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Authors: Krystyna Lesińska, Alicja Szymańska, Mariusz Ślachciński, Grzegorz M. Szymański, Bogdan Wyrwas

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EFFICIENCY OF BREWERY WASTEWATER TREATMENT

Krystyna Lesińska* (ORCID: 0009-0001-4311-9568)

Alicja Szymańska* (ORCID: 0009-0009-5888-5861)

Mariusz Ślachciński* (ORCID: 0000-0001-8884-8644)

Grzegorz M. Szymański** (ORCID: 0000-0002-2784-9149)

Bogdan Wyrwas* (ORCID: 0000-0002-4791-5318)

* Institute of Technical Chemistry and Electrochemistry, Faculty of Chemical Technology, Poznań University of Technology, Berdychowo 4, 60-965 Poznań

** Institute of Transport, Faculty of Civil Engineering and Transport, Poznań University of Technology, Piotrowo 3, 61-138 Poznań

Corresponding author: Alicja Szymańska (alicja.szymanska.1@student.put.poznan.pl)

ABSTRACT

Wastewater is contaminated liquids discharged from homes and industrial plants. A wastewater treatment plant is a complex of basic technological facilities directly used for wastewater treatment, along with auxiliary facilities located on a shared site, necessary for supplying electricity and water, creating appropriate operating conditions, and maintaining the treatment plant. Brewing industries produce wastewater with high organic loads, characterized by high values of parameters such as BOD_5 and COD. For this reason, these plants typically have their own wastewater treatment systems or cooperate with local municipal wastewater treatment plants. There is growing interest in energy recovery in this industry, for example, through the use of biogas generated during treatment processes, which contributes to cost reduction and a reduction in pollutant emissions. However, the variable composition and load of wastewater remain a challenge, as does the need to properly combine mechanical, biological, and chemical methods to reduce waste volume and its environmental impact. Preparations containing surfactant compounds are used to clean these types of industrial installations. The work was supplemented with an analysis of the content of anionic and nonionic surfactants. Their levels in wastewater—both raw and treated—can be determined using dedicated cuvette tests and the MBAS (for anionic surfactants) and BiAS-thio (for nonionic) methods. The assessment of treatment plant efficiency was based on the pollution reduction index, comparing the content of specific parameters before and after treatment, and the permissible pollutant values in treated wastewater discharged to surface waters.

Keywords: brewery wastewater, wastewater treatment plant, surfactants, MBAS method, BiAS-tio method, degree of pollution reduction, food waste

1. INTRODUCTION

The brewing industry, or brewing, is a branch of the food industry engaged in the commercial production of beer, encompassing breweries, malt houses, malt and hop factories, and the production of non-alcoholic beverages. It focuses on the production of beer on an industrial (or craft) scale from basic ingredients: malt, water, and hops, using the process of alcoholic fermentation. It is a significant part of the economy, requiring agricultural products and generating by-products for animal feed. The Polish brewing industry is a leader in both production volume, employment generation, and state budget revenue. Since the 1920s, it has become one of the most important markets for the development of craft beer in the world **(Wojtyra et al., 2017).**

Poland is currently one of the leading beer producers in Europe. Annual production has reached 40 million hectolitres, ranking third in the EU behind Germany and Spain, and production has remained at a similar level from 2010 to 2020 (with a decline in 2020 due to the pandemic). The Polish beer market is made up of large producers, several dozen medium-sized breweries, and hundreds of small and micro-breweries – this represents approximately 350 entities nationwide. The market is dominated by three corporations (Kompania Piwowarska, Grupa Żywiec, Carlsberg Polska), which account for approximately 80% of sales, but there is also a growth in craft breweries and the non-alcoholic beer segment. Key corporation brands include: Tyskie, Lech, Żubr (KP), Żywiec, Warka (GŻ), Okocim, and Kasztelan (Carlsberg). The annual volume of beer production in Poland reaches 4 billion liters, the market value of this industry is estimated at PLN 21 billion, and annual consumption is at the level of 100 liters of beer per person **(Isbiznes, 2023; UOKiK, 2024).**

However, beer production generates significant amounts of wastewater, the chemical and physical composition of which varies depending on the raw materials used, production technology, and the degree of automation in the brewery. Brewery wastewater is characterized by a high content of organic compounds, such as sugars, proteins, and yeast, as well as inorganic substances – primarily mineral ions derived from water and technological additives. The presence of these components results in a significant variability in physicochemical parameters, such as BOD_5 (biochemical oxygen demand), COD (chemical oxygen demand), and total suspended solids, making its treatment a significant technological challenge **(Environmental Protection Portal, 2023)**

In an era of growing environmental awareness and tightening environmental regulations, effective industrial wastewater treatment is becoming crucial not only for water and soil protection but also for the sustainable development of the brewing industry itself. The use of modern biological, chemical, and physicochemical methods allows not only for reducing harmful environmental impacts but also for the recovery of valuable raw materials, such as process water and organic components, giving wastewater potential utility. The aim of this research is to analyze the effectiveness of various methods of treating domestic and industrial wastewater in the brewing industry, with particular emphasis on biological and physicochemical processes **(Simate et al., 2011).**

2. SEWAGE

Wastewater can be defined as waste liquids, solutions, colloids, or suspensions, as well as waste solids discharged via pipelines to wastewater treatment plants or natural receiving bodies, such as reservoirs, watercourses, septic tanks, etc. Wastewater includes industrial waste, food waste, and fecal matter from urban and residential households. Due to the high biological harmfulness of wastewater, both municipal and industrial, it should be treated in treatment plants before being discharged into the receiving body **(Daniels-Azoma et al., 2024).** Wastewater can be divided into:

- domestic sewage (originating from water used in households; very turbid, yellow-grey in colour; characteristic odour and slightly alkaline reaction; contain about 40% inorganic pollutants and about 60% organic pollutants) **(Henze et al., 2008)**
- industrial wastewater (originating from various types of industrial activities, they usually contain various chemical compounds, which are by-products of technological processes used in industrial plants; in most cases they do not pose a sanitary and epidemiological threat because they do not contain pathogenic bacteria, with the exception of wastewater from food industry plants, tanneries and waste disposal plants) **(Kumar et al., 2012)**
- agricultural sewage (originates from water flowing from fields and farms and usually contains artificial fertilizers, pesticides and microbial contamination; liquid manure is particularly dangerous as it may contain thousands of times more organic and inorganic pollutants than domestic sewage) **(García-Galán et al., 2012)**
- rainwater is formed from atmospheric precipitation that washes away built-up areas and from meltwater; it contains large amounts of organic and inorganic pollutants, mainly in the form of suspensions, and can be recovered for own needs, e.g. watering green areas) **(Zgheib et al., 2012)**
- municipal sewage (regardless of the source, it may be domestic sewage, industrial sewage, precipitation sewage, meltwater or a mixture of these sewages found in the municipal sewage system) **(Eriksson et al., 2002)**
- fresh sewage (characterized by a dissolved oxygen concentration of approximately 6 g O_2/m^3, faint odor, yellow-gray or white-gray color, containing easily settling suspensions) **(Sperling, 2007)**
- old sewage (characterized by the concentration of dissolved oxygen in the range of 1-2 g O_2/m^3, opalescent, milky in color, containing highly hydrated suspensions) **(Hvitved-Jacobsen et al., 2013)**
- putrid sewage (characterized by the lack of dissolved oxygen, the smell of hydrogen sulphide and a black color, opaque, containing fine suspensions that do not settle easily; this type of sewage is also characterized by an immediate chemical demand for oxygen) **(Modzelewska et al., 2020)**

The volume of brewery wastewater is equal to the amount of water used minus the water contained in the product and losses (evaporation, water in waste). In total, 1.3–1.8 hL of water/hL of beer is discharged into the wastewater. Brewery wastewater is biodegradable, with higher concentrations of organic substances than municipal wastewater. Organic pollutants, most often expressed as chemical oxygen demand (COD) and suspended solids, originate from raw materials, product losses, contact between organic waste and wastewater, and organic cleaning agents containing surfactants (***Ministerstwo Środowiska, 2005).***

3. SEWAGE TREATMENT PLANTS

A sewage treatment plant is a complex of buildings consisting of basic technological facilities used directly for sewage treatment and sewage sludge disposal, as well as auxiliary facilities located on the same premises, necessary for the supply of energy, the creation of appropriate working conditions for the staff, the conduct, management and control of technological processes **(Zdebik et al., 2010).**

A wastewater treatment plant is a complex system in which individual units work together to ensure optimal quality of treated wastewater while minimizing environmental impact. Treatment processes can be divided into four groups, also known as treatment stages:

• **mechanical treatment** involves the use of physical processes and simple mechanical operations, such as sieving, flotation, and sedimentation. The purpose of mechanical treatment is to initially remove larger contaminants and substances that may hinder subsequent treatment steps. The main contaminants removed at this stage include larger floating and dragged solids (screenings), granular particles with a conventional size of 0.1 mm and larger (sand), easily settling suspensions, and oils and greases susceptible to separation. Mechanical treatment also reduces the load on biological and chemical processes, increasing their efficiency and extending the life of the equipment used **(Jarvis et al., 2005)**

• **biological treatment** – occurs under aerobic, hypoxic, and anaerobic conditions and involves the oxidation and mineralization of organic compounds contained in wastewater using micro- and macroorganisms. Microorganisms metabolize organic compounds, converting them into simpler compounds such as carbon dioxide, water, and biomass. Biological treatment is crucial for reducing BOD_5 and COD, which are indicators of the primarily organic load of wastewater. In practice, activated sludge reactors, biological filters, biofilters, and sequential systems are used, among others, which allow for the effective use of microflora under various oxygen conditions ***(Błaszczyk, 2007)***

• **Chemical treatment** – chemical wastewater treatment methods are primarily used for industrial wastewater containing substances that are difficult to biodegrade, known as refractory substances. The most important chemical and chemical-physical wastewater treatment processes include neutralization, oxidation, coagulation, precipitation, ion exchange, and extraction. Neutralization corrects wastewater pH, which is crucial for protecting equipment and the environment. Oxidation enables the decomposition of organic compounds and some inorganic contaminants, while coagulation and precipitation facilitate the removal of fine suspended solids and heavy metals. Ion exchange and extraction are used to remove specific chemical components that cannot be reduced by biological methods (***Mańczak, 2018)***.

• **Additional treatment (applies to some technologies)** – some treatment plants use additional steps, such as carbon filtration, reverse osmosis, UV disinfection, or ozonation, to remove microorganisms, detergent residues, and poorly biodegradable compounds. Such processes are becoming increasingly important in the food industry, including brewing, given the environmental requirements and water quality requirements in recirculation processes **(Shannon et al., 2008).**

Integrating all treatment stages allows for effective wastewater management, minimizing environmental impact and enabling the recovery of raw materials and energy, for example, in the form of biogas. Implementing comprehensive technological solutions also helps optimize the operating costs of industrial plants and ensures compliance with legal regulations regarding wastewater disposal. Any investment requiring the use of water or potentially impacting water quality (discharge of wastewater into water or soil) will require a water permit. This requires meeting a number of conditions contained in the permit **(Pozwolenie wodnoprawne, 2024).**

4. SURFACTANTS

Surfactants (surface-active substances) are chemical compounds that exhibit surface activity, meaning they effectively reduce the surface tension at the interface between two phases. In industrial wastewater, including breweries, surfactants can originate from both raw materials used in the production process and from detergents used in cleaning and disinfecting technological installations. The presence of surfactants in wastewater affects not only the physicochemical properties of wastewater but also the effectiveness of biological and chemical treatment processes, as they can interact with microorganisms or react with chemical reagents used in wastewater treatment plants. Their content in both raw and treated wastewater can be determined using commercial cuvette tests, which are imprecise **(Hach, 2024)** or dedicated methods:

- MBAS method (for determining anionic surfactants)

- BiAS-thio method (for the determination of non-ionic surfactants) **(Szymańska et al., 2025).**

The MBAS (Methylene Blue Active Substances) method is an analytical technique used to determine the concentration of anionic surfactants in raw and treated wastewater samples. The method is based on the reaction of anionic surfactants with the dye methylene blue at appropriate pH conditions, which forms a colored complex soluble in the organic phase. The anionic surfactants present in the sample react with the positively charged methylene blue molecules, forming an ionic compound that passes into the organic phase (usually chloroform, hexane, or another compatible solvent). The color intensity in this phase is proportional to the amount of anionic surfactants and can be measured photometrically. The MBAS method allows for the determination of low and medium concentrations of anionic surfactants, and its advantages include its simplicity and the ability to rapidly monitor wastewater quality in industrial laboratories **(PN-EN 903, 2002).**

The BiAS-thio (Bismuth Active Substances) method is a simplified analytical technique for determining the content of nonionic surfactants in water and wastewater samples. It is based on the precipitation of an orange precipitate of nonionic surfactants with Dragendorff's reagent. After washing the precipitate with glacial acetic acid, it is dissolved in an acidic thiourea solution. The resulting yellow bismuth-thiourea complex can be determined spectrophotometrically in the visible spectrum. The color of the complex solution is proportional to the amount of nonionic surfactants in the analyzed sample. This method allows for the accurate determination of ethoxylate concentrations even in the presence of other chemical compounds in the wastewater. The BiAS-thio method is particularly useful in monitoring wastewater after cleaning and disinfection processes, when the wastewater contains a mixture of different detergents **(Szymańska et al., 2025).**

Commercial cuvette tests, although quick and convenient, do not provide high accuracy due to high sample contamination. Such contamination leads to clouding of solutions in the measuring cuvettes and even causes the formation of emulsions that interfere with the spectrophotometric analytical signal **(López-García et al., 2014).**

Surfactants, both anionic and nonionic, play a significant role in assessing the quality of industrial wastewater. Their presence can influence foam formation, reduce sedimentation and flotation efficiency, and affect the microflora used in biological treatment. Therefore, systematic monitoring and control of surfactant concentrations in wastewater is essential to ensure the effectiveness of treatment processes and compliance with environmental requirements ***(Wyrwas, 2012).***

5. POLLUTION REDUCTION DEGREE

The degree of pollutant reduction can be defined as an indicator of the efficiency of the wastewater treatment process by comparing the amount of pollutants before and after treatment **(*Ambulkar, 2020*).** This is one of the fundamental parameters used in assessing wastewater treatment plant performance, allowing for comparison of the effectiveness of different treatment technologies and process optimization. A higher reduction ratio indicates greater contaminant removal efficiency, which is particularly important in the food industry, where wastewater can be characterized by significant variability in chemical and biological composition **(Fillaudeau et al., 2006).**

The degree of pollution reduction can be determined as a percentage using the formula:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \cdot 100\% \tag{1}$$

where:
η– degree of pollution reduction [%]
C_{in}– concentration of pollutants before the purification process
C_{out}– concentration of pollutants after the purification process

Table 1 presents the anionic detergent reduction rates for 10 samples. The conducted studies revealed significant variations in the reduction rates for these pollutants. The minimum value was 52.04%, while the maximum was as high as 99.19%. This may be due to significant variations in the concentration of anionic surfactants in the inlet raw sewage, ranging from 0.8 mg/dm^3 to as much as 55 mg/dm^3, caused by the discharge of system cleaning solutions and the discharge of wastewater treatment plant solutions, ranging from 0.1 mg/dm^3 to 15 mg/dm^3, as well as the efficiency of the treatment plant itself. An average anionic surfactant reduction rate of 78% was achieved.

Table 1. Degree of reduction of anionic detergents (own work)

Sample No.	Degree of reduction of anionic surfactants [%]
1	55
2	99
3	79
4	52
5	75
6	87
7	80
8	86
9	85
10	79
On average	**78**

Table 2 presents the nonionic detergent reduction rates for 10 samples collected at the inlet and outlet of the treatment plant. Changes in the concentration of nonionic surfactants in the inlet raw sewage ranged from 3.2 mg/dm^3 to 6.3 mg/dm^3 and in the outlet from the treatment plant from 0.2 mg/dm^3 to 0.5 mg/dm^3. The nonionic surfactant reduction rates were within a narrow range of 91.01–95.23%. The average reduction rate of nonionic surfactants was good and reached 94%.

Table 2. Reduction rate of non-ionic detergents (own work)

Sample No.	Degree of reduction of non-ionic surfactants [%]
1	95
2	94
3	91
4	91
5	94
6	95
7	95
8	94
9	94
10	92
On average	**94**

Figure 1 presents a comparative summary of the degree of reduction of anionic and nonionic detergents for individual samples.

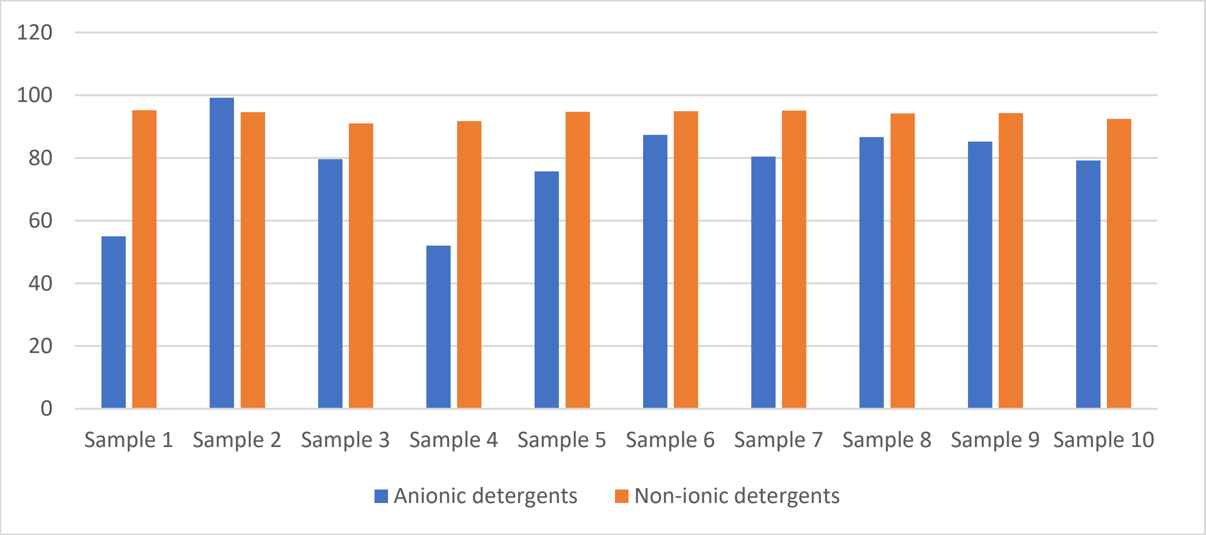

Figure 1. Degree of reduction of contamination of anionic and nonionic detergents (own work)

6. BREWING INDUSTRY

The brewing industry discharges wastewater with high BOD_5 and COD concentrations, primarily due to the presence of organic compounds such as sugars, proteins, yeast, and fermentation byproducts. Consequently, wastewater treatment plants are designed as separate units within the plant or are integrated with municipal treatment plants located in local communities. Separating treatment processes allows for better control of physicochemical and biological parameters of wastewater, minimizing the risk of exceeding permissible standards for water discharged into the environment. Breweries are increasingly implementing energy recovery systems, for example, through the use of biogas produced in wastewater treatment plants, which simultaneously reduces pollutant emissions and lowers plant operating costs. Biogas generated from the anaerobic digestion of sewage sludge is a valuable energy resource that can be used to generate heat and electricity for the plant itself or the local power grid. However, challenges related to the heterogeneity of the brewery wastewater stream remain. Parameters such as organic compound load, pH, suspended solids, and chemical composition can fluctuate significantly throughout the day and seasonally, requiring flexibility in the design and operation of wastewater treatment plants. In practice, this requires the use of integrated treatment systems, encompassing mechanical treatment (removal of larger particles and suspended solids), biological treatment (decomposition of organic compounds by microorganisms), and chemical treatment (neutralization of poorly biodegradable substances or pH adjustment). This combination of processes allows for the production of treated wastewater that meets environmental standards while minimizing the risk of post-production wastewater burdening the ecosystem. Monitoring and control of key water quality indicators, such as BOD_5, COD, total suspended solids, nitrogen, and phosphorus, are also a significant aspect of wastewater management in breweries. Regular measurements and automatic treatment process control systems allow for a rapid response to changes in wastewater parameters and enable optimization of energy and chemical consumption **(Olajire, 2020).**

Moreover, the brewing industry is an integral part of the food industry, as it relies on agricultural raw materials such as barley, hops, water, and yeast, and the production process itself relies on biological transformations typical of food technology. Beer production shares many similarities with other food industries, such as the dairy and fermentation industries, where microbiological processes and quality control of raw materials and final products play a key role. Furthermore, breweries often collaborate with other sectors of the food industry by utilizing byproducts – for example, brewer's spent grain is used as animal feed, a baked goods ingredient, or a raw material for the production of functional foods, while brewer's yeast is used in the production of feed additives, yeast extracts, and dietary supplements. Increasingly, attempts are being made to use spent grain to produce biodegradable packaging or biocomposites. This approach aligns with the concept of a circular economy and reduces resource losses **(Mussatto et al., 2006; Lynch et al., 2016).**

At the same time, the brewing industry has both a negative and positive impact on food waste. On the one hand, losses can occur during the storage of raw materials (e.g., grains), the production process (e.g., extract loss), and the distribution of beer, particularly in the case of products with a limited shelf life or improper storage. Globally, significant amounts of food are also lost in the supply chain, including raw materials for the brewing industry **(Gustavsson et al., 2011).** On the other hand, the brewing industry is actively developing waste-reduction solutions, such as the reuse of by-products, the production of biogas from organic waste, the recovery of process water, and the use of unsold beer for the production of distillates, vinegar, or energy. Another example is initiatives involving the use of unsold bread as a raw material, partially replacing malt in the brewing process, which helps reduce waste in other sectors of the food industry. Such activities are consistent with sustainable development and circular economy strategies **(Tonini et al., 2020; Brancoli et al., 2017).**

Figure 2 presents a comparison of average pollutant values in treated sewage obtained over the years (2016-2021).

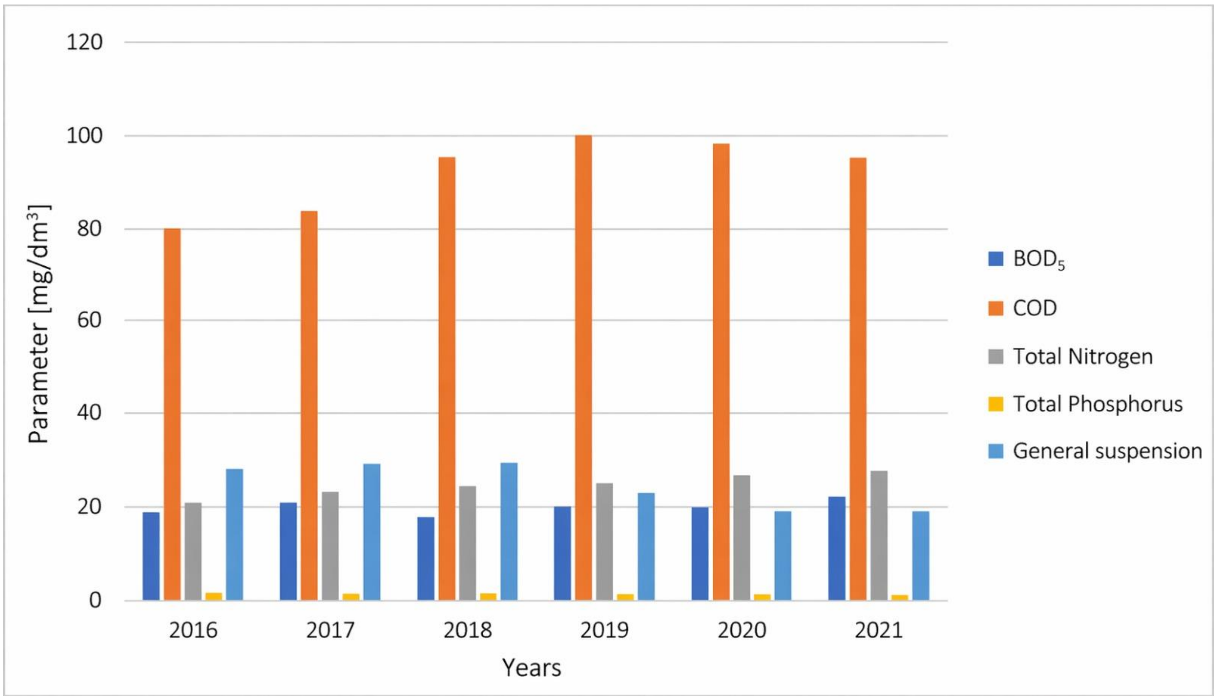

Figure 2. Comparison of average pollutant values in treated sewage over the years 2016-2021 (own work)

Based on the above data, Fig. 3 presents the reduction rates for individual pollutant parameters from 2016 to 2021. The reduction rates for BOD_5, COD, total nitrogen, total phosphorus, and total suspended solids are presented. It can be seen that in 2019, there was a decrease in the reduction of total nitrogen, total phosphorus, and total suspended solids. This may be due to the launch of a new bottling line this year, its testing, and changes in the characteristics of the beer produced and bottled, which resulted in changes in the characteristics of the raw wastewater and, in turn, required the adaptation of microorganisms in the anaerobic and aerobic reactors to the new conditions. Since then, the reduction rate has been gradually increasing again since 2020.

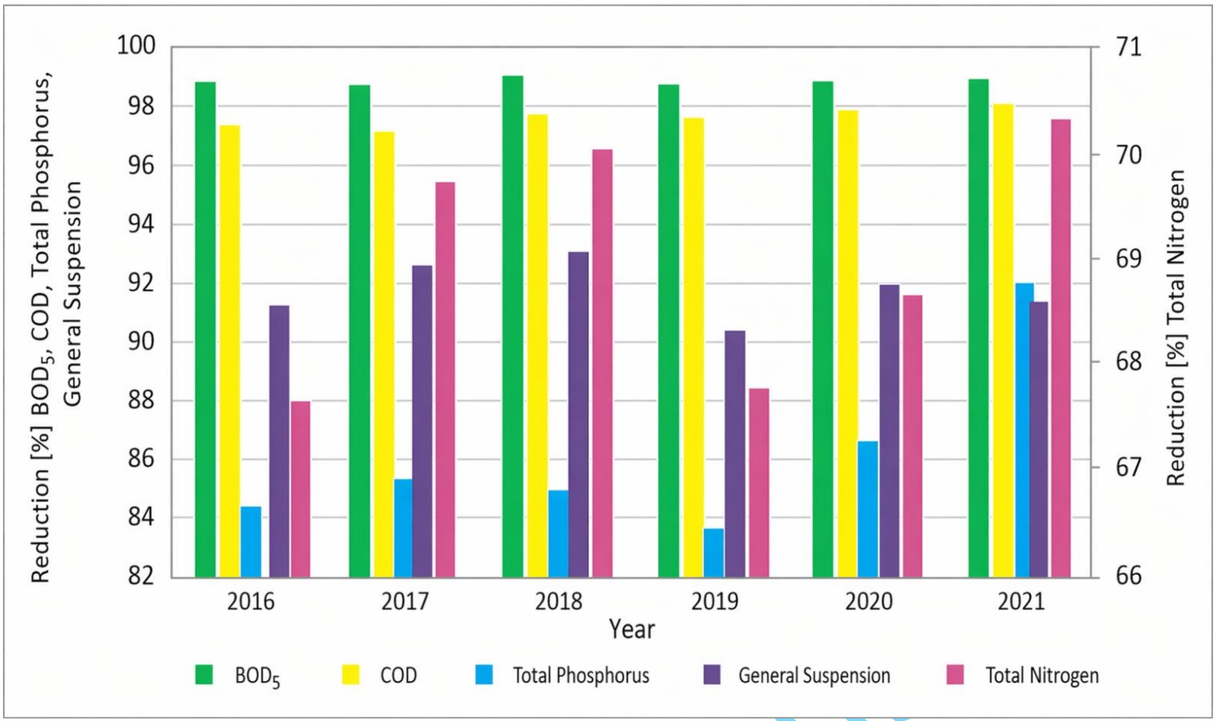

Figure 3. Pollution reduction rate in 2016-2021 (own work)

The most important document for the on-site wastewater treatment plant, specifying the requirements for treated wastewater discharged into surface waters (the Western Oder River), is the Integrated Permit for the plant, issued by the Mayor of Szczecin. This permit allows for industrial operations. Since 2001, it has been able to replace previously applicable partial environmental permits. It combines multiple types of environmental impacts and further indicates the interconnections between these impacts. It is required for installations that, due to the type of activity and its scale, pose a risk of environmental pollution in the surrounding area **(Hillary, 2004).**

The brewery in question holds a single Integrated Permit (IP) for all installations. In the event of gross violations of the provisions contained in the IP, the issuing authority has the right to revoke the permit, which would require the plant to cease operations **(Ebbesson, 2010).** Table 3 presents the average annual pollutant values and their maximum values specified in the IP. Each value falls within the required range. The parameters for total nitrogen are closest to the maximum value, practically bordering on the maximum value. The remaining parameters are significantly lower than those specified in the IP.

Table 3. Comparison of average pollutant values in treated sewage with the permitted values of the Integrated Permit (IP) (own work)

Type of pollution	Year						
	2016	2017	2018	2019	2020	2021	IP value
BOD$_5$ [mg O_2/L]	19	21	18	20	20	22	25
COD [mg O_2/L]	80	83	96	99	99	95	125
Total Nitrogen [mg N_2/L]	21	23	24	25	27	27	30
Total Phosphorus [mg P/L]	1.6	1.6	1.7	1.4	1.2	1.1	2
General suspension [mg/L]	29	29	29	23	19	19	35

The presented data show that in the case of BOD_5, there was a slight upward trend from 19 to 22 mg O_2/L from 2016 to 2021. COD values increased from 80 to 100 mg O_2/L in 2016-2019, and decreased to 96 mg O_2/L in 2021. Total Nitrogen is characterized by a steady upward trend from 21 to 28 mg N_2/L, while total phosphorus shows a downward trend from 1.6 to 1.1 mg P/L. Total suspended solids values showed an upward trend in 2016-2018, but after 2019, the values began to decline to an acceptable level of 19 mg/L. The average surfactant content in treated effluent discharged into the river was also below the permissible value. All presented parameters of treated sewage were within the values of the water permit.

7. SUMMARY AND CONCLUSIONS

The brewing industry generates significant amounts of wastewater with high organic pollutant loads, requiring advanced treatment technologies. The characteristics of brewery wastewater and its variable composition necessitate the integration of mechanical, biological, and chemical methods to ensure environmental safety and meet regulatory requirements. This article also discusses the importance of determining surfactants—both anionic and nonionic—using the MBAS and BiAS-thio methods, which enable the assessment of treatment effectiveness for these two most numerous groups of surface-active compounds.

The conducted studies showed that the reduction rate of anionic surfactants was characterized by quite high variability, with an average value of 78%. For nonionic surfactants, the reduction rates were less variable, with an average value of 94%. Analysis of operational data from 2016–2021 confirmed that the treatment plant meets the requirements specified in the integrated permit, and the parameters of BOD_5, COD, total phosphorus, and suspended solids are within permissible levels. Regarding the permissible content of anionic and nonionic surfactants in treated effluent discharged into the environment, which is 5 mg/dm^3 for anionic surfactants and 10 mg/dm^3 for nonionic surfactants, respectively (***ROZPORZĄDZENIE MINISTRA ŚRODOWISKA, 2009)***, it was not exceeded by the treatment plant even though the level of surfactants in the raw sewage reached a high level of 55 mg/dm^3.

Treating domestic wastewater from breweries is a demanding process due to its high organic load and variable composition. Therefore, the appropriate selection and combination of treatment methods is crucial. Anionic surfactant determinations performed using the MBAS method show greater variability in results, which may be due to the specificity of the wastewater, the sensitivity of the method to matrix composition, and the operation of the treatment plant itself. The MBAS and BiAS-tio methods are useful tools for assessing wastewater quality by monitoring anionic and nonionic surfactants. The analyzed treatment plant achieves a high level of pollution reduction efficiency and has thus far met applicable environmental standards. Total nitrogen remains the most demanding technological parameter. Regulations have been tightened (European Commission Implementing Decision of November 12, 2019, and the Polish Waters decision) establishing recommendations for Best Available Technology (BAT). For the food industry, the total nitrogen value in treated wastewater has been reduced to 20 mg/dm^3. However, this also depends on the sensitivity of the specific receiving body of water into which the treated wastewater is discharged. This may require modernization of the installation or the introduction of additional treatment stages. Further industry development and growing environmental requirements indicate the need to implement innovative solutions, including energy recovery from treatment processes and improved methods for monitoring wastewater parameters.

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