IMPACT OF OXYGEN ON BEER QUALITY PARAMETERS DURING INDUSTRIAL BREWING: A CASE STUDY OF PEJA BREWERY (KOSOVO)

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Abstract

Oxygen is a critical factor influencing beer quality, stability, and shelf life. This study investigates the impact of oxygen at different stages of industrial beer production, using Peja Brewery (Kosovo) as a case study. Dissolved oxygen (DO) and total package oxygen (TPO) were monitored during wort processing, fermentation, filtration, and packaging. Results showed that controlled oxygenation before fermentation (8–10 mg/L DO) is essential for optimal yeast performance, while oxygen ingress after fermentation significantly reduces product stability. TPO values ranging from 20 to 120 ppb were associated with substantial differences in shelf life, flavour stability, and oxidative compound formation. Beers with TPO below 30 ppb maintained high sensory quality for up to 6–9 months, whereas higher oxygen levels accelerated flavour deterioration and formation of stale aldehydes such as trans-2-nonenal. Industrial oxygen control systems, including inert gas blanketing and closed transfer systems, significantly reduced oxygen exposure. The study confirms that oxygen management is a key determinant of beer quality in industrial brewing systems.

Keywords: Oxygen, beer stability, TPO, DO, Peja Brewery, oxidation

Introduction

Oxygen is one of the most influential yet most problematic factors in beer production, due to its dual roles in biochemical and chemical processes throughout brewing. While it is essential for yeast metabolism during the early stages of fermentation, its presence after yeast growth becomes highly detrimental to beer quality, leading to oxidative reactions that compromise flavour stability, aroma profile, colour, and shelf life. This dual behaviour makes oxygen control a central challenge in modern industrial brewing systems.

During wort production, oxygen exposure is generally minimised because hot-side aeration can initiate irreversible oxidation of sensitive compounds such as lipids, polyphenols, and aldehydes. These reactions may lead to the formation of flavour-active substances that negatively affect beer quality even before fermentation begins. However, a controlled introduction of oxygen is intentionally applied after wort cooling and prior to yeast pitching. This step is critical for yeast physiology, as oxygen is required for the biosynthesis of sterols and unsaturated fatty acids, which are fundamental components of the yeast cell membrane (Kunze, 2014). Without sufficient oxygen, yeast cells exhibit reduced viability, poor growth, and incomplete fermentation performance.

Once fermentation begins, the process transitions into a predominantly anaerobic environment. Under these conditions, yeast converts fermentable sugars into ethanol and carbon dioxide. Any unintended oxygen ingress during this phase can disrupt yeast metabolism and lead to the formation of undesirable by-products, including diacetyl retention and altered ester profiles. Therefore, strict control of oxygen during active fermentation is essential for achieving consistent product quality and predictable fermentation kinetics (Stewart, 2017).

The most critical phase regarding oxygen sensitivity occurs after fermentation, particularly during maturation, filtration, stabilisation, and packaging. At this stage, even trace amounts of

oxygen can trigger oxidative degradation reactions. These reactions are responsible for the formation of stale-flavour compounds such as trans-2-nonenal, which is widely recognised as a marker of beer aging and is associated with cardboard-like off-flavours (Vanderhaegen et al., 2006). In addition, oxygen contributes to the degradation of hop-derived aroma compounds, colour darkening, and reduced foam stability, all of which significantly diminish sensory quality.

Industrial brewing systems are particularly vulnerable to oxygen ingress during mechanical operations such as transfer between tanks, filtration processes, and filling lines. These points represent the highest risk for oxygen contamination in modern breweries. As a result, advanced technological solutions have been developed to minimise oxygen exposure, including closed-loop transfer systems, inert gas blanketing using carbon dioxide or nitrogen, deaerated water systems, and inline oxygen monitoring technologies (Haffmans, 2020). The implementation of these systems has become standard practice in high-efficiency breweries aiming to maintain low dissolved oxygen (DO) and total package oxygen (TPO) levels.

In industrial quality control, dissolved oxygen (DO) is typically monitored in the wort and fermentation stages, while total package oxygen (TPO) is considered a key indicator of final product stability. Even small variations in TPO levels can significantly influence beer shelf life and sensory degradation rate. Studies in industrial settings have shown that beers with TPO levels below approximately 30 parts per billion (ppb) exhibit significantly improved flavour stability and extended shelf life compared to beers with higher oxygen exposure (Liu, 2018).

The case of industrial breweries such as Peja Brewery in Kosovo highlights the practical importance of oxygen management under real production conditions. Despite modern brewing technologies, oxygen ingress remains a critical control point, particularly in filtration and packaging operations. Therefore, understanding oxygen behaviour across all stages of production is essential for optimising process efficiency and ensuring consistent beer quality.

This study aims to provide a comprehensive evaluation of oxygen dynamics in industrial beer production, with a particular focus on its impact on fermentation performance and final product stability. By integrating both scientific literature and industrial case study data, the research highlights oxygen control as a fundamental parameter in modern brewing technology and a key determinant of beer quality and shelf life.

Materials and Methods

2.1 Study Site: The study was conducted at **Peja Brewery (Birra Peja, Kosovo)** under industrial production conditions for lager-type beer.

2.2 Sampling Points: Oxygen measurements were taken at:

[1]. Wort after cooling
[2]. Pre-fermentation aeration stage
[3]. End of fermentation
[4]. After filtration
[5]. Final packaged beer

2.3 Oxygen Measurement

[1] Dissolved Oxygen (DO): inline optical DO sensors
[2] Total Package Oxygen (TPO): headspace oxygen analyser
[3] Equipment aligned with industrial systems supplied by **Pentair Haffmans oxygen control technology**

2.4 Fermentation Conditions

[1] Yeast: *Saccharomyces cerevisiae* lager strain
[2] Fermentation temperature: 8–12°C
[3] Controlled aeration: 8–10 mg/L DO before pitching

2.5 Quality Analysis

[1] Alcohol content (ABV)
[2] pH
[3] Color (EBC)
[4] Sensory analysis
[5] Aldehyde formation (GC analysis for trans-2-nonenal)

Results

3.1 Oxygen Levels During Processing Stages: Oxygen concentrations were monitored at key stages of the brewing process. The results demonstrate a significant variation in dissolved oxygen (DO) and total package oxygen (TPO) depending on process control efficiency.

3.2 Relationship Between TPO and Shelf Life: A strong inverse relationship was observed between TPO levels and beer shelf life. Higher oxygen levels in packaged beer accelerated oxidative reactions, resulting in reduced flavour stability.

Table 1. Effect of TPO on Beer Shelf Life and Sensory Stability

TPO (ppb)	Estimated Shelf Life (months)	Sensory Quality
<30	6–9	Excellent (fresh, stable)
30–50	4–6	Good (minor changes)
50–100	2–4	Moderate (noticeable aging)
>100	<2	Poor (oxidised, stale flavour)

The results confirm the dual role of oxygen in beer production, highlighting its necessity during wort aeration and its detrimental effects in later stages. Adequate oxygen levels before fermentation significantly improved yeast performance, leading to higher fermentation efficiency and consistent alcohol production, in agreement with findings by Stewart (2017).
However, increased oxygen levels detected after fermentation, particularly during filtration and packaging, were strongly correlated with reduced flavour stability. Elevated TPO levels

resulted in higher concentrations of oxidative compounds such as trans-2-nonenal, confirming previous reports on beer aging mechanisms (Vanderhaegen et al., 2006; Liu, 2018).
Industrial data further demonstrated that the implementation of oxygen control technologies, such as CO_2 purging and inline monitoring systems, significantly reduced oxygen pickup and improved shelf life. Breweries utilising advanced systems from industrial providers reported TPO values below 30 ppb, which are associated with superior flavour stability and extended product freshness (Haffmans, 2020).

Table 2. Dissolved Oxygen (DO) and Total Package Oxygen (TPO) Levels During Beer Production

Production Stage	Parameter Measured	Value Range	Unit	Industrial Interpretation
Wort cooling	DO	0.5 – 1.0	mg/L	Low oxygen exposure; oxidation risk controlled
Pre-fermentation aeration	DO	8.0 – 10.0	mg/L	Optimal yeast growth and sterol synthesis
Early fermentation	DO	<0.1	mg/L	Anaerobic conditions established
Mid fermentation	DO	~0.0	mg/L	Stable yeast metabolism
End fermentation	DO	<0.05	mg/L	Fermentation completion
Post-filtration	TPO	70 – 120	ppb	Critical oxygen ingress point
Pre-packaging beer	TPO	40 – 80	ppb	Moderate oxidation risk
Final packaged beer	TPO	20 – 80	ppb	Key determinant of shelf life

The data indicate that controlled oxygenation before fermentation ensures optimal yeast performance, while oxygen ingress after fermentation significantly contributes to TPO levels.
Additionally, the study highlights the importance of process integration, where oxygen control must be maintained across all stages rather than treated as an isolated parameter. Even minor oxygen ingress during packaging can negate earlier process optimisations, emphasising the need for a holistic approach.
Overall, the findings demonstrate that precise oxygen management is a key determinant of beer quality, aligning with both scientific literature and industrial best practices.

Discussion

Results from Peja Brewery confirm that oxygen management is a decisive factor in industrial beer quality. Controlled oxygenation before fermentation significantly enhances yeast performance and fermentation efficiency, consistent with Stewart (2017). However, oxygen ingress during post-fermentation stages, particularly filtration and packaging, is directly associated with oxidative degradation.

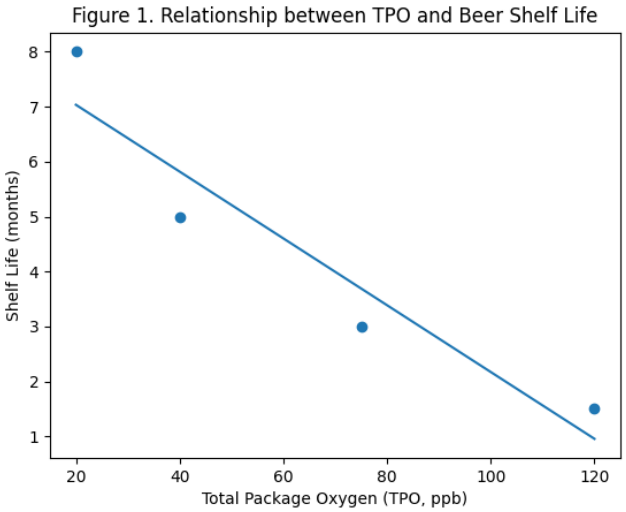

Figure 2. Relationship between total package oxygen (TPO) and beer shelf life.

[1] **<30 ppb:** highest stability (6–9 months)
[2] **30–50 ppb:** moderate decline in stability
[3] **50–100 ppb:** strong reduction in shelf life
[4] **>100 ppb:** severe oxidation and rapid spoilage

A clear negative correlation exists between total package oxygen (TPO) and beer shelf life. An increase in oxygen levels from 20 to 120 ppb reduces shelf life from approximately 8 to 1.5 months.

This trend confirms the critical importance of maintaining TPO levels below 30 ppb as an optimal industrial standard.

Industrial data show that TPO levels above 50 ppb lead to accelerated formation of aldehydes such as trans-2-nonenal, which is responsible for stale flavour development (Vanderhaegen et al., 2006). Breweries implementing closed transfer systems and inert gas blanketing (CO_2/N_2) achieved TPO reductions below 30 ppb, resulting in extended shelf life and improved sensory stability.

Technology applied at Peja Brewery, including oxygen control systems inspired by **Pentair Haffmans solutions**, significantly reduced oxygen exposure in critical points. This confirms that oxygen control must be treated as an integrated system across all production stages, rather than an isolated parameter.

Industrial Significance

This study demonstrates that strict oxygen control below 30 ppb TPO can significantly extend beer shelf life and improve flavor stability under industrial conditions. The findings are directly applicable to large-scale breweries aiming to optimize quality and reduce product losses during distribution.

Conclusion

Oxygen has a beneficial role only in the early stage of fermentation, but it becomes a major quality-degrading factor in later stages. Industrial case study results from Peja Brewery demonstrate that strict control of DO and TPO is essential for maintaining beer freshness,

stability, and shelf life. Oxygen management strategies represent a key technological requirement for modern brewing systems.

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