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RESEARCH ON THE RECOVERY OF RINSE WATER IN A MICROBREWERY

Summary

Background. Water usage during beer production is one of the highest in the food processing industry. The dynamically growing microbrewery market requires the implementation of water recycling systems. The research investigated and presented the technology for the recovery of rinse water from the brewing industry. A case study examined the usage of water during the brewing and cleaning process in a small brewery. Moreover, an analysis of brewery rinse water before and after purifying was conducted.

Results and conclusions. The purified water obtained had high technological values, including lower turbidity, reduced content of nitrates and over two-fold increased content of chlorides and met the requirements for drinking-grade water. The implementation of the analyzed system may both provide financial benefits and ensure compliance with sustainable development trends initiated by the largest breweries. The design and features of the analyzed purifying system make it possible to use it commercially in the microbrewing industry.

Keywords: wastewater, beer, brewing, water recovery, sustainable development

Introduction

Beer is one of the oldest beverages in the human history. According to recent studies, brewing started in neolithic communities [8]. Beer is also widely consumed in modern times, being the fifth most popular drink in the world: after tea, water, milk and carbonated soft [23]. In recent years, production of beer has increased by 1.3 % from 1.870 m hl in 2021 to 1.890 m hl in 2022 [16]. Countries with the highest beer consumption per capita include the Czech Republic (184 l), Austria (98 l), Lithuania (96 l), Romania (95 l) and Poland (94 l) [17]. The brewing process includes extracting sugars from malt, boiling wort with hops and fermenting with yeast [36]. Beer proper-

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ties, such as color, taste, flavor, the level of alcohol, depend on raw materials selected – water and its composition, the type of malt, the varieties of hops, yeast strains and brewing methods [30].

One of the most important trends in the beer industry since 1978 includes a dynamic growth and development of small breweries, called "the beer revolution" [1]. Many of them are regional facilities with owners and workers independent of big brewing corporations and create products with high traceability. Breweries identified with "the beer revolution" allegedly stand in opposition to the aforementioned large brewing corporate factories with automated production and highly processed beers [15, 33]. The smallest breweries are often called microbreweries, although the terminology varies between countries. According to the European Union law, a small and independent brewery is characterized by beer production volume. Directive 92/83/EEC states, that a small brewery could not produce more than 200,000 hl of beer per year [12]. In Poland, the beer revolution began in the second decade of the 21st century, and from the very beginning, it was based on breweries established by home brewers. From 2010 to 2016, 173 new breweries were created in Poland, and this tendency continued in the following years [37].

Water is a basic element of the food industry, both in terms of raw materials and technological use. Within a year, processing plants in Poland used more than 585.6 billion liters of water, of which 12.3 % was used for the needs of the food industry, in which 59.4 % was utilized for dairy and meat processing [34]. Beer production also consumes a major portion of industrial water, as water is the main raw material used by this sector [35]. Beer brewing ranges depend on the production volume and the technology applied. They usually range from 4.7 ÷ 13.3 hl per hl of produced beer [31]. The lowest usage in Poland was achieved by the biggest Polish brewing company, Kompania Piwowarska, owned by an international brand Asahi, and according to their reports, reached 2.63 hl/hl in 2019 [21].

Water consumption in a brewery can be divided into three sections: technological process water, municipal water (bathrooms, employee kitchens) and rainwater [31]. This study analyzes the first of the aforementioned sections, which takes different results, depending on the technological advancement of the production, the type of beer produced and a brewer's abilities. Technological process water includes such areas like a brewhouse, cellar, packaging and cleaning. The amount of used water leaving a brewery as an effluent oscillates between 65 to 70 % [24]. Water usage ranges in different brewery processes are shown in Table 1, based on [31].

Table 1. Water consumption for different brewery processes [31]
Tabela 1. Zużycie wody w poszczególnych procesach produkcji piwa [31]

Brewery Departament / Dział browaru	Water consumption / Zużycie wody [dm^3/ dm^3]
Brewhouse / Warzelnia	1.7 ÷ 2.6
Cold Storage / Chłodzenie	1.1 ÷ 2.4
Fermentation / Fermentownia	0.4 ÷ 0.8
Storage Cellar / Leżakownia	0.1 ÷ 0.6
Filtering / Filtracja	0.1 ÷ 0.8
Bottling / Butelkowania	0.9 ÷ 1.0
Casking / Beczkownia	0.1 ÷ 0.2
Miscellaneous / Różne	0.3 ÷ 4.0
Total process / Całość procesu	4.7 ÷ 13.3

The greatest losses of water in the brewing process occur during the initial washing / rinsing of the installation, during the transfer of the wort and in the process of cooling wort during transfer to the fermentation tank. In the case of the installations that use tap water as a heat sink in the exchanger, there are solutions that allow for the reuse of the cooling material. Water lost by evaporation during boiling and with spent grains could not be retrieved. However, as a by-product, spent grain is used as a feed material or raw material for biogas production, therefore it is assumed that the bounded water is fully reused [5]. The largest consumption of water is related to cleaning and rinsing. Water used for washing and rinsing brewhouses may contain both biological contaminants: malt residues, hops, and chemical residues of cleaning agents: alkaline or acidic ones, and in exceptional cases, based on chlorine. Such water requires a treatment system to be re-used [18]. The contamination of wastewater is also a big concern for environmental science, as well as for producers. The overgrowing of undesirable microorganisms may have a negative effect on aquatic lifeforms and leads to water scarcity [2]. In Poland, water used to produce beer as raw material, must meet certain requirements stated in the Regulation of the Minister of Health (Journal of Laws of 2017, item 2294) (*Rozporządzenie Ministra Zdrowia Dz.U. z 2017 r. poz. 2294*). Table 2. presents selected parameters of drinking grade water, based on document.

Some of the most important water parameters for brewing include pH, hardness, concentration of nitrates and chlorides. Optimal pH levels for beer production are 5.2 ÷ 5.8 for the mashing process. This allows for the highest activity of enzymes, alpha and beta amylase, responsible for the effectiveness of starch conversion into fermentable sugars and beta-gluconase, affecting the speed and effectiveness of filtration. Optimal pH also limits the extraction of malt and hop tannins to wort, which may adversely affect the taste of final product [38]. Beer is also influenced by the carbonate hardness.

The high concentration of carbonate, as well as bicarbonate ions, increases the extraction of tannins and the risk of residual bitterness and tartness, unpleasant in the perception by consumers [7]. The prominent level of nitrates may inhibit a yeast growth [19]. Chlorides are essential for the mellowness of a final product, as well as improve clarification and provide colloidal stability [27]. Residual alkalinity is a commonly used indicator to assess the usefulness of water in brewing. It is defined as a difference between properties of ions in water - alkalizing anions, including mainly bicarbonates and acidifying cations, such as Mg^{2+} and Ca^{2+}. It is calculated from a formula based on water hardness and the concentration of calcium and magnesium ions. The higher the residual alkalinity, the higher the pH of the water and wort, and bigger impact of carbonate hardness, which can slow down and worsen the mashing process [22].

Table 2. Selected parameters of drinking grade water [26]
Tabela 2. Wybrane parametry wodny pitnej [26]

Parameter/Parametr	Wymagane wartości lub ich przedziały / Required values or their ranges
pH	6.5 ÷ 9.5
Hardness (as $CaCO_3$) / Twardość (jako $CaCO_3$)	60 ÷ 500 mg/dm^3
Conductivity / Przewodność	< 2500 µS/cm
Bromides / Bromki	< 10 mg/dm^3
Ammonium ion / Jon amonowy	< 0.5 mg/dm^3
Nitrates / Azotany	< 50 mg/dm^3
Chlorides / Chlorki	< 250 mg/dm^3
Turbidity / Mętność	< 1NTU

The aim of the research was to test possibilities and effectiveness of the designed water treatment system for use in a microbrewery after the production process and installation cleaning. Solutions enabling the reuse of water are used by the largest breweries, consuming enormous amounts of raw materials, and are part of their sustainable development systems, often in combination with technologies that reduce water consumption at each stage of production. We believe that the research we have carried out will allow us to obtain an easy and widely available water treatment system, targeted at the smallest beer producers.

Materials and methods

Case study

The brewery where the water consumption was measured is located in north-central Poland. After being put into operation in 2019, it has been operating continuously since 2020. The size of a single production batch in the plant varies between

230 ÷ 270 liters. The brewhouse consists of a two-section, single tun, electrically powered and heated by steam. Wort is transferred to fermentation tanks through a countercurrent heat exchanger fed with cold running water. The three fermentation tanks with a capacity of 500 l each are cooled by a closed chilled water circuit. The facility belongs to the micro-brewery segment, as its annual beer production does not exceed 200,000 hectoliters. The brewery uses municipal water for production (further untreated in the production area) and electricity from the public grid. The most crucial elements of the production line were:

1. A two-section brewing tun with a maximum capacity of 320 l, made of stainless steel, intended for the production of beverages.
2. A steam generator, operating in a closed circuit with an installed power of 21 kilowatts (kW).
3. An electric heating boiler for water with a capacity of 600 l and a capacity of 12 kW.
4. A circulation pump with a 1.1 kW motor
5. A stirrer with an engine power of 0.75 kW
6. A solenoid valve with a power of 0.007 kW
7. A brewing support system (a control cabinet) with a power of 0.01 kW

Readings taken from meters installed in the production facility provided data on water consumption during the brewing process and installation cleaning . Measuring accuracy of water was 1 dm^3, and for the purposes of the experiment it was assumed that 1 l (dm^3) of used water equals 1 kg (kg).

Water treatment system

The water treatment system used in the research consists of a closed-circuit system of a rinse water flocculation tank, a circulating pump with a pre-filter, an ultrafiltration system, an additional disinfection system and an expansion tank. Water is supplied to the treatment system from an external system and drained by an overflow solenoid valve to the sewage system. The duration of flocculation process is less than an hour, of which 15 minutes are aggregated, and the sedimentation itself takes about 30 minutes. When the process is finished, the built-in system allows the tank to be disinfected and sediment to be removed. The circulation pump built into the installation forces the water to circulate throughout the system. Flocculated water is passes through the sand solid bed, which allows the removal of suspensions, solid particles and colloids. The next step involves the ultrafiltration system, consisting of dozen or more medical grade membrane filter modules made of dialysis tubes. Impurities of 0.03 μm are retained on the membrane fibers, while slower flow allows for the retention of particles ten times smaller. Subsequently, purified water goes to the expansion tank, from which it is fed to the brewing installation (brewhouse) and collected by the circulation pump for rinsing the filter tubes. Tubes are cleaned by rinsing them with clear water going in the opposite direction. The filtration area of each tube is about $2m^2$. The device is operated with use of PLC. A schematic plan of water treatment system is presented in Fig. 1.

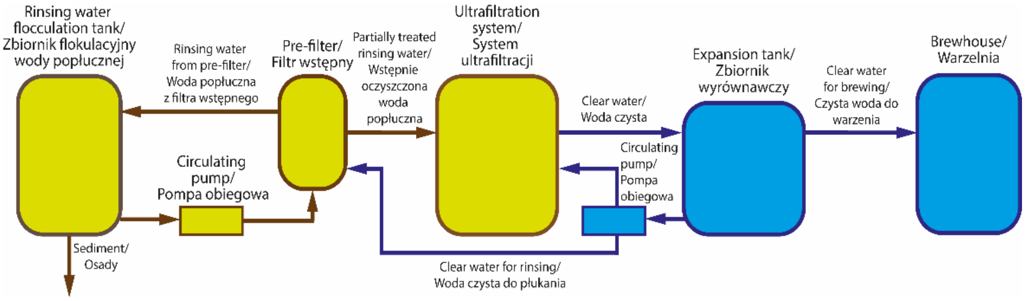

Figure 1. Schematic plan of rising water treatment system
Rycina 1. Schematyczny plan systemu oczyszczania wody

Production process

This process description covers a single cycle of brewing beer and washing the brewing installation after the production stage.

1. The preparatory stage consists in starting an electric heating boiler and heating production water to a set temperature of 70 °C, which is optimal for the entire process and for cleaning the installation. Throughout the system's operating cycle, the boiler remains on and heats water. At this stage, the brewing system and the steam generator were also activated.
2. Mashing begins with filling the tun with water at 70 °C and adding 50 kg of crushed barley malt to the tun, which lowers the mash temperature to 67 °C, and thus guarantees appropriate technological conditions for the process to be conducted. At the same time, the process parameters were set on the control cabinet by supplying steam, regulated by the operation of the generator, solenoid valve and PLC controller. The agitator in the vat was turned on.
3. After the completion of the one-hour mashing process, the effectiveness of the process is checked in the iodine test, and after turning off the stirrer and the steam supply, the mash is transferred to a separate part of the system, which is a filter tun, 20 dm^3 of water from the boiler was added before the transfer to fill the filtration space under the sieves. Next, for a quarter of an hour, the filter bed was built up.
4. Filtration was performed by transferring the filtered wort with the circulating pump. The filtration time was 3 hours, and it was completed after reaching the ap-

propriate volume in the brewing tun, determined by a reading from an accredited gauge. During the filtration, 40 liters of water from the heating boiler were poured twice on the surface of the bed.

5. The transferred wort was heated with steam from a chiller to a boiling point and held for one hour, while stirring the solution with the stirrer. During the brewing, 1 kg of hops in the form of dry granules was added twice during the brewing process, which did not affect the temperature changes of the medium. The closed system of the brewhouse limited the losses related to evaporation. No losses caused by evaporation were observed after transitioning wort to the filtering tun in step 7.
6. Spent grains remaining in the filter tun were removed and handed over to a farmer free of charge for fodder and composting purposes. The obtained weight of the spent grain was 60 kg.
7. After the end of the brewing process, the wort was gravitationally transferred to the filtering tun, where, after the hot sediments had settled, it was pumped to the fermentation tank. Sediments weighing 12 kg were removed.
8. During the transfer of the wort to the fermentation tank, it was cooled to 20 °C by the use of a counter-stream plate cooler supplied with cold running water. For cooling down, 600 l of freezing water was used, which ended up in the sewage drain.
9. Cleaning was started with the initial rinsing of the installation with 50 dm^3 of water from the boiler at 70 °C, then the brewing vessel was filled with 200 dm^3 of water and 10 kg of alkaline cleaning agent was added. The circulation pump was started and the installation was washed in a closed circuit for 45 minutes.
10. The pump was turned off. The contents of the installation were removed, leaving a small amount of solution with the cleaning agent, and proper rinsing was started with 100 dm^3 of warm water, and the installation was drained, leaving a small number of washings in the system.
11. Secondary rinsing was conducted with 300 dm^3 of water from the boiler at 70 °C, allowing the system to drain completely. A portion of the rinse water was taken for laboratory tests. The heating boiler and the brewhouse control system were turned off.

Sampling and sampling frequency

During the triple brewing and cleaning of the brewing installation in the brewery, water consumed by the devices included in the brewing installation was measured. During each brewing, raw materials used in production and conservation, as well as production and washing of waste, were weighed.

Laboratory tests

Rinse water for laboratory tests was collected in accordance with the guidelines of PN-ISO 5667-5: 2017-10. Water flowing in an even stream from the system was collected in the middle of the secondary rinse process. Polypropylene bottles were filled to overflow. Subsequently, they were tightly closed to prevent contamination of the plugs. After collection, water was marked for later identification. Water tests were carried out to determine the following parameters: pH, water hardness (as $CaCO_3$), water conductivity, bromides, ammonium ion, nitrates, chlorides, turbidity. Chemical tests for each trial were repeated three times, and the results obtained were presented in the form of mean values.

The following methods were used for the laboratory testing of water:

1. To measure pH, the potentiometric method was employed according to the PN-EN ISO 10523:2012 standard using the Methrom OMNIS titrator.
2. Water hardness (calculated as $CaCO_3$) was determined according to the PN-ISO 6059:1999 standard using the titration method with Methrom OMNIS titrator.
3. Water conductivity was determined using the conductometric method, in accordance with the PN-EN 27888:1999 standard, with a Methrom OMNIS titrator.
4. Bromides were determined using the photometric method PN-ISO 10304-1:2009 with a Lovibond PM620 photometer.
5. Ammonium ion was determined by photometric method using the Lovibond PM620 photometer in accordance with the PN-ISO 7150-1:2002 standard.
6. Nitrates were determined by photometric method in accordance with the PN-EN ISO 13395:2001 standard using the Lovibond PM620 photometer.
7. Chlorides were determined by titration with silver nitrate in accordance with the PN-ISO 9297:1994 standard using the Methrom OMNIS titrator.
9. Turbidity was determined with the nephelometric method using Methrom OMNIS titrator, in accordance with the PN-EN ISO 7027-1:2016 standard.

Method of processing the results and statistical analysis

The results obtained were presented by calculating the mean value and standard deviation for the analyzed variables. Subsequently, the results were statistically analyzed using the t test at $p < 0.05$. The results are presented in the form of tables. The research results were processed using a Microsoft Excel spreadsheet.

Results

The tables below present the total consumption of raw materials and the generation of waste, as well as the detailed consumption of water in the production process. Table 3 contains data on materials usage during the brewing process. Table 4 presents mass water usage during specified steps of the production process.

Table 3. Materials usage during brewing process
Tabela 3. Żużycie surowców w trakcie warzenia piwa

Material / Waste / Unit Materiał / Odpad / Jednostka	Usage/ Zużycie x̄ ± SD
Water/Woda [kg]	1530 ± 1.73
Malt/Słód [kg]	50 ± 0.00
Hops/Chmiel [kg]	2 ± 0.00
Spent grains/Młóto [kg]	60 ± 1.00
Cleaning agent/Środek myjący [kg]	10 ± 0.00
Residues/Osady [kg]	12 ± 0.00

Explanatory notes / Objaśnienia:
x̄ – mean value / wartość średnia; SD – standard deviation / odchylenie standardowe

Table 4. Mass water usage during production process
Tabela 4. Masowe zużycie wody podczas produkcji piwa

Production step / Unit Etap procesu / Jednostka	Usage / Zużycie x̄ ± SD
Mashing / Zacieranie [kg]	180±1.73
Filtration / Filtracja [kg]	100±0.00
Cooling / Chłodzenie [kg]	600±0.00
Initial rinsing / Płukanie wstępne [kg]	250±0.00
Main rinsing / Płukanie właściwe [kg]	100±0.00
Secondary rinsing / Płukanie wtórne [kg]	300±0.00

Explanatory notes / Objaśnienia:
x̄ – mean value / wartość średnia; SD – standard deviation / odchylenie standardowe

Based on the research of the rinse water obtained in the brewery and rinse water treated in the treatment system, the following results were obtained, presented in Table 5.

Most water parameters significantly changed compared to the rinse water obtained from the brewery. The pH level in the purified water decreased from 7.71 pH to 7.31 pH, which is related to the reduction in the number of alkaline ions due to the purification of the water. Water treatment did not change hardness. The difference between the rinse and purified water is insignificant and falls within the measurement error. The conductivity of purified water decreased by 25.6 %. It is related to the reduction of the total number of substances dissociated in water. The content of bromides in the purified water decreased by 61 % in relation to the rinse water, which results from the reduction of disinfection residues by the cleaning system. The ammonium content dropped from 0.19 to 0.063 milligrams per liter (mg/dm^3), which is a decrease of 66.8 %. The reduction of nitrates from 3.16 mg/dm^3 to 1.23 mg/dm^3 is a decrease in their amount by over 61.07 %. The chloride content in purified water more than doubled, from 41.7 mg/dm^3 to 93.6 mg/dm^3. The overall turbidity of the water improved, taking values below the required level of 1NTU.

Table 5. Comparison of chemical parameters of rinse water obtained in the brewery and treated rinse water.
Tabela 5. Porównanie właściwości fizykochemicznych wody popłucznej z browaru z oczyszczoną wodą popłuczną

Parameter/ Parametr	Unit / Jednostka	Rinse water / Woda popłuczna $\bar{x}$±SD	Treated rinse water / Oczyszczona woda popłuczna	*p*	Wymagane wartości lub ich przedziały według [26] / Required values or their ranges according to [26]
pH		7.71 ± 0.06	7.31 ± 0.01	0.004	6.5 ÷ 7.5
Hardness ($CaCO_3$) / Twardość (jako $CaCO_3$)	mg/dm^3	209 ± 1.15	208 ± 0.00	*	60 ÷ 500
Conductivity / Przewodność	µS/cm	925 ± 13.08	688 ± 4.0	0.001	< 2500
Bromides / Bromki	mg/dm^3	0.067 ± 0.012	0.026 ± 0.01	0.039	< 10
Ammonium ion / Jon amonowy	mg/dm^3	0.19 ± 0.01	0.063 ± 0.01	0.005	< 0.5
Nitrates / Azotany	mg/dm^3	3.16 ± 0.1	1.23 ± 0.01	0.0002	< 50
Chlorides / Chlorki	mg/dm^3	41.7 ± 2.8	93.6 ± 1.3	0.001	< 250
Turbidity / Mętność	mg/dm^3	2.09 ± 0.10	0.79 ± 0.00	0.002	< 1

Explanatory notes / Objaśnienia:
$\bar{x}$ – mean value / wartość średnia; SD – standard deviation / odchylenie standardowe; *p* – level of significance of differences by t test / poziom istotności różnic testu t; * - statistically insignificant differences / różnice nieistotne statystycznie

Discussion

The test results obtained confirm the suitability and effectiveness of the application of ultrafiltration technology in the microbrewery. The improvement of some of the rinse water parameters, including that from the brewhouse washing stages, is in line with the research carried out in an artisanal brewery in Belgium, where a decrease in pH and general conductivity was also observed [4]. Current studies indicate the high efficiency of ultrafiltration in removing suspended solids and reducing overall turbidity

[8, 20]. Purified water in the presented case study is characterized by a significantly reduced overall turbidity, which allows it to meet legal standards and facilitate its further use in the brewing process.

The results of the conducted research show the usability potential of rinse water treatment system in breweries with the smallest production scale. One of the most important aspects related to the use of purified water with ultrafiltration is its further modification by adding salts in order to obtain an ionic composition appropriate for the produced beer [11]. The chemical parameters of the water obtained indicate its safe use in the further process by meeting chemical standards for drinking grade water. Moreover, the purified water obtained may have beneficial properties for usage during a brewing process.

As mentioned in the literature, the high level of chlorides helps to maintain the proper flavor balance of the beer, emphasizing the malt character and smoothing the character of bitterness, also improving colloidal stability [6]. Nevertheless, chloride levels should not exceed 100 mg/dm^3 to avoid unpleasant salty taste and potentially corrosive effect on stainless steel in brewery [22, 32]. In presented research, obtained purified water contains 93.6 mg/ dm^3, which may have a positive effect on the quality of further produced beer, whilst not having any potential corrosive properties.

Reducing the level of nitrates through the tested water purification system may contribute to improving the quality of water used for brewing beer. It is recommended that the level of nitrates in brewing water be as low as possible, as other raw materials, such as malt and hops are their natural sources [22]. Nitrate levels that are too high, above 50 mg/l, can cause fermentation problems by inhibiting yeast growth. Higher concentration also negatively affects the taste of beer [28]. In the studied case, already low nitrate levels were reduced by as much as 61.07 %. Further testing of the system using water with higher nitrate concentrations should be conducted to confirm the validity of the tested system for more seriously contaminated brewery water.

Water contamination by ammonium is one of the biggest problems in the contemporary water development [9]. Although the level of ammonium in the rinse water obtained was below dangerous levels, a decrease by 66.8 % through purification may suggest that also with higher concentrations the proposed solution would be effective. Further studies and trials should be conducted to confirm the usefulness of the developed method.

The implementation of membrane solutions is difficult due to the high price in commercial terms [3]. However, the system presented in the research may be a solution to this problem, as it uses readily available, cheap components. Moreover, the validity of membrane solutions is demonstrated by the fact that the energy consumption is lower and the efficiency is higher than in the case of conventional treatment methods [25].

The use of the presented treatment system does not have to be limited only to rinse water obtained after the production process or cleaning at a brewhouse. The present research shows the great usefulness of membrane technologies for the removal of proteins, dextrins and pentosans and presents them as an alternative to the use of Kieselguhr filtration [13, 14, 23]. Appropriate modification of the system, supported by further research, may allow the solution to be used at many stages of beer production.

The reuse of rinse water from the studied brewery may potentially save almost 20 % of total water used in the production process, including 45 % of water used for washing and rinsing the brewing system. Further tests, including a sensory analysis of various beers brewed using the obtained purified water should be conducted.

Conclusion

1. The system presented in the study is an effective solution for a small-sized brewery.
2. Water obtained after purification of rinse water from the brewery is characterized by significantly changed chemical parameters and meets standards for drinking-grade water. Furthermore, some of the changed parameters, such as reduced turbidity and increased chlorides, may have a positive impact on the technological use of water in the brewery.
3. The compact size of the solution presented in the research and the use of cheap and widely available system components allow it to be used in the smallest breweries and is beneficial in terms of coordination and finances for small brewers.
4. Potentially lower water consumption not only translates into financial savings, but is also in line with the trend of sustainable development.

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BADANIA ODZYSKU WÓD POPŁUCZNYCH W MIKROBROWARZE

Streszczenie

Wprowadzenie. Zużycie wody podczas produkcji piwa należy do najwyższych w przemyśle spożywczym. Dynamicznie rozwijający się rynek małych browarów wymaga wdrożenia systemów recyklingu wody. W badaniach zbadano i przedstawiono technologię odzyskiwania wody płuczącej z przemysłu piwowarskiego. W studium przypadku zbadano zużycie wody podczas procesu warzenia i czyszczenia w małym browarze rzemieślniczym. Ponadto przeprowadzono analizę wody płuczącej browaru przed i po oczyszczeniu.

Wyniki i wnioski. Otrzymana oczyszczona woda charakteryzowała się wysokimi walorami technologicznymi, m.in. obniżonym zmętnieniem, obniżoną zawartością azotanów i ponad dwukrotnie zwiększoną zawartością chlorków oraz zgodnością z normą dla wody pitnej. Wdrożenie analizowanego systemu może pozwolić zarówno na korzyści finansowe, jak i zgodność z trendami zrównoważonego rozwoju inicjowanymi przez największe browary. Konstrukcja i cechy analizowanego układu oczyszczającego umożliwiają jego komercyjne wykorzystanie w przemyśle mikrobrowarniczym.

Słowa kluczowe: ścieki, piwo, piwowarstwo, odzyskiwanie wody, zrównoważony rozwój