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The impact of ethanol on the sensory perception and aroma release of alcohol-free beers

Abstract: Health-conscious consumers are increasingly turning to Alcohol-Free Beers (AFBs), leading to a rise in popularity of this category of beer in recent years. However, brewers still face significant challenges in producing AFBs that provide a sensory experience comparable to regular alcoholic beers. The absence of ethanol in AFBs leads to a diminished sensory experience. This study aims to understand the role of ethanol in beer through sensorial and analytical approaches. Commercial alcohol-free lager beers were spiked with ethanol to achieve different alcohol levels (0 %, 0.5 %, 2.5 %, 5 % ABV). The samples were assessed by two sensory panels using NappingTM, and headspace aroma compounds were analysed by Selected Ion Flow Tube Mass Spectrometry (SIFT-MS). Additionally, instrumental viscosity was measured using a rheometer. Results showed that at a 5 % ethanol level, there was a considerable increase in alcoholic, warming, full-bodied, and lingering sensations. In contrast, no-alcohol (0 % ABV) and low-alcohol (0.5 % & 2.5 % ABV) beers were perceived as more watery or light, with the differences driven by beer flavour. The addition of ethanol enhanced the release of aroma compounds (specifically aldehydes and esters) into the headspace and increased viscosity (as determined by instrumental measurement). These findings are relevant for scientists and brewers and contribute to knowledge for the development of AFBs, with acceptable aroma, taste, mouthfeel and an improved sensory experience for consumers.

Descriptors: Non-alcoholic beer, low-alcoholic beer, sensory evaluation, flavour release, mouthfeel

1 Introduction

Beer is one of the most popular alcoholic beverages in the world. Although its main component is water, it also contains essential nutrients including carbohydrates, amino acids, minerals, vitamins, and bioactive compounds such as polyphenols [1]. However, the presence of alcohol in beer raises concerns for health-conscious consumers and specific groups, such as pregnant women and individuals with certain medical conditions. In response, governments have launched national campaigns to reduce alcohol intake, as the World Health Organization (WHO) emphasises that there is no safe level of alcohol intake [2]. Non-alcoholic beer or alcohol-free beer is typically defined as a type of beer that contains little to no alcohol. The definitions and regulations vary by country, but it generally refers to beer with an alcohol by volume (ABV) of 0.5 % or less. In recent years, the non-alcoholic beer or Alcohol-Free Beer (AFBs) beverage category has grown significantly, driven by shifting consumer preferences, heightened health consciousness, and a growing trend toward moderation and responsible drinking. AFBs provide an appealing alternative for individuals who desire the taste of beer without the alcohol content. As illustrated in figure 1., the global non-alcoholic beer market generated approximately $ 34.1 billion in revenue in 2023 and is projected to soar to $ 50 billion in the coming years [3].

Despite significant progress, brewers still face challenges in producing AFBs that match the sensory experience of regular beers. AFBs often exhibit flavour imperfections. For instance, AFBs produced by membrane processes usually have less body and a low aromatic profile, thermally dealcoholised AFBs may suffer heat-related damage, while AFBs obtained by biological methods often have a sweet and worty off-flavour [4]. Ethanol plays a crucial role in beer; while its impact on aroma release and bitterness is well-documented, there is a lack of knowledge about how it affects other sensory aspects of beer, such as body and fullness. Moreover, directly comparing alcohol-free and lager beer is complex. Alcohol-free beer has no more than 0.5 % ethanol but contains dextrins and fermentable sugars up to 8 °Plato (1 °Plato equals 1 g of extract per 100 g of beer). Lager beers typically contain around 5 % ethanol, residual dextrins up to 3 °Plato, and no fermentable sugars if attenuation is complete [5]. Consequently, ethanol/water mixtures or model beer solutions have been used to study the effect of ethanol on flavour release [6–8]. In the present study, commercial alcohol-free lager beers were used as a base, and different ethanol levels were achieved by adding ethanol to the base. Overall, the aim of this study is to understand the role of ethanol in beer through sensorial and analytical approaches.

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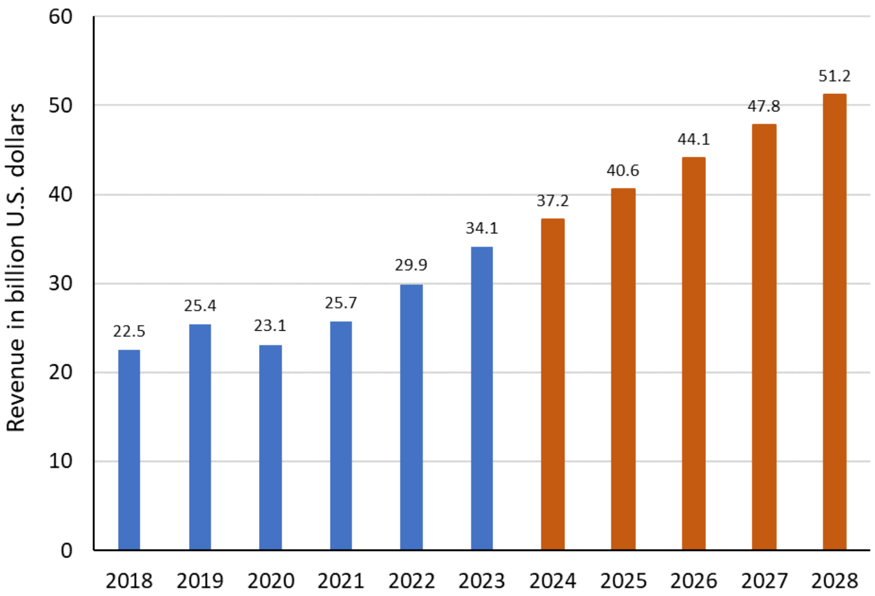

Fig. 1 **Revenue of non-alcoholic beer worldwide from 2018 to 2028 (in billion U.S. dollars), with revenue from 2024 onwards being predicted. Adapted from Statista information that was released in April 2024**

2 Materials and methods

2.1 Beer samples

In this study, 0 % ABV lager-style beers from three different commercial brands (anonymised as brand A, B, and C) were used as base beers. All commercial beers were produced through physical dealcoholisation. For each brand, four experimental beer samples were prepared to achieve different ethanol levels (0 %, 0.5 %, 2.5 % and 5 % ethanol). These concentrations were selected to reflect a full ethanol beer (5 %), an intermediate ethanol concentration (2.5 %), a low ethanol beer (0.5 %), and an alcohol-free beer (0 %). To create these experimental samples, ethanol (96 % vol) and/or water were added in different quantities to ensure that all samples were treated the same. Table 1 provides an overview of the beer samples used in the study.

2.2 Sensory assessment

For sensory evaluation, Napping™ tests [9] were conducted by two individual panels, each consisting of 9 panellists. Panel 1 consisted of trained experts who regularly attended beer evaluations, while Panel 2 comprised trainees who had recently passed a sensory screening test and received training in beer. Thus, the main differences between the two panels were their level of training in beer and beer evaluation experience. The samples were simultaneously presented to the panellists, who were asked to lay out the samples on a two-dimensional space using a computer software such that similar beer samples were placed close to each other and different beer samples were placed farther apart. The panellists were also asked to use predefined attributes to describe the sensory differences and similarities of the beer samples. Panel 1 used 16 sensory attributes including grainy/cereal, hoppy, flavour intense, alcoholic, estery/fruity, sulphury/lightstruck, sweet, sour, bitter, watery, full-bodied, harsh, smooth, warming, lingering, and prickly. Panel 2 employed 18 sensory attributes, involving most of those used by Panel 1. However, astringent and worty notes were exclusive to Panel 2, while sulphury/lightstruck was unique to Panel 1.

Table 1 **Beer brands A, B and C and their respective ethanol levels**

Vol % Ethanol	Brand A	Brand B	Brand C
0 %	A – 0 % ABV	B – 0 % ABV	C – 0 % ABV
0.5 %	A – 0.5 % ABV	B – 0.5 % ABV	C – 0.5 % ABV
2.5 %	A – 2.5 % ABV	B – 2.5 % ABV	C – 2.5 % ABV
5 %	A – 5 % ABV	B – 5 % ABV	C – 5 % ABV

2.3 Aroma analysis

The beer samples were submitted for analysis of headspace aroma compounds using Selected Ion Flow Tube Mass Spectrometry (SIFT-MS) on a SYFT VOICE200ultra (SYFT Technologies, Christchurch, New Zealand). SIFT-MS is an advanced analytical technique for rapidly and sensitively detecting and quantifying volatile organic compounds (VOCs) and trace gases in real time. In this methodology, a carrier gas containing the analyte is introduced into a flow tube in which it reacts with selected reagent ions, typically H_3O^+, NO^+, or O_2^+. These reagent ions are chosen based on their well-known and predictable reaction chemistries with the target analytes, leading to the formation of product ions. The product ions are then detected and quantified using a mass spectrometer, providing detailed information on the identity and concentration of the compounds present [10]. In total, 8 volatile compounds that were commonly present in AFBs were targeted and analysed, including 2-methylbutanal (85, $C_5H_9O^+$), acetaldehyde (43, 61, 74, $C_2H_3O^+$, $C_2H_3O^+{\cdot}H_2O$, $C_2H_4O{\cdot}NO^+$), ethyl acetate (118, $C_3H_8O_2{\cdot}NO^+$), ethanol (45, 63, 81, $C_2H_5O^+$, $C_2H_5O^+{\cdot}H_2O$, $C_2H_5O^+.2H_2O$), ethyl hexanoate (174, $C_8H_{16}O_2{\cdot}NO^+$), furfural (126, $C_5H_4O_2{\cdot}NO^+$), isoamyl acetate (160, $C_7H_{14}O_2{\cdot}NO^+$), and methional (104, $C_4H_8OS^+$). With increasing ethanol concentration in the samples, only NO^+ was used as a reagent ion due to its low reaction kinetics with ethanol, ensuring as low as possible diminishing quantification due to saturation. The m/z and composition of the product ions used for quantification are stated in the above list after the compound. The samples were injected at a rate of 30 µl/sec, and the syringe and injection port were heated to 80 °C.

2.4 Viscosity measurement

Viscosity measurement was performed using a Discovery HR-1 rheometer from TA/Waters set up with a double-cylinder geometry according to [11]. It operates using advanced rotational rheometry principles, where a sample is subjected to controlled shear forces, and the response is measured to determine its flow and deformation behaviour. An aliquot (14 mL) of degassed beer was poured into a test tube. The determination is based on the measurement of torque and speed of a rotating magnet.

2.5 Statiscal analyses

To analyse the data, the Napping™ sensory data from the two panels were analysed using Multiple Factor Analysis (MFA). The mean values with standard errors for both aroma data and viscosity data were calculated from two replicates.

3 Results and discussion

3.1 Sensory evaluation of AFBs

The sensory evaluation by the trained panel (Panel 1) indicated that the differences between the samples were driven by ethanol levels and beer flavour. As shown in figure 2., one cluster contained all 5 % ABV beer samples, which were characterised by sweet, alcoholic, warming, full-bodied, lingering, prickly, and estery/fruity notes. Among the no- and low-alcohol beers, the differences were driven by flavour; for instance, beers from brand A and B were perceived as grainy/cereal, sour, and bitter, while beers from brand C were more hoppy and sulphury/lightstruck. A previous study similarly reported sensory differences among beers with varying ethanol levels, with 5% beer having significantly more sweetness, fullness/body and alcohol warming, highlighting the significant role of ethanol within beer [12]. Several other studies also reported an increase in perception of sweetness and fullness at increasing ethanol concentrations [7, 13–16]. *Malfliet* et al. [17] concluded that lower fullness in light beers was mainly driven by the lower content of ethanol, residual extract, carbohydrates, soluble protein and iso-α-acids.

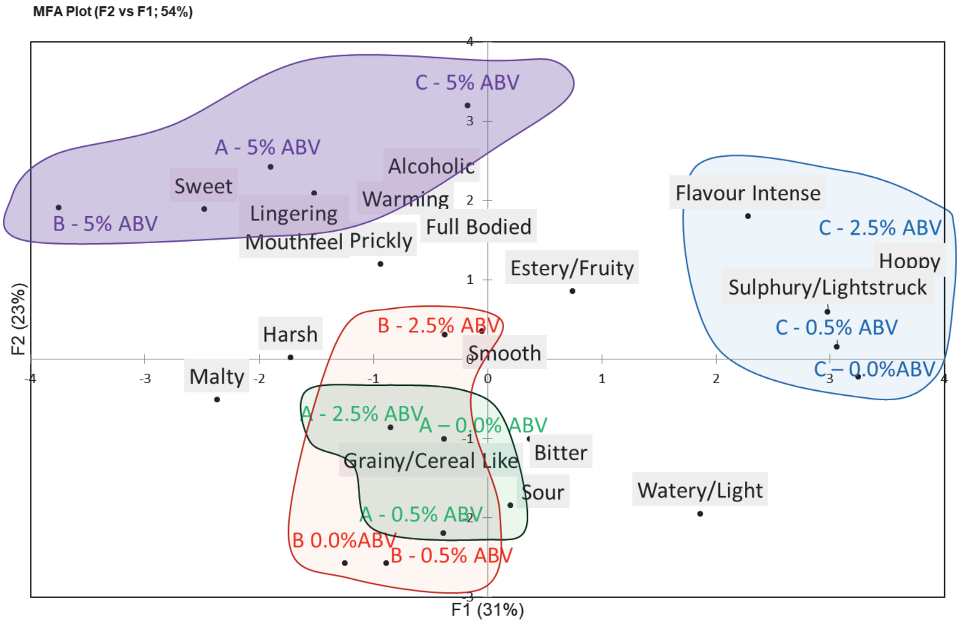

Fig. 2 The effect of ethanol level on the sensory profile of beers (Panel 1)

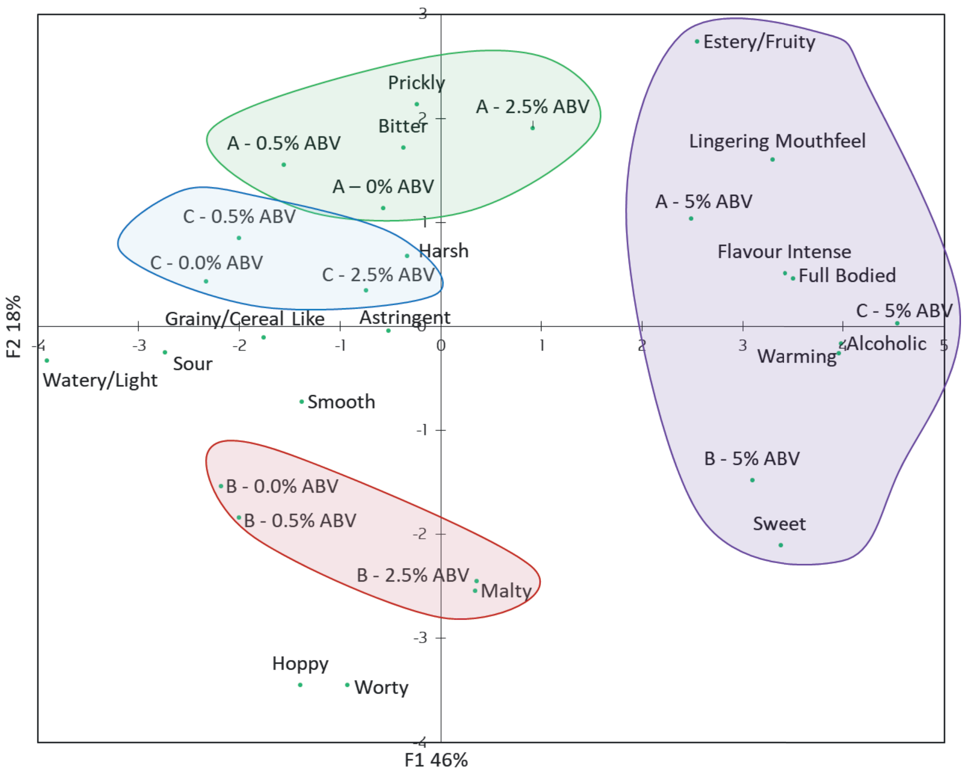

Fig. 3 The effect of ethanol level on the sensory profile of beers (Panel 2)

The same beer samples were evaluated by another panel consisting of beer trainees (Panel 2). As shown in figure 3., the 5 % ABV beer samples were grouped together again and characterised as alcoholic, warming, sweet, full-bodied, lingering mouthfeel and estery/fruity notes. In contrast, the no- and low-alcohol beers were noted to be watery/light and sour. Specifically, beers from brand A were described with bitter and prickly notes; those from brand B were perceived more malty; and brand C beers had more harsh and astringent notes. Although slightly different patterns were observed by the two panels, when considering the other two factorial planes (F1 vs. F3, data not shown), the two panels provided similar sample configurations. These results indicate that both trained panellists and trainees agreed in their assessment of the samples. Previous research has shown that fast sensory methodologies can produce results comparable to those from more time- and resource-intensive full descriptive analyses [18].

3.2 Aroma analysis of AFBs

For the aroma analysis by SIFT-MS, 4 aldehydes and 3 esters commonly associated with AFBs were targeted and analysed. As displayed in figure 4., the addition of ethanol increased aroma release into the headspace, especially for 5 % ABV beers, which exhibited a considerably strong increase of aldehydes and esters (data from one brand shown). This finding agrees with a previous study that determined aroma compounds by Atmospheric Chemical Ionization Mass-Spectrometry (APCI-MS) over simple ethanol/water solutions, where a range of 17 compounds were increased in the ethanol/water solution compared to the water solution, showing better mass transfer due to the presence of ethanol, in addition to partition coefficient variation [6]. Certain other publications have reported that the presence of ethanol lowered aroma release, suggesting that this is due to ethanol increasing the affinity of aroma compounds to the beer matrix, thereby reducing their partition coefficient and concentration in the headspace [5, 12]. The conflicting results may have been attributed to the sampling techniques. Researchers summarised that a higher concentration of ethanol decreased the volatile headspace in static systems, while it tended to increase the volatile headspace in dynamic systems [19].

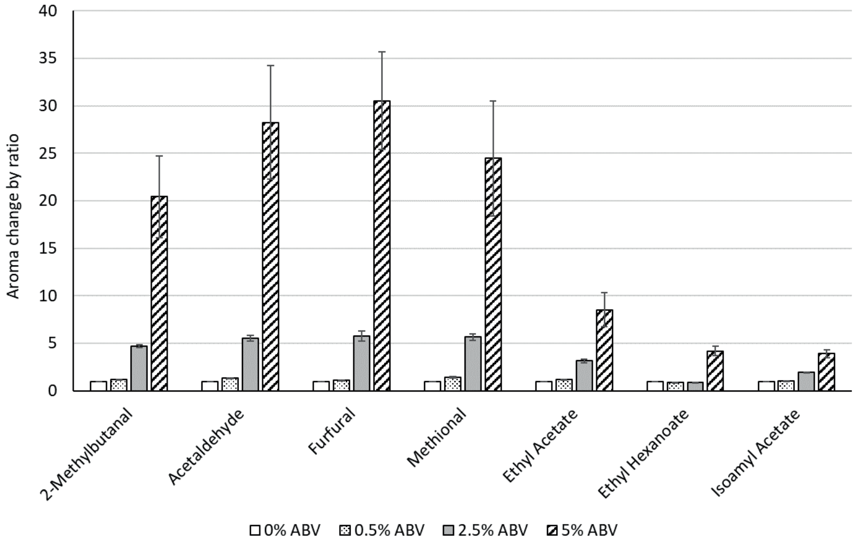

Fig. 4. The effect of ethanol level on aroma release using SIFT-MS

3.3 Viscosity measurement of AFBs

As displayed in figure 5., there was a strong positive linear relationship between ethanol level and instrumental viscosity (R^2=0.9863, data from one brand shown), demonstrating the addition of ethanol into AFBs resulted in increased instrumental viscosity. This result aligns with earlier studies, for example, a study that measured physical and chemical properties of 30 commercial beers reported a positive correlation between instrumental viscosity and alcohol level (correlation coefficients 0.80) [20]. Some authors consider body within the category of fullness and relate it to physical density and viscosity [21–22], and thus a higher viscosity is likely to give an improved mouthfeel and body in beer. Nonetheless, certain researchers failed to find apparent correlation between instrumental viscosity and the sensory perceptions of palate fullness, mouthfeel or sweetness within the narrow range of lager beers and non-alcoholic lager beers [23].

4 Conclusions

To summarise, the addition of ethanol into commercial alcohol-free beers significantly enhanced their sensory and physical properties, thereby giving an insight into the role that ethanol plays in beer. Specifically, the addition of ethanol at a 5 % level resulted in a considerable increase in the perception of alcoholic, warming, full-bodied, and lingering sensations, whereas no-alcohol (0 % ABV) and low-alcohol (0.5 % and 2.5 % ABV) beers were perceived to be more watery or light, with differences at this ABV levels driven more by beer flavour. The addition of ethanol led to an increased release of aroma compounds into the headspace, thereby intensifying the beer's aroma profile. Instrumental analysis also revealed a notable increase in viscosity with addition of ethanol, which is likely to contribute to a fuller mouthfeel. Overall, the role of ethanol in beer is multifaceted, affecting various aspects of human perception. The results of the study provide improved understanding of the analytical and sensory characteristics of alcohol-free beers.

5 Future perspectives

To fully understand the vital role of ethanol in beer and subsequently enhance the quality of alcohol- free beer, further research is necessary. In this study, it was observed that beers with ABV levels between 0 – 2.5 % were primarily differentiated by their flavour profiles rather than their ABV levels. Therefore, optimising the flavour of no- and low-alcoholic beers could be an effective approach to enhancing their overall sensory experience.

Future studies should also focus on in-vivo flavour release during beer consumption. Traditional headspace sampling measures volatiles in the air above the sample, with concentrations dependent on the compound's ability to partition from the sample matrix into the gaseous phase, surface area, and temperature, typically under controlled equilibrium conditions [24]. However, equilibrium is rarely achieved during consumption, meaning these methods fail to capture volatile release under dynamic conditions involving air flow, saliva addition, and temperature changes.

Additionally, while considerable work has been done on optimising ethanol removal, there is a need to better capture the sensory

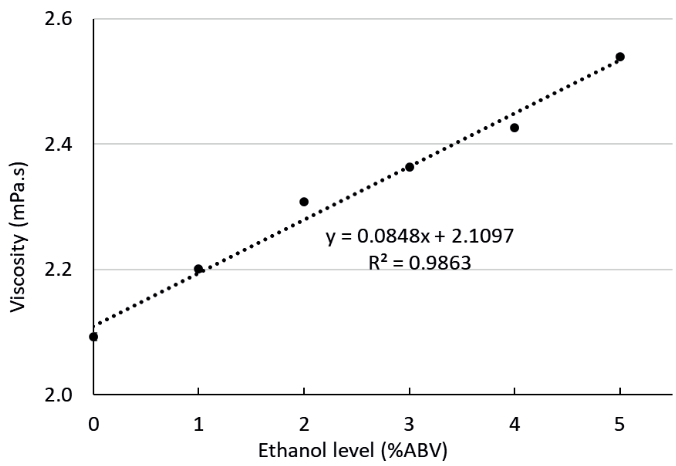

Fig. 5 The effect of ethanol level on instrumental viscosity

properties of the resulting beers. More research is needed to provide detailed sensory descriptions of beer prototypes, understand consumer perceptions and preferences, and establish connections between sensory and analytical data. Lastly, comparing commercial lager beers with their non-alcoholic counterparts is a valuable way to assess ethanol's impact on flavour, aroma, and sensory experience. Future research could combine different methods to better understand ethanol's role in beer quality [25–26].

Given the multifaceted role of ethanol in beer, producing a high-quality alcohol-free beer remains challenging. This requires a multi-perspective approach, including but not limited to optimization of the brewing process, research on the use of unconventional microorganisms, removal of off-flavours, and investigation into ingredients that could play a similar role to ethanol in AFBs.

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