Oxygen-driven 2-furfural accumulation and its influence on beer sensory stability

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Abstract

Introduction. Key criteria for ensuring high beer quality and flavor stability include the quality of raw materials and auxiliaries, the efficiency of technological processes, and the concentration of oxidation products in the finished beer, particularly 2-furfural.

Materials and methods. The study objects were milled malt, wort, and pasteurized beer. Physicochemical parameters of beer were determined using the Anton Paar DMA 4500 analyzer; 2-furfural concentration was measured by ultraviolet spectrophotometry; alcohol and real extract by distillation; color by colorimetric titration; bitterness using spectrophotometric analysis.

Results and discussion. The concentration of 2-furfural and the intensity of its formation depend directly on the duration and degree of oxygen exposure during all stages of malt handling, wort production, and beer processing. As oxygen initiates a cascade of oxidative and thermal degradation reactions, the level of 2-furfural progressively increases, leading to deteriorated flavor, premature aging, and the development of stale, cardboard-like notes in the final product. To prevent excessive oxidation and maintain 2-furfural levels within the desirable range of 4–10 μg/l, the storage time of milled malt should not exceed 50 minutes, as prolonged exposure to air promotes early oxidative reactions already at the raw material stage. The most intensive formation of 2-furfural occurs during wort boiling with hops at elevated temperatures, where thermal degradation processes accelerate dramatically: within a 90-minute boil, its concentration increases six fold, rising from 122 to 793 μg/l. Oxygen uptake during subsequent stages also plays a crucial role. When dissolved oxygen increases from 20 to 120 μg/l during wort fermentation and green beer filtration, the concentration of 2-furfural rises accordingly – from 56.6 to 185.2 μg/l. Heat treatment further contributes to this process: even minimal pasteurization nearly doubles the level of 2-furfural (from 56 to 104 μg/l). Once its concentration reaches 150–200 μg/l, beer begins to exhibit clear oxidized notes, loses freshness, and shows noticeable sensory deterioration. Moreover, the presence of oxygen in the bottle headspace drastically accelerates this process, increasing 2-furfural content by 262% (from 107 to 388 μg/l), which severely compromises beer quality and shortens its shelf life. Ultraviolet spectrophotometry is recommended for measuring oxidation products and 2-furfural in raw materials and finished beer, as its results correlate well with chromatographic data.

Conclusions. To enhance beer sensory properties and flavor stability, it is essential to prevent oxygen exposure at all technological stages. The concentration of 2-furfural in beer should not exceed 150–200 μg/l.

Introduction

As regular natural products, beer tends to age, that is, to deteriorate over time under the influence of oxygen. It is well known that oxygen negatively affects beer quality parameters at all stages of production—from malt milling to beer packaging (Bamforth, 2004). During malt storage, oxidation may occur due to contact with oxygen and moisture, altering its chemical composition and decrease quality of both the raw material and the final beer (Filipowska et al., 2021). Components the most sensitive to oxidation, such as lipids and essential oils, can cause undesirable changes in aroma, flavor, and color in finished beer (Kunz et al., 2013).

Malt is most susceptible to oxygen exposure during milling, as its protective cellulose husk is destroyed. Milling should therefore be carried out as fast as possible or in an inert gas atmosphere (e.g., CO_2). Oxidation of grain products at this stage can lead to papery and fruity-oxidized notes in fresh beer (Bettenhausen et al., 2018; Filipowska et al., 2021).

Oxidation also affects hop components, resulting in the loss of characteristic aroma and bitterness essential for beer quality (Krofta et al., 2013). Beer aging leads to the formation of compounds that impair its flavor and aroma. Oxygen promotes the formation of aldehydes that impart vinous or fruity notes; it may increase the level of diacetyl and produce a buttery flavor, and in cases of microbiological spoilage, lactic acid may form (Diaz et al., 2022).

Improper storage conditions, particularly high temperatures and light, accelerate oxidation processes. Thermal treatment intensifies melanoidin formation, sugar caramelization, and the degradation of hop volatiles, causing changes in beer color and flavor. Undesirable oxidation products such as acetaldehyde and carbonyl compounds (e.g., 2,3-butanedione) are formed (Baert et al., 2015; Pieczonka et al., 2021).

The degree of beer aging is indicated by the presence of Maillard reaction products, which can impart caramel, oxidized, papery, fruity, leathery, and other off-flavors (Carneiro and Guido, 2006; Lohinova and Petrusha, 2023). This reaction may result in the formation of heterocyclic aldehydes and ketones in beer, including 2,3-butanedione; 2-ethyl-3,5-dimethoxy-4-hydroxyhydro-2(3H)-furanone, and 5-hydroxymethyl-2-furfural. 2-furfural belongs to the group of furan aldehydes formed during thermal load of foods in the presence of atmospheric oxygen. Such processes occur during malt production (at kilning and drying stages) and during wort boiling with hops. Thermal load increases its formation and contributes to the color development of wort (Baert et al., 2012; Kunze et al., 2016). The sensory threshold of 2-furfural is 150–200 μg/l. Its formation is preceded by the synthesis of 3-deoxypentosone. During the Maillard reaction, furfural is produced through a series of reactions initiated by interactions between amino acids and pentoses. Its presence in malt and wort may also result from pentose caramelization; in this case, 3-deoxypentosone is formed directly from pentoses (Rakete et al., 2014).

According to the literature, the level of 2-furfural in fresh beer is influenced by malt type (pale, caramel, dark, roasted), the thermal load on wort during boiling, and beer pasteurization (Vanderhaegen et al., 2006). When using the same wort-boiling system, specifically an internal boiler, increasing the evaporation rate from 4 to 11% decreases furfural content in cold wort from 339 to 274 μg/l. During fermentation, yeast actively reduces this aldehyde to the corresponding alcohol (furfuryl alcohol), which further lowers its concentration in fresh beer to 20–70 μg/l. During pasteurization, furfural content may rise again by a factor of 10–15 compared to the unpasteurized beer. Its concentration continues to increase during beer storage, with higher temperatures accelerating its accumulation. For example, after 12 weeks of storage at 20 °C, furfural concentration may increase nearly tenfold (from 25–30 to 190–200 μg/l). This is associated with the oxidation of furfuryl

alcohol, which forms in significant amounts during wort boiling (1.8–3.0 mg/l) (Kunze, 2007; Vanderhaegen et al., 2004).

One of the commonly used methods for determining 2-furfural as a marker of beer aging is ultraviolet spectrophotometry. Absorption peaks for oxidation products, including 2-furfural, lie in the wavelength ranges of 277 nm and 310 nm. The intensity of these peaks is used to determine the degree of beer oxidation (Cuifer-Rada et al., 2015; Rico-Yuste et al., 2016).

The aim of the present study was to investigate the impact of oxidative processes occurring during wort production, fermentation, and beer storage on the quality indicators and flavor characteristics of the final product, with particular emphasis on the influence of 2-furfural concentration on the intensity and degree of beer aging.

Materials and methods

Materials

The study materials included: milled malt obtained after cold extraction with deaerated water; unhopped wort, 14 °P original extract (100% malt); hopped wort, 15 °P original extract (100% malt); pale filtered beer, 10 °P beer extract; pale filtered and pasteurized beer, 10 °P beer extract; bottled pale filtered and pasteurized beer, 10 °P beer extract.

Methods

All samples were analysed for physicochemical parameters, 2-furfural concentration, and sensory attributes according to current technical standards and established analytical protocols.

Determination of extract content (°P) by the cold extraction method. A 10.0 g sample of milled malt was placed in a 250 ml conical flask. Then, 100 ml of deaerated water at 20 °C was added, the flask was capped, and the mixture was stirred for 1 min every 5 min. After 15 min of extraction, the mixture was filtered. Oxygen content in the filtrate was determined using an Anton Paar 4500 DMA beer analyser.

For physicochemical analyses, 100 ml of beer was placed in a 100 ml cuvette and degassed on a magnetic stirrer for 5 min. Measurements were performed using the Anton Paar 4500 DMA complex beer analyser (Bamforth, 2000; Ciocan et al., 2020).

Determination of 2-furfural concentration. The concentration of 2-furfural (μg/l) was determined by UV-VIS spectrophotometer at 277 nm and 310 nm (Olšovská et al., 202; Rico-Yuste et al., 2015).

Physico-chemical properties of the finished beer. Physico-chemical parameters in the finished beer (acidity, ml of 1 M NaOH per 100 ml of wort; color, ml of 0.1M I2 per 100 ml of water; carbon dioxide content, %) were determined using an Anton Paar analyser (Ciocan et al., 2020).

Determination of the dry matter content. The method is based on the determination of the content of extractive substances in beer by relative density (Kunze, 2007). The beer free from carbon dioxide was poured into a cylinder, which was placed on a flat surface, the temperature was measured and an areometer was immersed. The upper meniscus was used to read the areometer and determine the concentration of dry matter (DM), taking into account the correction for temperature.

Determination of the alcohol concentration. The method is based on distilling alcohol from a weighed beer sample, followed by determining the alcohol mass fraction using a refractometer and measuring the solids content by the areometric method (Kunze, 2007). In a dry distillation flask 200 ml of beer freed from carbon dioxide were taken, the flask was connected to a refrigerator through a droplet eliminator and the beer was distilled. After distillation of 1/3 of the sample volume, the rest of the distillation flask was brought to the original volume with water, mixed thoroughly, cooled to the temperature of 20 ºC and the concentration of DM (actual content of the extract) was determined by areometric method. The distillate in the receiving flask was brought with water to the initial volume, mixed thoroughly and the mass fraction of alcohol in the sample was determined at 20 ºC by a dip refractometer using alcohol tables.

Determination of beer bitterness. Bitterness was determined spectrophotometrically in quartz cuvettes with a 10 mm path length. Two identical 50 ml flasks were filled with 10 ml of prepared beer, 1 ml of 3 M HCl, and 20 ml of iso-octane. Flasks were capped and shaken at 750 rpm for 15 min. After phase separation for 10 min, the upper layer was measured spectrophotometrically at 275 nm (Kunze, 2007).

Determination of SO_2 content. Sulfur dioxide content was determined by distillation from an acidified beer sample, collection into a neutralized hydrogen peroxide solution (oxidizing SO_2 to sulfuric acid), and titration of the resulting solution with sodium hydroxide (Kunze, 2007).

Determination of sensory properties. Off-flavors and deviations from the brand profile were evaluated using a 25-point scale. Based on the overall sample intensity, the average score for panelists D1–D7 was calculated, an overall table of individual panelist scores was compiled, and the final score for each experimental sample was determined.

Experimental samples were categorized on the 25-point scale as follows: excellent (22–25 points), good (19–21 points), satisfactory (13–18 points) end unsatisfactory (12 points and below) (Bocharova et al., 2017).

Experimental procedures. *Stage I* involved examining the dependence of 2-furfural concentration on the contact time of malt grist with atmospheric oxygen. Aqueous solutions of malt grist were prepared by cold extraction. Samples were analysed after storage for 15, 30, 60, 120, 180, and 200 minutes, while the control sample had a contact time of 5minutes.

Stage II investigated the effect of temperature on the oxidation level of unhopped wort (100% malt wort with an original extract of 14°P). The concentration of 2-furfural was measured as a function of contact time between the wort and oxygen during filtration on a filter press. Samples were taken after 15, 30, 60, 120, 180, and 200 minutes, with a 5-minute control.

Stage III studied the impact of wort boiling time on 2-furfural formation in hopped wort (15°P original extract). Contact times with oxygen were 15, 30, 45, 60, 90, and 120 minutes, with the control sample having 5 minutes of exposure.

Stage IV assessed the influence of fermentation and beer filtration on the formation and concentration of 2-furfural in the finished beer. Filtered pale beer with an original extract of 10°P was artificially aerated through a sparging tube to obtain dissolved oxygen concentrations of 40, 60, 80, 100, 120, and 140 µg/L, while 20 µg/L was used as the control.

Stage V determined the effect of pasteurization intensity on 2-furfural levels in beer samples. The beer was subjected to pasteurization at 15, 30, 50, 100, and 300 pasteurization units (PU).

Stage VI examined changes in 2-furfural concentration during beer packaging. Beer samples with dissolved oxygen levels of 50, 80, 90, 110, 130, and 150 µg/l were analysed, with the control being packaged pasteurized beer at 50 µg/l oxygen.

Stage VII measured physico-chemical properties of filtered and pasteurized pale beer (10°P original extract) after packaging. The control sample consisted of pasteurized beer in 0.45 l glass bottles with minimal dissolved oxygen (50 µg/l) and 2-furfural concentration of 107 µg/l. Test samples included: Sample 1 – 140 µg/l oxygen, 211 µg/l 2-furfural; Sample 2 – 145 µg/l oxygen, 254 µg/l 2-furfural; Sample 3 – 200 µg/l oxygen, 583 µg/l 2-furfural.

Stage VIII investigated the dependence of sensory attributes on 2-furfural concentration through organoleptic evaluation of samples stored for six months. The 2-furfural concentration was determined on the day of bottling, and the samples were packaged in 0.45 l glass bottles. The sensory detection threshold for 2-furfural was 150–200 µg/l.

Data Processing: All physico-chemical parameters of wort and beer were determined in triplicate, and average values were used for analysis. The experimental error did not exceed 5%.

Results and discussion

Dependence of 2-furfural concentration on malt grist contact time with oxygen

The 2-furfural concentrations in malt grist, depending on the duration of contact with atmospheric oxygen, are presented in Figure 1.

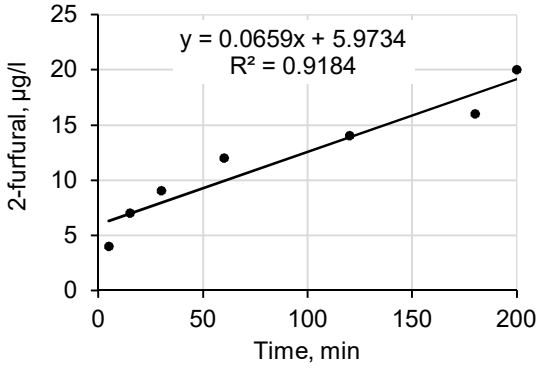

Figure 1. Dependence of 2-furfural concentration on malt grind exposure time to atmospheric oxygen

The trend illustrated in Figure 1 shows a clear linear relationship between 2-furfural concentration and exposure time. The initial concentration, measured after minimal air contact, was 4 µg/l and increased fivefold to 20 µg/l after 200 minutes of exposure. This finding underscores the detrimental effect of delayed processing after grinding on malt quality, leading to the accumulation of oxidation-derived secondary metabolites. To minimize the formation of undesirable compounds, it is recommended that malt grind storage time be kept below 50 minutes (Filipowska et al., 2021). The high coefficient of determination ($R^2 = 0.9184$) confirms that the linear regression model adequately describes the observed relationship.

Dependence of 2-furfural concentration on wort contact time with oxygen

Figure 2 shows the 2-furfural concentration in wort prior to hopping as a function of exposure time to atmospheric oxygen.

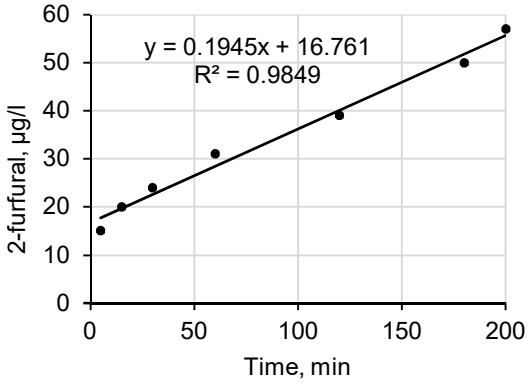

Figure 2. Dependence of 2-furfural concentration on wort exposure time to atmospheric oxygen

When the lautering step was prolonged to 200 min at 78 °C, the 2-furfural concentration in unhopped wort increased almost fourfold (from 15 to 57 µg/l). This trend was accompanied by higher spectrophotometric readings at 310 nm and 277 nm, reflected in the rise of absorbance differences from 0.003 to 0.063.

These observations suggest an intensification of thermal carbohydrate transformation reactions and a concomitant increase in aldehyde content in the wort (Vanderhaegen et al., 2006). Prolonged exposure of wort to elevated temperatures led to the accumulation of undesirable oxidation products, negatively affecting beer aroma and taste (Ditrych et al., 2019; Krofta et al., 2013).

Dependence of 2-furfural concentration on boiling duration

The concentration of 2-furfural as a function of wort exposure to atmospheric oxygen during hopping and boiling is presented in Figure 3. Analysis revealed that increasing the exposure time from 5 to 120 min at 100 °C resulted in a 2-furfural increase from 122 to 839 µg/l. This phenomenon can be attributed to the acceleration of Maillard-type reactions between sugars and amino acids.

The highest formation of 2-furfural occurred at elevated temperatures during wort boiling with hops. Extending the boiling time from 5 to 200 min increased the 2-furfural concentration nearly eightfold, reaching 839 µg/l.

Table 6 shows that the control sample, which was exposed for only 5 min, exhibited a higher content of oxidation products during boiling than the wort during lautering at 78 °C for an equivalent duration (200 min). This is explained by the fact that prolonged boiling substantially increases the wort's surface area in contact with atmospheric oxygen, thereby enhancing the formation of oxidation products, including 2-furfural (Ditrych et al., 2019).

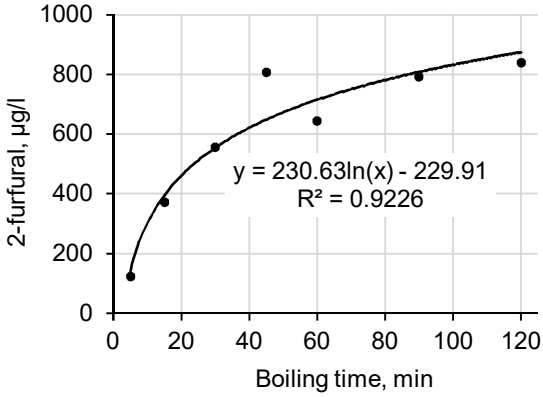

Figure 3. Dependence of 2-furfural concentration on wort exposure to atmospheric oxygen during boiling

As illustrated in Figure 3, the formation of 2-furfural is most pronounced during the initial stage of boiling (up to 30 min). During this period, 2-furfural concentration increased approximately 5.5-fold relative to the control (from 100 to 550 µg/l). Between 40 and 120 min, the rate of formation decreased, with concentrations rising only 1.5-fold compared to the control (from 550 to 850 µg/l). The regression model adequately describes the kinetics of this process.

Effect of wort fermentation and beer filtration on 2-furfural formation and concentration

The concentration of 2-furfural in filtered beer as a function of oxygen content is presented in Figure 4.

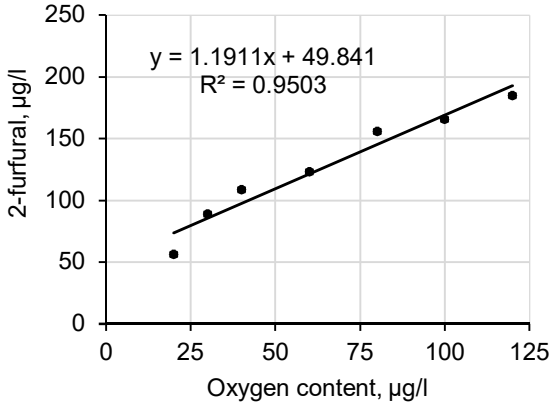

Figure 4. Dependence of 2-furfural concentration on oxygen content during wort fermentation and beer filtration

Analysis of Figure 4 reveals a linear relationship between 2-furfural concentration and dissolved oxygen in beer. The 2-furfural content in beer is markedly lower than in wort, likely

due to its reduction to furfuryl alcohol by yeast during fermentation (Dack et al., 2017). Increasing dissolved oxygen from 20 to 120 µg/l resulted in a 127 % rise in 2-furfural concentration (from 56.6 to 185.2 µg/l). This confirms that atmospheric oxygen is a key factor driving oxidative reactions in beer, which promote accumulation of undesired aromatic compounds and reduce flavor stability (Olaniran et al., 2017). Controlling dissolved oxygen during fermentation and filtration is therefore critical for maintaining product quality. The calculated R^2 value supports the reliability of the linear model and the stepwise influence of oxygen on 2-furfural formation and accumulation.

Effect of pasteurization on 2-furfural concentration in beer

The concentration of 2-furfural in pasteurized beer as a function of pasteurization intensity is presented in Figure 5.

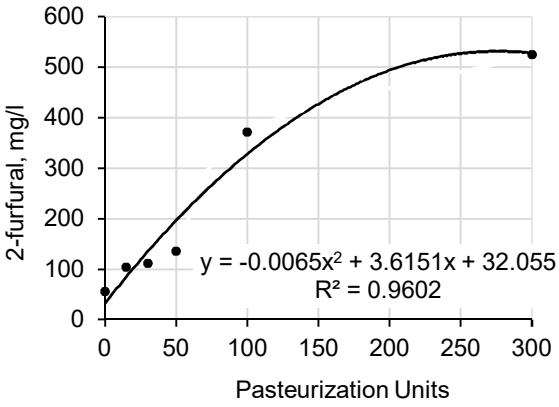

Figure 5. Dependence of 2-furfural concentration on the degree of beer pasteurization

Increasing pasteurization intensity enhances oxidative processes in beer. Even at minimal dissolved oxygen, oxidative reactions proceed rapidly under heat and with longer exposure time. At the lowest pasteurization intensity, 2-furfural concentration nearly doubled (from 56 to 104 µg/l). Increasing pasteurization intensity to 300 PU amplified oxidation processes tenfold, raising 2-furfural concentration to 525 µg/l.

As shown in Figure 6, increasing the pasteurization units (PU) results in a parabolic rise in 2-furfural concentration, reflecting the nonlinear nature of thermal transformations. During the initial stage of pasteurization (up to 100 PU), a sharp increase in 2-furfural content is observed, attributed to the activation of Maillard reactions and thermal stress. Further prolongation of heat treatment (beyond 200 PU) leads to a slowdown or stabilization of 2-furfural concentration, possibly due to partial decomposition of the compound or the reactions reaching equilibrium (Pieczonka et al., 2021).

The obtained regression equation is: $y = -0.0064x^2 + 3.6151x^2 + 32.055$, with a coefficient of determination R^2 = 0,9602, indicating high reliability of the quadratic model. This highlights the significant impact of thermal load on Maillard reaction products and underscores the need to optimize pasteurization conditions to prevent excessive formation of compounds that contribute to beer aging.

Analysis of 2-furfural concentration in finished beer

The concentration of 2-furfural in finished beer as a function of dissolved oxygen content is presented in Figure 6.

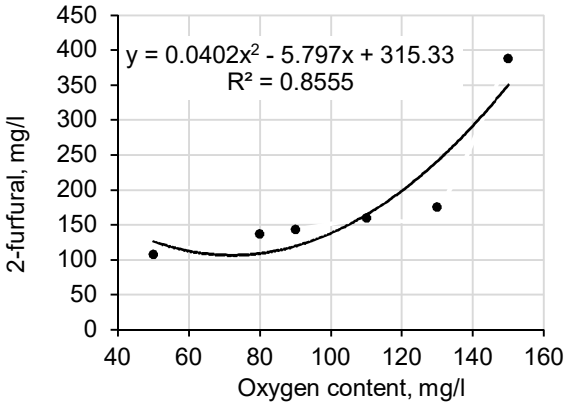

Figure 6. Dependence of 2-furfural concentration on the dissolved oxygen content in packaged beer

Figure 6 shows the relationship between 2-furfural concentration (μg/l) and oxygen content (μg/l). A nonlinear, parabolic dependence is observed between oxygen levels and 2-furfural concentration. The regression equation is expressed as: $y=0.0402x^2-5.797x+315.33$. This indicates that at low oxygen concentrations, 2-furfural formation is minimal; however, as oxygen content increases from 60 to 150 μg/l, the accumulation rate rises sharply. The calculated coefficient of determination R^2 demonstrates a strong correlation between the studied parameters, and the mathematical model is considered adequate.

The data indicate that oxygen present in the headspace of bottled beer after sealing promotes undesirable oxidative processes, adversely affecting beer quality. Evidence for this is the observed 262% increase in 2-furfural concentration (from 107 to 388 μg/l). Concurrently, spectrophotometric readings at 310 nm and 277 nm significantly increased, reflected in the growing difference between measurements, indicating active oxidation post-packaging. Elevated dissolved oxygen accelerated the formation of undesirable compounds, negatively impacting flavor, aroma, and stability of the beer (Wietstock et al., 2016).

Determination of physicochemical parameters of finished beer

The physicochemical parameters of filtered and pasteurized “Light” beer (10% extract content), packaged in containers, are presented in Table 1.

The physicochemical parameters of the beer comply with regulatory standards. The beer can be classified as a light, pale style with moderate bitterness, satisfactory CO_2 saturation, and typical organoleptic characteristics. However, elevated oxygen content (total 50 μg/l) may promote the formation of oxidation products such as 2-furfural, negatively affecting flavor stability during storage (Jaskula-Goiris et al., 2019).

Table 1

Physicochemical characteristics of beer

Characteristics	Value
Extractivity of the initial wort	10.0 % mass. extract
Alcohol content	4.5 %/vol.
Color	6 EBC
Bitterness	13 mg/l
CO_2 content	5.0 g/l
Dissolved O_2	20 µg/l
Total O_2	50 µg/l
pH	4.2
Acidity	1.80 ml of 1 M NaOH per 100 ml of wort
SO_2 content	4 mg/l

Dependence of sensory attributes of beer on 2-furfural concentration

The results of sensory evaluation of industrially produced beer samples are presented in Table 2.

Table 2

Dependence of sensory attributes of beer on 2-furfural concentration

Beer	2-furfural content, µg/l	Quality assessment panel members							Overall score	Comments
		D1	D2	D3	D4	D5	D6	D7		
Control	107	24	23	24	24	24	25	24	24	No defects
1	211	20	19	20	20	21	20	20	20	Slightly oxidized, mild aging
2	254	16	16	15	16	17	16	16	16	Noticeably aged, slightly oxidized
3	583	13	12	11	12	12	12	12	12	Strongly oxidized, pronounced aging, musty aroma, Strecker aldehydes present

Data indicate dependence of sensory attributes of beer on 2-furfural concentration. During six months of storage, beer samples exhibited deterioration in sensory properties. The control beer, with the lowest 2-furfural content, received the highest overall score of 24 out of 25 and showed minimal defects, confirming excellent quality. Samples 1 and 2, with moderately elevated 2-furfural concentrations (211 and 254 µg/l, respectively), received

lower overall scores (20 and 16) and exhibited mild oxidation and aging, remaining within acceptable quality limits. Sample 3, with a markedly elevated 2-furfural concentration (583 µg/l), received the lowest score (12) and was characterized by pronounced oxidation, evident aging, musty aroma, and the presence of Strecker aldehydes (Wietstock et al., 2016), classifying it as unsuitable or non-consumable beer.

It was established that 2-furfural concentration directly influences sensory quality deterioration, particularly in terms of oxidation, aging, and the development of undesirable aromatic notes (Jaskula-Goiris et al., 2019). Monitoring this parameter is therefore critical for preserving the organoleptic properties of the final product.

Figure 7 shows the aroma profilogram of beer samples exhibiting varying levels of oxidative deterioration. The control sample displayed a relatively balanced aroma profile, characterized by moderate overall intensity and well-defined hop- and malt-derived notes.

Sample 1 exhibited a slight increase in the "oxidized" attribute accompanied by a minor decline in malt and hop character, which is consistent with early-stage oxidative changes and the onset of staling.

In sample 2, the oxidized aroma became more pronounced, while the malt and hop notes were noticeably weakened. This deterioration correlates with the elevated concentration of 2-furfural (254 µg/l), a key carbonyl compound associated with beer aging. Sample 3 showed the highest oxidation scores, marked by a substantial suppression of malt and hop attributes and a simultaneous rise in alcoholic and sulfur-related notes. Such changes indicate advanced oxidative degradation, intensified staling, and the presence of undesirable Strecker-derived aldehydes.

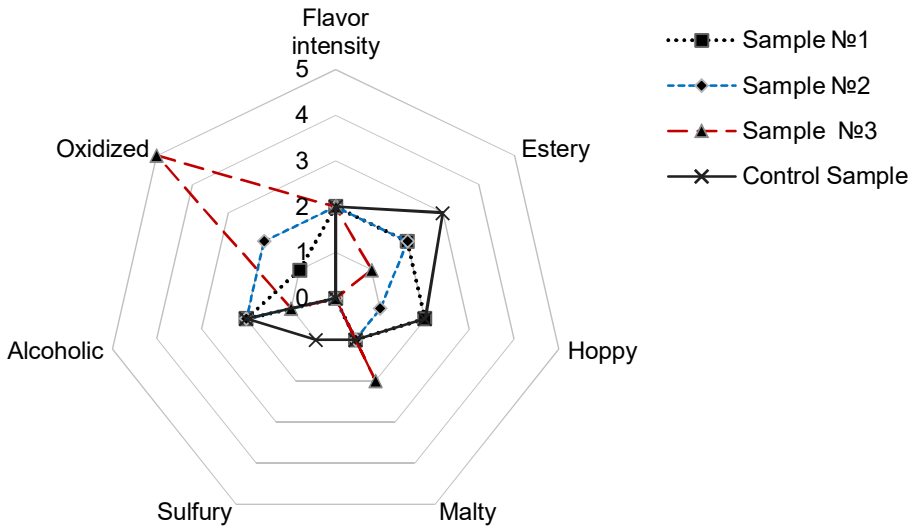

Figure 7. Aroma profile of beer samples with different degrees of oxidation

The taste profile of beer samples with varying degrees of oxidation, presented in Figure 8, demonstrates a gradual deterioration of sensory characteristics with increasing 2-furfural concentration and oxidation level. The control sample exhibited the most balanced taste, characterized by pleasant sweetness, harmonious bitterness, well-developed body, and clean aftertaste.

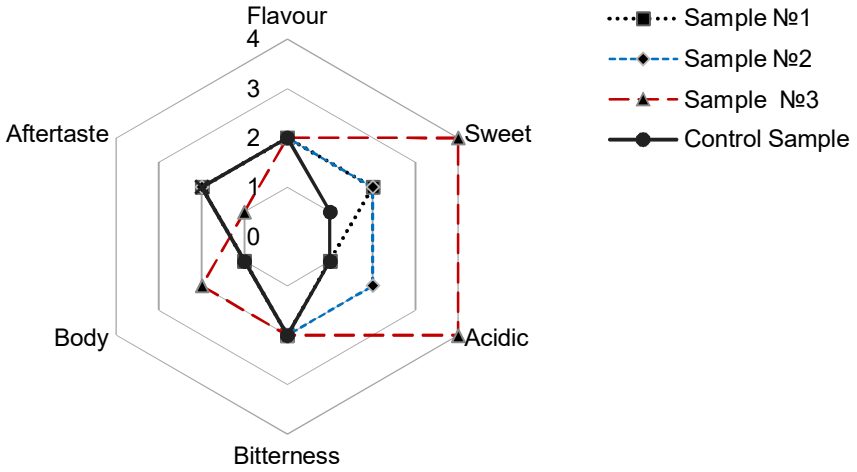

Figure 8. Taste profile of beer samples with different degrees of oxidation

Sample 1 showed a slight decrease in taste intensity and a minor increase in acidic notes, corresponding to initial stages of beer aging. Sample 2 exhibited further attenuation of body and finish, accompanied by more pronounced acidity and bitterness. Sample 3 displayed the most significant negative changes, including elevated acidity and an unpleasant lingering aftertaste, substantially impairing overall sensory perception. This was associated with a more than two times increase in 2-furfural concentration (up to 583 µg/l).

Conclusions

The study demonstrates that 2-furfural, a key oxidation product, is formed at all stages of beer production and has a direct impact on beer quality. Its accumulation begins at the malt milling stage, where exposure of crushed grains to air leads to rapid increases in 2-furfural concentration. High temperatures during wort preparation, boiling with hops, and pasteurization further accelerate its formation, while elevated dissolved oxygen levels during fermentation and filtration contribute to additional accumulation. Oxygen in the bottle headspace also promotes undesirable oxidation reactions, resulting in sensory deterioration characterized by oxidized notes and loss of freshness at concentrations of 150–200 µg/l.

The results highlight the importance of controlling malt storage time, temperature, oxygen exposure, and pasteurization conditions to minimize 2-furfural formation. The proposed UV-spectrophotometric method provides a simple, rapid, and reliable approach for monitoring oxidation products throughout the brewing process, offering a practical tool for maintaining the organoleptic quality and stability of beer.

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