of up to 20% by volume (B20). In Poland, diesel fuel contains 7% biodiesel by volume (B7).

Biodiesel consists of a mixture of fatty acid methyl esters derived from vegetable or animal fats and as such is a renewable material [9]. Very low sulphur diesel is used to make the blend and the addition of biodiesel restores the lubricity lost by the removal of sulphur compounds [10, 11]. Blends up to 20% can be used without modification to existing engines or infrastructure and show favourable combustion and atmospheric emission characteristics [12].

The corrosion problems associated with the use of biodiesel pose a challenge to those working on these issues and no effective practical solution has yet been found [13]. Although a great deal of research is being carried out, the results are not being applied in industrial practice. This is due, among other things, to the diversity of microorganisms in individual plants, their adaptability and increasing regulatory restrictions on the toxicity of compounds used as biocides.

2. Microbial corrosion in diesel tanks

2.1. Microorganisms

The presence of the “three M’s” is required for microbial corrosion [13]: microorganisms, a medium, and metal (more generally: a material). Microorganisms are commonly found in fuel tanks (Fig. 1), fuel transport equipment and elements of fuel supply chains, from where they are distributed to other elements of the infrastructure. In addition, bacteria and fungal spores, as well as dirt and water, can enter the tank through breather valves and inspection hatches. After a certain period of time when no preventive measures are taken, such as cleaning the tanks or draining them, a biofilm can form, constituting a seedbed for microbial corrosion [13].

So-called planktonic microorganisms can be found in the fuel which, under favourable conditions, produce a biofilm on the tank wall surface [14, 15].

The most favourable conditions for the growth of microorganisms occur when they form a biofilm as a result of their ability to communicate intercellularly using the so-called quorum sensing (QS) mechanism [16–18]. According to this mechanism, bacteria produce, release, and detect signalling molecules called autoinducers throughout the colony, through which they communicate with each other. QS also coordinates motility, spore formation, resistance to hazards, pigment production, bioluminescence and virulence factors. Behaviours controlled by QS are only effective when bacteria live in a colony, forming a biofilm, rather than being dispersed. By allowing bacteria to coordinate group behaviour, QS enables them to take on some of the characteristics of multicellular organisms and gives them greater defence capabilities against external agents [5, 16–18].

Biofilm formation is shown schematically in Fig. 2 and involves the following steps [19]:

1. Attachment: at the initial stage, free-floating microbial (planktonic) cells attach to surfaces (biotic or abiotic) through weak interactions such as acid-base, Van der Waals and electrostatic interactions.
2. Colonisation: bacteria irreversibly attach to surfaces through stronger interactions (using adhesion proteins, lipopolysaccharides, flagella and pilli).
3. Proliferation (multiplication): bacterial cells accumulate and produce large amounts of exopolysaccharide substances (EPS), which serve to protect the microorganisms from external factors that may threaten their life.
4. Maturation: attached bacterial cells grow and multiply to form microcolonies, which in the course of further development leads to the formation of a biofilm with a three-dimensional structure, which may be single-species or multi-species; the biofilm develops as long as favourable conditions exist.
5. Dispersion: under unfavourable conditions, the biofilm is destroyed by the action of agents that destroy the cells or the extracellular matrix they produce; these agents can be chemicals of abiotic or biotic origin, including acids and enzymes. Under favourable conditions, biofilm proliferation can occur through the action of various mechanisms related to the movement of

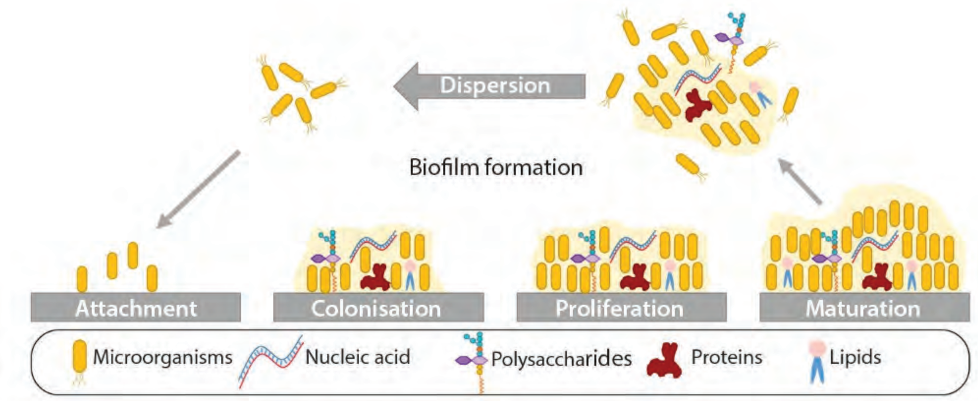

Fig. 2. Biofilm formation scheme
Source: own work based on [19].

Rys. 2. Schemat powstawania biofilmu
Źródło: opracowanie własne na podstawie [19].

the fluid stream (liquid or gas); one of these is the dispersal of progenitor cells in which gene expression is altered to allow them to live in planktonic form and reproduce under these conditions.

Differences in the species composition of the bacteria that make up the biofilm, and the resulting differences in their metabolism within the biofilms, may explain why corrosion rates can vary significantly under the same environmental conditions. It has been observed that the corrosion rate of carbon steel under the same conditions can vary from 0.05 mm/year to 3 mm/year depending on the species composition of the microorganisms in the biofilm [20].

Table 1 shows the bacterial, fungal and yeast strains isolated from diesel samples taken from both the fuel and aqueous phases. Most were able to use the hydrocarbon components of the fuel directly as a carbon source. Some of the strains listed consume degradation products of fuels, additives or organic compounds [21].

Table 1. Bacteria, fungi and yeasts isolated from diesel fuels
Tabela 1. Bakterie, grzyby oraz drożdże wyizolowane z olejów napędowych

Bacteria	Filamentous fungi and yeasts
Acinetobacter cerificans	*Alternaria alternata*
Acinetobacter junii	*Alternaria sp.*
Acinetobacter sp.	*Amorphoteca resinae*
Actinomycetes sp.	*Aspergillus*
Aeromonas hydrophila	*Aspergillus flavus*
Alcaligenes spp.	*Aspergillus fumigatus*
Arthrobacter sp.	*Aspergillus niger*
Bacillus cereus	*Aspergillus usus*
Bacillus firmus	*Aspergillus versicolor*
Bacillus sp.	*Candida sp.*
Bacillus subtilis	*Candida guilliermondii*
Sulphate-reducing bacteria	*Candida lipolytica*
Iron-oxidizing bacteria of the genus *Leptothrix*	*Candida rugowa*
Iron-oxidizing bacteria of the genus *Siderocapsa*	*Candida silvicola*
Cochliobolus lunatus	*Candida tropicalis*
Desulfovibrio desulfuricans	*Cephalosporium sp.*
Desulfovibrio sp.	*Cladosporium sp.*
Klebsiella sp.	*Fusarium sp.*
Micrococcus spp.	*Humicola sp.*
Mycobacterium sp.	*Paecilomyces spp.*
Nocardia sp.	*Paecilomyces variotii*
Phialophora sp.	*Penicillium citrinum*
Pseudomonas fluorescens	*Penicillium sp.*
Pseudomonas aeruginosa	*Penicillium spinulosum*
Pseudomonas oleovorans	*Rhodotorula glutinis*
Pseudomonas sp.	*Rhodotorula sp.*
Sphaerotilus sp.	*Trichoderma viride*
Sphingomonas paucimobilis	

Source: [21, p. 171].
Źródło: [21, s. 171].

2.2. Medium

Biodiesel contains more dissolved oxygen than fossil diesel, which reduces its oxidative stability and increases the risk of fuel biodegradation [22]. Biodiesel is also more hygroscopic [23], causing its blends with fossil diesel to absorb and retain more water by a factor of up to 20–30 [7]. Water in fuel is essential for the metabolism and growth of microorganisms; it allows them to multiply, leading to fuel contamination. Water has a higher density than fuel and therefore accumulates at the bottom of any storage tank. Microorganisms at the fuel-water interface live in an aqueous environment with the fuel as an oxidisable substrate and a source of dissolved oxygen [24], Fig. 1. Contamination (e.g. accumulated biomass) is greatest at the fuel-water interface and microbial metabolism depletes the oxygen in the water [25, 26]. Microbial growth and subsequent corrosion depends on the chemical composition of the fuel and the amount of water present [26, 27].

Each bacterial group can affect the corrosion mechanism in a different way [28]. Selected examples are given in Table 2.

Table 2. Microorganisms and their mode of action causing metal corrosion
Tabela 2. Mikroorganizmy i ich sposób działania powodujący korozję metali

Group of bacteria	Examples of microorganisms	Corrosion mechanism
Sulphur or sulphide oxidisers	*Thiobacillus thiooxidans, T. concretivorus*	sulphuric acid production
Iron bacteria	*Gallionella*	oxidation of Fe^{2+} to Fe^{3+} ions involved in the formation of iron hydroxide bubbles on the metal surface
Filamentous bacteria	*Sphaerotilus, Crenothrix, Leptothrix, Clonothrix, Pedomicrobium*	xidation of Mn^{2+} to Mn^{4+} (in MnO_2)
Manganese bacteria	*Metalogenium, Leptothrix*	cathodic depolarisation
Hydrogen-consuming bacteria	*Clostridium, Desulfovibrio*	hydrogen ionisation
Hydrogen-producing bacteria	Sulphate-reducing *Clostridium*	cathodic depolarisation
Thermophilic bacteria	*Desulfovibrio thermophilus*	reduction of Fe^{3+} ions to soluble Fe^{2+} compounds
Biofilm-forming bacteria	*Pseudmonas sp.*	biofilm and sludge formation

Source: [28, p. 2].
Źródło: [28, s. 2].

Photo 1. Corrosion pitting on internal surfaces of storage tanks

Fot. 1. Wżery korozyjne na powierzchniach wewnętrznych zbiorników magazynowych

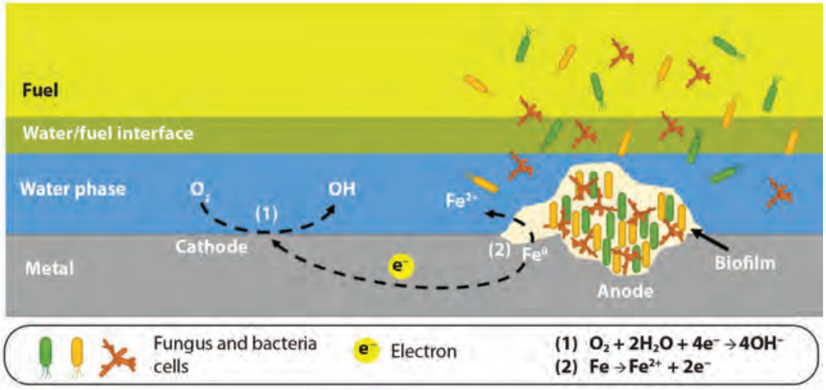

Fig. 3. Illustration of localised corrosion formation caused by the development of a concentration cell as a result of oxygen depletion under a biofilm
Source: own work based on [16].

Rys. 3. Powstanie lokalnego wykorodowania spowodowanego utworzeniem ogniwa stężeniowego w wyniku wyczerpania tlenu pod biofilmem
Źródło: opracowanie własne na podstawie [16].

2.3. Construction materials

According to the Regulation of the Minister of Economy of 21 November 2005, the material that comes into contact with fuel should possess the necessary strength properties, chemical and fire resistance, as well as electrical conductivity [29]. The most commonly used material for the construction of fuel storage tanks is S235JR carbon steel, selected according to the recommendations of PN EN 100025-1 [30]. In the case of fuel transfer pipelines, these are made of L360NB steel based on the recommendations of EN ISO 3183 [31].

3. Mechanisms of microbial corrosion

3.1. Classification of mechanisms

Microbial corrosion cannot be attributed to a single mechanism or a single species of microorganism. A wide variety of microorganisms are responsible for the corrosion of various metals, including aerobic and anaerobic bacteria, algae, fungi, etc. A group of sulphate-reducing bacteria (SRB) is considered to be particularly important in the initiation and development of MIC [5, 32]. Enning and Garrelfs [32] highlight two main theories on the mechanisms of microbial corrosion involving SRB:

- MIC electrical mechanism (EMIC), in which SRBs cause direct oxidation of iron, contributing to the corrosion of the metal (Fe) or its alloys.
- MIC chemical mechanism (CMIC) in which the corrosion of Fe or its alloys occurs as a result of a series of chemical reactions under the influence of and involving the metabolic products of specific SRBs.

3.2. Corrosion cells with different degrees of oxygenation

Biofilms of varying composition and thickness develop on all surfaces in contact with the aqueous environment. Under these conditions, corrosion of the metal is caused by the formation of corrosion cells resulting from the different concentrations of oxygen present at different locations on the metal surface. The effect of different oxygen concentrations at different locations may be due to active oxygen consumption by microorganisms in biofilms that are unevenly distributed on the metal surface. It may also be due to a passive mechanism where oxygen access to certain areas is physically impeded. As the microorganisms grow on the metal surface and the thickness of the biofilm layer increases, the penetration of oxygen in the biofilm layer to the metal surface will be low. An anode will form at the point of lower oxygen concentration and localised metal loss (corrosion) will be observed at this point. Photo 1 shows an example of the damage caused to the tank wall, while Fig. 3 provides a schematic illustration of the corrosion mechanism. Where the biofilm is absent (or present but much thinner), a cathode is formed due to greater access to oxygen according to reaction (1). In contrast, where the biofilm has formed, there is less oxygen access to the surface, therefore an anode is formed at such location and localised corrosion of the steel occurs according to equation (2) [16].

3.3. Creation of a corrosive environment through metabolic processes

This mechanism of microbial corrosion is closely related to the type of microorganisms active in the biofilm and their metabolic reactions. Most heterotrophic organisms, including bacteria and fungi, secrete organic acids as metabolic products. This results in a locally more corrosive environment. It has been observed that the effect of organic acids is greater when they are trapped at the biofilm/metal interface [2, 3, 5, 7, 8].

3.4. Cell formation at the water/fuel interface

A corrosion cell forms on the side wall of the tank near the water/fuel interface (Fig. 4). The part of the tank immersed in the water area constitutes the anode while the part of the tank in contact with the biodiesel represents the cathode. It was previously thought that there was no ion flow between these areas, but it turns out that fungal hyphae can act as an electrolytic key. It is this mechanism of cell formation that takes place and results in the development of corrosion cavities in the tank wall near the water/fuel interface [33].

4. Microbiological corrosion – risks and implications

One of the effects of the processes discussed is the corrosion of the internal surfaces of tanks, shown in Photo 3, observed during chemical cleaning trials and monitoring of tank surface cleanliness at petrol stations. The formation of corrosion cavities on the internal surfaces of tanks leads to economic losses resulting from the

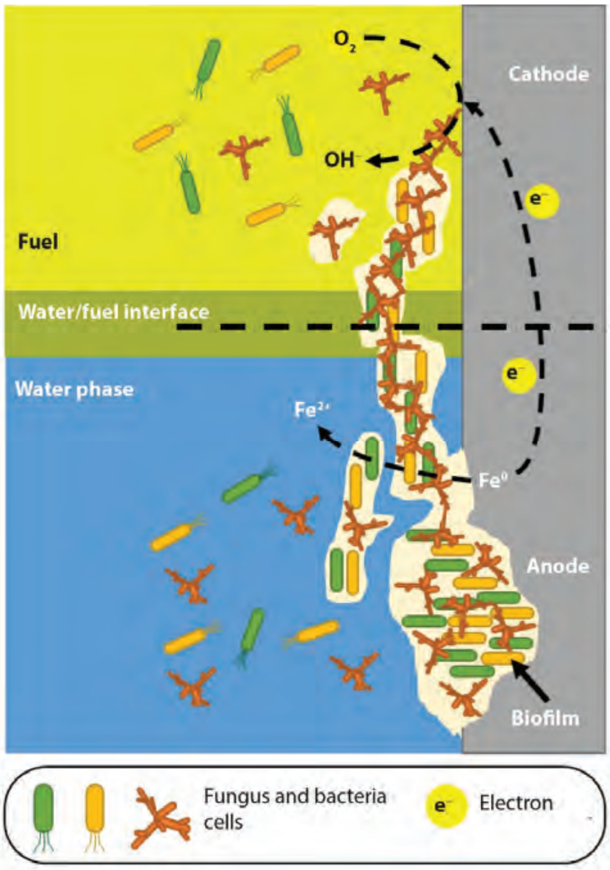

Fig. 4. Schematic illustration of the formation of a corrosion cell on a steel tank wall near the fuel/water interface in the presence of microorganisms
Source: own work based on [33].

Rys. 4. Schemat powstawania ogniwa korozyjnego na stalowej ścianie zbiornika w okolicy granicy faz paliwo/woda w obecności mikroorganizmów
Źródło: opracowanie własne na podstawie [33].

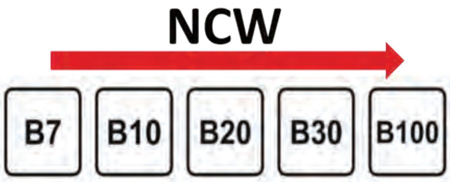

Fig. 5. Increase in the share of biocomponents in diesel as a result of NIT regulations, EU directive RED II and the planned RED III
Source: own work based on [37].

Rys. 5. Wzrost udziału biokomponentów w oleju napędowym z uwagi na regulacje NCW oraz dyrektywy UE: RED II i planowaną RED III
Źródło: opracowanie własne na podstawie [37].

Photo 2. Photograph of clogged fuel filter
Source: [38, p. 5].

Fot. 2. Przykładowa fotografia zatkanych filtrów paliwa
Źródło: [38, s. 5].

interruption of product sales, tank shell welding, replacement of protective surfaces and, in the worst case, entire tank replacement, and environmental pollution.

Biocides, whose main ingredient is formaldehyde, are currently used to control the growth of microorganisms in fuels. Its use is to be banned by the European Union. Formaldehyde can no longer be used in cosmetic products due to its carcinogenicity [34]. The use of toxic biocides is gradually being reduced due to their negative environmental impact. Therefore, their elimination may exacerbate the effects caused by microorganisms.

Member States of the European Union are obliged to use the specified minimum share of renewable energy in fuels (Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and, from 1 July 2021, Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources). This will be achieved by blending biocomponents or renewable fuels into conventional fuels at specified levels. The national programme that incorporates these provisions in the transport sector is the so-called National Indicative Target (NIT), introduced by the provisions of the Law of 25 August 2006 on biocomponents and liquid biofuels [35].

In order to meet the NIT, the share of renewable fuels will gradually increase. Regulations allow the Council of Ministers to analyse the implementation of the programme every two years and to revise the target, taking into account biocomponent supply and price relations on the market of biocomponents and liquid fuels [35, 36]. Introducing the provisions of the RED II Directive, known as the Biofuels Directive, and the RED III Directive (from 2025) concerning the reduction of greenhouse gas emissions from fuel combustion, will also increase the proportion of biocomponents in fuels (Fig. 5) [37].

These measures will result in an increased risk of microbial corrosion of the entire fuel infrastructure, as well as electrochemical corrosion due to increased water content in the fuel.

One of the effects of microbial growth in fuel is the clogging of distributor filters (Photo 2) due to the transfer of microbial contamination, resulting in fouling of subsequent points along the distribution chain, including tanks at petrol stations.

Komariah et al. [39] showed that a filter which had contact with biodiesel clogged faster than when in contact with diesel alone. When dealing with filter problems in biodiesel and biodiesel blends, the contribution of sterol glucosides has not gone unnoticed. The surface of a filter that has come into contact with biodiesel gets covered to a greater extent with oil deposits in the form of sludge. This indicates a high fatty acid content in the biodiesel and the formation of compounds that can easily gel, which also leads to filter clogging.

5. Good practices in combating microbial corrosion

Considering the aforementioned risks and implications, the following good practices have been adopted [15]:

1. Quality control of diesel fuel in accordance with PN-EN 590 [40] and the Ordinance of the Minister of Economy dated 9 October 2009 [41] for stability, water content, and continuous fuel improvement tests.
2. Draining tanks and monitoring water levels in tanks (the stand-ard allows a maximum of 200 ppm for diesel fuel [40, 41] and 500 ppm for biocomponents [42]).
3. Testing tanks at fuel terminals for microbiological contamination in order to estimate the level of fouling in the bottom layers of the tanks and take appropriate action.
4. Monitoring the quality of biocomponents according to PN-EN 14214 [42], testing of every delivery, e.g. water content, but also the content of sterol glucosides or acylglycerols; there are also positive effects from working with suppliers and monitoring trends in improving biocomponents.
5. Doping fuel with biocides and anti-corrosion additives to protect the fuel in the logistics infrastructure and the infrastructure itself.
6. Chemical cleaning combined with mechanical cleaning: mechanical cleaning alone is not effective as it leaves behind spores, whereas chemical cleaning removes them.
7. Development of new filters with a longer life (reducing the frequency of filter changes) and with biocidal substances in the fibres.
8. Surface modification – use of coatings with passive additives to reduce the possibility of microbial colonisation (reduced adhesion of microorganisms to tank walls and piping), which should reduce microbial growth without the use of toxic biocides, and finding ways to disrupt communication between microorganisms.
9. Developing detectors for rapid assessment of the total microbial content of fuel; current culture methods take at least a week to produce results. This will allow a more rapid response if “safe” levels of microorganisms are exceeded in the fuel or in the bottom layer of tanks.

6. Assumptions for monitoring microbiological contamination

The London Energy Institute has published an example of the required limits for microbiological contamination of fuels, including diesel, for long-term storage in its guidelines for testing microbiological contamination of fuels [43] (Table 3).

Table 3. Examples of microbiological contamination limits for diesel
Tabela 3. Przykłady limitów skażenia mikrobiologicznego w wypadku oleju napędowego

Material	Stored 2–3 years [cfu/l]		For long-term storage: >3 years [cfu/l]	
	fungi and yeast	bacteria	fungi and yeast	bacteria
Diesel	$<10^3$	$<10^2$	$<10^2$	<50
Diesel near the water phase	total $<10^4$		$<5 \times 10^2$	$<10^2$

cfu – colony-forming units

Source: based on [43, p. 27].

Źródło: na podstawie [43, s. 27].

According to the guidelines for diesel fuel intended to be stored for up to 3 years, the limit for fungal contamination is 10^3 cfu/l while for bacterial contamination it is 10^2 cfu/l. For fuel taken from the point of contact with the water phase in the tank the limit for total contamination (bacterial and fungal) is $<10^4$ cfu/l. No limits are given in the London Energy Institute guidelines or other available literature for fuels intended for short term storage.

Our own experience suggests that the following steps should be taken with particular care:

- regular monitoring of the water level and drainage of product tanks, as water has a decisive influence on the dynamics of the life of microorganisms;
- monitoring the quality of biocomponents in terms of microbiological contamination, contacting and collaborating with suppliers and striving to use new biocomponents (so-called second generation biocomponents) with more favourable parameters in order to meet the requirements of NIT, as well as the RED II and RED III directives;
- monitoring the quality of produced and imported diesel fuel;
- monitoring the effectiveness of biocides – checking the dosage to assess whether the fuel is adequately protected;
- monitoring the microbiological risk, especially in spring and summer (differences in contamination levels depending on the season have been noted).

7. Main lines of research

Based on an analysis of the literature in the field of microbial corrosion [44–52] and our own experience, the following lines of research are currently being pursued:

- protection of the inner walls of fuel tanks with coatings – analysis of the behaviour of coatings and their selection in terms of durability of protection, exploiting the potential of self-polishing coatings;
- use of UV radiation to reduce microorganisms in fuels;
- use of sensors to rapidly assess the amount of microorganisms in the fuel, preferably with the possibility of continuous monitoring.

There are ways to improve the resistance of organic coatings used to protect fuel tanks and other infrastructure components from microbial attack through appropriate surface modifications of the coatings. An example is the work of two research teams on the use of graphene oxide in various compositions, the results of which indicate its positive effect on increased corrosion resistance and antimicrobial activity [44, 45]. Research is being carried out on coatings that reduce the adhesion of microorganisms to the coating surface and increase its biocidal properties. Unmodified and modified epoxy coatings have been studied in diesel containing biocomponents and with different microorganisms. It was found that each microorganism affected the coating differently.

Work is being carried out on the use of ultraviolet radiation which, according to studies, reduces the presence of microorganisms in diesel by more than 50%, especially in samples with high water content. Unfortunately, these effects are not long lasting, with a duration of only up to ten days after the initial irradiation [46].

There is great hope for the development of rapid methods to measure the microbial content of fuel, without having to wait a week or so for the results of culture tests. Impedance measurements, including those in the microwave range, are being used for this purpose [47–51]. The presence of microorganisms is indicated by a change in the impedance of the samples tested [50].

Attempts are being made to develop a network model to predict the dynamics of microbial corrosion in fuel systems. Taleb-Berrouanne et al. [52] analysed the interactions between a total of

60 factors influencing the development of microbial corrosion and 20 microbiological parameters identified by screening methods. The proposed model provides a means of capturing the complex interdependencies and synergistic interactions of indicators used to assess microbial corrosion risk. The model is currently being tested and validated using real data.

8. Summary

1. Microbial corrosion in fuel tanks and transmission infrastructure (pipelines) represents a serious challenge.
2. There is a lack of scientific research that can be directly applied to reduce the adverse effects of microbial corrosion.
3. Research is needed to control the level of microbial contamination using environmentally friendly (non-toxic) methods.
4. There is a need to find methods, other than culture methods, that can rapidly verify the level of microbial contamination in various media and environments, including fuel tanks and fuel transport infrastructure.

CRediT authorship contribution statement
Michał Kuna: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.
Andrzej Miszczyk: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

BIBLIOGRAPHY

[1] A. K. Lahiri. 2017. *Applied Metallurgy and Corrosion Control: A Handbook for the Petrochemical Industry*. Singapore: Springer.

[2] B. Kermani, D. Harrop. 2019. *Corrosion and Materials in Hydrocarbon Production: A Compendium of Operational and Engineering Aspects*. Hoboken, New Jersey: John Wiley and Sons.

[3] A. K. Singh. 2020. *Microbially Induced Corrosion and Its Mitigation*. Singapore: Springer.

[4] L. N. Komariah, T. K. Dewi, C. Ramayanti. 2019. "Study on Corrosion Behavior of Storage Tanks Filled with Biodiesel and the Blends." *IOP Conference Series: Materials Science and Engineering* 543: 012033. DOI: 10.1088/1757-899X/543/1/012033.

[5] B. Cwalina. 2023. „Korozja Mikrobiologiczna: pytania – odpowiedzi – pytania…". XXIX Ogólnopolska Konferencja Naukowo-Techniczna „Antykorozja": Systemy – Materiały – Powłoki. Ustroń-Jaszowiec, 10–12 maja 2023.

[6] A. J. Ragauskas (ed.). 2014. *Materials for Biofuels*. Singapore: World Scientific Publishing.

[7] G. Sørensen, D. V. Pedersen, A. K. Nørgaard, K. B. Sørensen, S. D. Nygaard. 2011. "Microbial Growth Studies in Biodiesel Blends." *Bioresource Technology* 102(8): 5259–5264. DOI: 10.1016/j.biortech.2011.02.017.

[8] B. W. Stamps, C. L. Bojanowski, C. A. Drake, H. S. Nunn, P. F. Lloyd, J. G. Floyd, K. A. Emmerich, A. R. Neal, W. J. Crookes-Goodson, B. S. Stevenson. 2020. "*In Situ* Linkage of Fungal and Bacterial Proliferation to Microbiologically Influenced Corrosion in B20 Biodiesel Storage Tanks." *Frontiers in Microbiology* 11: 167. DOI: 10.3389/fmicb.2020.00167.

[9] A. Islam, P. Ravindra. 2017. *Biodiesel Production with Green Technologies*. Cham, Switzerland: Springer.

[10] B. R. Moser. 2009. "Biodiesel Production, Properties, and Feedstocks." *In Vitro Cellular and Developmental Biology – Plant* 45: 229–266. DOI: 10.1007/s11627-009-9204-z.

[11] S. S. Gill, A. Tsolakis, J. M. Herreros, A. P. E. York. 2012. "Diesel Emissions Improvements through the Use of Biodiesel or Oxygenated Blending Components." *Fuel* 95: 578–586. DOI: 10.1016/j.fuel.2011.11.047.

[12] Air Force Infrastructure Energy Plan. 2010. https://www.dm.af.mil/Portals/99/Docs/Infrastructure.pdf?ver=2016-02-22-172103-900 (access: 2.10.2023).

[13] B. J. Little, D. J. Blackwood, J. Hinks, F. M. Lauro, E. Marsili, A. Okamoto, S. A. Rice, S. A. Wade, H. C. Flemming. 2020. "Microbially Influenced Corrosion – Any Progress?" *Corrosion Science* 170: 108641. DOI: 10.1016/j.corsci.2020.108641.

[14] R. Krakowski. 2016. „Zanieczyszczenie mikrobiologiczne olejów napędowych i smarowych oraz możliwości jego ograniczania". *Autobusy: Technika, Eksploatacja, Systemy Transportowe* 17(12): 286–291.

[15] D. Kwiatkowska. 2004. „Skażenie mikrobiologiczne ropy naftowej i jej produktów". *Ochrona przed Korozją* 47(2): 31–36.

[16] R. Jia, T. Unsal, D. Xu, Y. Lekbach, T. Gu. 2019. "Microbiologically Influenced Corrosion and Current Mitigation Strategies: A State of the Art Review." *International Biodeterioration and Biodegradation* 137: 42–58. DOI: 10.1016/j.ibiod.2018.11.007.

[17] M. E. Taga, B. L. Bassler. 2003. "Chemical Communication among Bacteria." *Proceedings of the National Academy of Sciences* 100: 14549–14554. DOI: 10.1073/pnas.1934514100.

[18] A. Camilli, B. L. Bassler. 2006. "Bacterial Small-Molecule Signaling Pathways." *Science* 311(5764): 1113–1116. DOI: 10.1126/science.1121357.

[19] S. Das, N. A. Kungwani (eds.). 2023. *Understanding Microbial Biofilms: Fundamentals to Applications*. London: Academic Press.

[20] I. B. Beech, J. Sunner. 2004. "Biocorrosion: Towards Understanding Interactions between Biofilms and Metals." *Current Opinion in Biotechnology* 15(3): 181–186. DOI: 10.1016/j.copbio.2004.05.001.

[21] J. Lasocki, E. Karwowska. 2010. „Wpływ mikroorganizmów bytujących w środowisku oleju napędowego i biodiesla na układ paliwowy pojazdów napędzanych silnikami o zapłonie samoczynnym". *Archiwum Motoryzacji* 3: 167–183.

[22] H. K. Speidel, R. L. Lightner, I. Ahmed. 2018. "Biodegradability of New Engineered Fuels Compared to Conventional Petroleum Fuels and Alternative Fuels in Current Use." *Applied Biochemistry and Biotechnology* 84–86: 879–897. DOI: 10.1007/978-1-4612-1392-5_69.

[23] P. B. L. Fregolente, L. V. Fregolente, M. M. R. Wolf, M. R. W. Maciel. 2012. "Water Content in Biodiesel, Diesel, and Biodiesel–Diesel Blends." *Journal of Chemical and Engineering Data* 57(6): 1817–1821. DOI: 10.1021/je300279c.

[24] R. C. Prince, C. Haitmanek, C. C. Lee. 2008. "The Primary Aerobic Biodegradation of Biodiesel B20." *Chemosphere* 71(8): 1446–1451. DOI: 10.1016/j.chemosphere.2007.12.010.

[25] F. J. Passman. 2013. "Microbial Contamination and Its Control in Fuels and Fuel Systems since 1980 – A Review." *International Biodeterioration and Biodegradation* 81: 88–104. DOI: 10.1016/j.ibiod.2012.08.002.

[26] D. F. Aktas, J. S. Lee, B. J. Little, R. I. Ray, I. A. Davidova, C. N. Lyles, J. M. Suflita. 2010. "Anaerobic Metabolism of Biodiesel and Its Impact on Metal Corrosion." *Energy and Fuels* 24(5): 2924–2928. DOI: 10.1021/ef100084j.

[27] J. S. Lee, R. I. Ray, B. J. Little. 2010. "An Assessment of Alternative Diesel Fuels: Microbiological Contamination and Corrosion under Storage Conditions." *Biofouling* 26(6): 623–635. DOI: 10.1080/08927014.2010.504984.

[28] A. Sałek. 2010. „Biokorozja w przemysłowych systemach wodnych. Cz. 2. Biokorozja tlenowa i beztlenowa". *Przemysł Fermentacyjny i Owocowo-Warzywny* 54(1): 15–16.

[29] Rozporządzenie Ministra Gospodarki z dnia 21 listopada 2005 r. w sprawie warunków technicznych, jakim powinny odpowiadać bazy i stacje paliw płynnych, rurociągi przesyłowe dalekosiężne służące do transportu ropy naftowej i produktów naftowych i ich usytuowanie (Dz.U. 2005 nr 243, poz. 2063).

[30] PN-EN 100025-1:2007: Wyroby walcowane na gorąco ze stali konstrukcyjnych – Część 1: Ogólne warunki techniczne dostawy.

[31] PN-EN ISO 3183:2020-03: Przemysł naftowy i gazowniczy – Rury stalowe do rurociągowych systemów transportowych.

[32] D. Enning, J. Garrelfs. 2014. "Corrosion of Iron by Sulfate-Reducing Bacteria: New Views of an Old Problem." *Applied and Environmental Microbiology* 80(4): 1226–1236. DOI: 10.1128/AEM.02848-13.

[33] R. B. Miller II, A. Sadek, A. L. Crouch, J. G. Floyd, C. A. Drake, B. S. Stevenson, W. Crookes-Goodson, C. N. Monty, J. M. Senko. 2020. "Novel Mechanism of Microbially Induced Carbon Steel Corrosion at an Aqueous/Non-Aqueous Interface." *Industrial and Engineering Chemistry Research* 59(35): 15784–15790. DOI: 10.1021/acs.iecr.0c02497.

[34] Rozporządzenie Komisji (UE) 2019/831 z dnia 22 maja 2019 r. zmieniające załączniki II, III i V do rozporządzenia Parlamentu Europejskiego i Rady (WE) nr 1223/2009 dotyczącego produktów kosmetycznych.

[35] Ustawa z dnia 25 sierpnia 2006 r. o biokomponentach i biopaliwach ciekłych (Dz.U.2022.403, art. 23b oraz art. 24).

[36] Dyrektywa Parlamentu Europejskiego i Rady (UE) 2018/2001 z dnia 11 grudnia 2018 r. w sprawie promowania stosowania energii ze źródeł odnawialnych.

[37] Dziennik Urzędowy Unii Europejskiej. https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=CELEX:32018L2001&from=ES (access: 2.10.2023).

[38] Raport z badań LB/19/2017 wykonanych przez ORLEN Laboratorium, zleconych przez ORLEN SA, z dnia 10.11.2017 r.

[39] L. N. Komariah, F. Hadiah, F. Aprianjaya, F. Nevriadi. 2018. "Biodiesel Effects on Fuel Filter; Assessment of Clogging Characteristics." *IOP Conference Series* 1095: 012017. DOI: 10.1088/1742-6596/1095/1/012017.

[40] PN-EN 590:2022-08: Paliwa do pojazdów samochodowych – Oleje napędowe – Wymagania i metody badań.

[41] Rozporządzenie Ministra Gospodarki z dnia 9 października 2015 r. w sprawie wymagań jakościowych dla paliw ciekłych (Dz.U. 2015 poz. 1680).

[42] PN-EN 14214+A2:2019-05: Ciekłe przetwory naftowe – Estry metylowe kwasów tłuszczowych (FAME) do użytku w silnikach samochodowych o zapłonie samoczynnym (Diesla) i zastosowań grzewczych – Wymagania i metody badań.

[43] Energy Institute. 2008. *Guidelines for the Investigation of the Microbial Content of Petroleum Fuels and for the Implementation of Avoidance and Remedial Strategies*. London: Energy Institute.

[44] R. Guo, W. Li, X. Wang, Y. Lv, M. Chen, Z. Chen, Z. Liu, G. C. Han. 2023. "Antimicrobial Corrosion Study of the Epoxy Coating with the Graphene Oxide Supported Schiff Base Quaternary Ammonium Salt Additives." *Materials Today Communications* 35: 105517. DOI: 10.1016/j.mtcomm.2023.105517.

[45] M. S. Selim, N. A. Fatthallah, S. A. Higazy, X. Chen, Z. Hao. 2023. "Novel Blade-Like Structure of Reduced Graphene Oxide/α-Mn_2O_3 Nanocomposite As an Antimicrobial Active Agent Against Aerobic and Anaerobic Bacteria." *Materials Chemistry and Physics* 298: 127436. DOI: 10.1016/j.matchemphys.2023.127436.

[46] M. A. Polinarski, A. C. Neves, A. Fiorini, F. R. Rosado, E. A. da Silva, H. J. Alves. 2022. "Ultraviolet Radiation As an Antimicrobial Treatment in Brazilian Diesel Oil: Effect of Biodiesel, Sulfur, and Water Contents." *Fuel* 308: 122076. DOI: 10.1016/j.fuel.2021.122076.

[47] M. Jönsson, K. Welch, S. Hamp, M. Strømme. 2006. "Bacteria Counting with Impedance Spectroscopy in a Micro Probe Station." *Journal of Physical Chemistry B* 110(20): 10165–101169. DOI: 10.1021/jp060148q.

[48] L. Yang. 2008. "Electrical Impedance Spectroscopy for Detection of Bacterial Cells in Suspension Using Interdigitated Microelectrodes." *Talanta* 74(5): 1621–1629. DOI: 10.1016/j.talanta.2007.10.018.

[49] S. Kim, G. Yu, T. Kim, K. Shin, J. Yoon. 2012. "Rapid Bacterial Detection with an Interdigitated Array Electrode by Electrochemical Impedance Spectroscopy." *Electrochimica Acta* 82: 126–131. DOI: 10.1016/j.electacta.2012.05.131.

[50] A. I. Furst, M. B. Francis. 2019. "Impedance-Based Detection of Bacteria." *Chemical Reviews* 119(1): 700–726. DOI: 10.1021/acs.chemrev.8b00381.

[51] D. C. Spencer, T. F. Paton, K. T. Mulroney, T. J. J. Inglis, J. M. Sutton, H. Morgan. 2020. "A Fast Impedance-Based Antimicrobial Susceptibility Test." *Nature Communications* 11: 5328. DOI: 10.1038/s41467-020-18902-x.

[52] M. Taleb-Berrouane, F. Khan, K. Hawboldt, R. Eckert, T. L. Skovhus. 2018. "Model for Microbiologically Influenced Corrosion Potential Assessment for the Oil and Gas Industry." *Corrosion Engineering, Science and Technology* 53(5): 378–392. DOI: 10.1080/1478422X.2018.1483221.

Rok 2024 rokiem gen. inż. Józefa Bema w FSNT-NOT

Obradująca 5 lutego w Warszawskim Domu Technika NOT Rada Krajowa Federacji Stowarzyszeń Naukowo-Technicznych NOT ustanowiła z okazji przypadającej w bieżącym roku 230 rocznicy urodzin rok 2024 rokiem gen. inż. Józefa Zachariasza Bema.

Postać gen. inż. Bema, bohatera trzech narodów: Polski, Węgier i Turcji, uczestnika kampanii napoleońskiej, Powstania Listopadowego i Wiosny Ludów na Węgrzech, twórcy wojsk rakietowych w wojsku polskim jest szczególnie ważna dla ruchu stowarzyszeniowego techników i inżynierów. To od założonego przez niego w Paryżu, w 1835 r. Towarzystwa Politechnicznego Polskiego datuje się blisko 190-letnia historia i tradycje, których spadkobierczynią jest Naczelna Organizacja Techniczna i sfederowane w niej Stowarzyszenia Naukowo-Techniczne.

Obchody roku gen. inż. Bema rozpoczną się uroczystościami w Tarnowie, mieście jego urodzenia i spoczynku. FSNT-NOT zaprasza do udziału wszystkie organizacje i instytucje, którym bliska jest postać Generała i Inżyniera, noszącymi jego imię.

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