



## OPEN ACCESS

EDITED BY  
Giuseppe Perretti,  
University of Perugia, Italy

REVIEWED BY  
Shima Saffarionpour,  
University of Toronto, Canada  
Giulio Cascone,  
University of Catania, Italy

\*CORRESPONDENCE  
Giorgia Spigno,  
✉ giorgia.spigno@unicatt.it

RECEIVED 27 March 2026  
REVISED 20 May 2026  
ACCEPTED 25 May 2026  
PUBLISHED 25 June 2026

CITATION  
Donadini G, D'Intino L, Spigno G and  
Gabrielli M (2026) A chemical and sensory  
comparison between commercial regular  
and alcohol-free beers from the  
Italian market.  
*Front. Food Sci. Technol.* 6:1840815.  
doi: 10.3389/frfst.2026.1840815

COPYRIGHT  
© 2026 Donadini, D'Intino, Spigno and  
Gabrielli. This is an open-access article  
distributed under the terms of the [Creative  
Commons Attribution License \(CC BY\)](#).  
The use, distribution or reproduction in  
other forums is permitted, provided the  
original author(s) and the copyright  
owner(s) are credited and that the original  
publication in this journal is cited, in  
accordance with accepted academic  
practice. No use, distribution or  
reproduction is permitted which does not  
comply with these terms.

# A chemical and sensory comparison between commercial regular and alcohol-free beers from the Italian market

Gianluca Donadini, Leonardo D'Intino, Giorgia Spigno\* and Mario Gabrielli

Department for Sustainable Food Process (DiSTAS), Università Cattolica del Sacro Cuore, Piacenza, Italy

This study presents a comprehensive chemical and sensory comparison between commercial regular beers and their alcohol-free beer (NAB) counterparts available in the Italian market. Eight paired samples were characterised using physicochemical analyses, volatile aroma profiling via bidimensional gas chromatography-mass spectrometry (GCxGC-MS), and sensory evaluation by a trained expert panel. The findings revealed that NABs exhibited significantly elevated total extract and pH values but reduced net extract relative to RBs. Volatile compound analysis demonstrated a marked reduction in fermentative esters, higher alcohols, and sesquiterpenes in NABs, with exceptions in specific terpene concentrations attributable to late or dry hopping techniques. Sensory profiling indicated that RBs possessed a fuller body and pronounced maltiness and alcoholic notes, whereas NABs were characterised by enhanced sweetness, fruitiness, and distinctive warty and honey-like flavours. Principal component analysis effectively differentiated the two beer categories, underscoring the disparities in residual sugars and aroma compounds as the principal discriminators. Despite advancements in brewing technologies, NABs continue to manifest sensory limitations, notably excessive sweetness and wortiness, diverging substantially from their alcoholic counterparts. These results underscore the persistent challenges in mimicking the sensory complexity of conventional beers in NAB production and highlight the critical role of brewing methodologies in shaping the final product quality.

## KEYWORDS

beer quality, GCxGC-MS, non-alcoholic beers, sensory analysis, volatile profiling

## 1 Introduction

The consumption of non- and low-alcoholic beer (NAB) has increased across numerous countries, particularly among younger populations (Eurostat, 2020; Gliszczynska-Swiglo et al., 2025). This trend appears to be driven by heightened health consciousness and increased awareness of the adverse effects associated with alcohol consumption (Catarino and Mendes, 2011). Epidemiological and clinical studies have indicated that moderate beer consumption may be associated with a reduced risk of cardiovascular disease, improved lipid profiles, and lower incidences of metabolic and neurodegenerative disorders, such as diabetes, osteoporosis, and dementia (Salanță et al., 2020; Sohrabvandi et al., 2012; Rossi et al., 2021). In this context, the Italian market is witnessing a growing popularity of low- and non-alcoholic beers. These options have seen a steady increase in consumption since 2020, achieving a 2.11% market share in 2024, an increase of 13.4% from 1.86% in 2023 (Assobirra,

2024). Non-alcoholic beer is typically defined as a beer that contains little to no alcohol. In most EU countries, NABs are divided into alcohol-free beer (AFB) and low-alcohol beer (LAB) with  $\leq 0.5\%$  and  $\leq 1.2\%$  (v/v) alcohol contents, respectively (Anderson et al., 2021).

Ongoing product innovations have enabled consumers to choose from a rich array of non-alcoholic beers, which vary significantly in terms of raw materials, brewing process, alcohol content, and organoleptic properties (Peeters et al., 2025; Borşa et al., 2022). NABs can be produced using physical, biological, or hybrid methods (Grover et al., 2022). Biological approaches aim to limit ethanol formation by modifying the brewing process, including alterations to the mashing step (Petelkov et al., 2021), adjustment of fermentation conditions (Kozłowski et al., 2021), or the use of special yeast strains with reduced ethanol-producing capacity (Klimczak et al., 2025). In contrast, physical methods remove ethanol from finished beer through thermal or membrane-based separation processes, such as vacuum distillation or rectification (Akdoğan and Baltacı, 2026; Krebs et al., 2019), reverse osmosis (Kumar et al., 2025), osmotic distillation (Liguori et al., 2015), dialysis, and pervaporation (Piornos et al., 2023). However, the complete and selective removal of ethanol is not achievable because of inherent thermodynamic and physicochemical limitations. Therefore, physical techniques often result in the co-removal of major volatile aroma compounds (i.e., fermentative esters, higher alcohols, and hop-derived compounds), resulting in NAB with low aromatic profiles (Piornos et al., 2023). Moreover, the selective extraction of ethanol from beer can also be performed by solvent and adsorption extraction (Muller et al., 2020). Solvent extraction involves the use of water-immiscible solvents with high solubility in ethanol, such as supercritical carbon dioxide. The adsorption extraction of ethanol involves the use of hydrophobic adsorbents, such as zeolites. The beer, inserted under pressure through carbon dioxide, is percolated in a column coated with zeolite until the eluent has a low alcohol concentration. The adsorbent must be regenerated by supercritical CO<sub>2</sub> and heat at the end, leading to high operation costs, but the organoleptic characteristics are well preserved. In contrast, biological methods result in the limited formation of aroma-active compounds and reduced carbonyl reduction capacity during fermentation (Brányik et al., 2012; Narziss et al., 1992). Generally, non-alcoholic beers contain higher concentrations of aldehydes and sugars than regular beers (RB) (Gernat et al., 2020; Andrés-Iglesias et al., 2019; Andrés-Iglesias et al., 2016; Riu-Aumatell et al., 2014). Ethanol, the primary product of alcoholic fermentation, is the most abundant volatile compound in conventional beers and plays a central role in flavour perception (Liu et al., 2024). In addition to its direct contribution to aroma and taste, ethanol influences overall sensory perception by stimulating the olfactory, gustatory, and trigeminal systems (Ramsey et al., 2020; Ivanova et al., 2023). In a water/ethanol mixture, the taste elicited by ethanol has mainly been described as bitter, but also highlights the sweet component (Ickes and Cadwallader, 2017). Moreover, ethanol has been shown to enhance the perceived sweetness of sugar-containing solutions compared to equivalent sugar-only matrices, suggesting a modulatory effect on taste perception (Nurgel and Pickering, 2006). Other studies have conducted different trials on synthetic beers and demonstrated that ethanol can increase sweetness perception linearly (Clark R. A. et al., 2011). In

addition, the vaporisation of aromatic compounds and their sensory perception are strongly affected by ethanol concentration, with different effects under dynamic and static systems or *in vivo* conditions (Ickes and Cadwallader, 2017). Previous studies have demonstrated that increasing levels of ethanol in synthetic beers significantly increase the delivery of other volatiles into the breath (e.g., ethyl acetate, isoamyl alcohol, and phenylethyl alcohol), whereas ethanol does not affect the aromas released under static conditions at 6 °C (Clark R. et al., 2011). Despite significant technological advances, brewers continue to face challenges in producing no- and low-alcohol beers (NABs) that closely match the sensory profiles of conventional beers. Membrane-based technologies can result in decreased aromatic intensity and reduced body in non-alcoholic beers, primarily due to non-selective permeation and concomitant loss of key flavour-active and mouthfeel-contributing compounds. Thermal techniques tend to induce heat-related sensory deterioration, including caramel-like off-flavor development and substantial depletion of volatile aroma compounds. In contrast, biological production methods frequently yield NABs with elevated diacetyl levels, wort-like off-flavours, and pronounced bready, grainy, and sweet sensory notes (Müller et al., 2021).

Aromas and tastes are the major factors influencing the consumer's perception of the quality of beer and other fermented beverages. More than 1,000 volatile organic compounds (VOC) have been identified in beer, including esters, higher alcohols, fatty acids, aldehydes, ketones, hydrocarbons, ethers, and alicyclic-, aromatic-, and heterocyclic compounds. These compounds are responsible for fruity, herbal, and floral notes and strongly influence the aroma and flavour of the final beer, both individually and through synergistic or antagonistic interactions (Dietz et al., 2020; Paszkot et al., 2023). Currently, most of the studies investigating food and beverage fingerprinting focus on the analysis of VOC isolated by HS-SPME using conventional one-dimensional gas chromatography (Ferreira and Guido, 2023). However, comprehensive two-dimensional gas chromatography (GC × GC) has been shown to be a powerful alternative for characterising the profile of volatiles from food samples, as it provides higher chromatographic resolution and increased sensitivity (Stefanuto et al., 2017). GC × GC enables the separation of several volatile and semi volatile components of a sample, and when associated with the study where the objective is the search and identification of the profile of volatiles responsible for the aroma and flavour of beers, GC × GC coupled to mass spectrometry (GC × GC-MS) is an extremely powerful technique in the elucidation of this multicomponent matrix sample (Zhang et al., 2023).

Chemical-analytical and sensory characterisation has been successfully applied by Bauwens et al. (2021) to compare non-alcoholic beers and their pale lager beer counterparts. Moreover, the same research group assessed the impact of the aging process on the chemical composition and sensory properties of commercial non-alcoholic beers and their lager beer counterparts (Bauwens et al., 2022). However, to our knowledge, this integrated approach has not yet been applied to the comparative assessment of non-alcoholic beers and their regular Italian counterparts using the two-dimensional gas chromatography technique (GCxGC-MS).

Therefore, the main objectives of this study were to (i) determine the chemical-analytical and sensory parameters that differentiate

TABLE 1 Non-alcoholic beers (NABs) and regular beers (RBs) declared style and ingredient lists according to the producers' labels or website.

Code	Style	Ingredients declared on the label
NABa	Pils	Water; barley malt; glucose syrup; hop extract; aroma
RBa	Pils	Water; barley malt; hop; hop extract
NABb	Lager	Water; barley malt; natural aroma; hop extract
RBb	Lager	Water; barley malt; hop
NABc	Lager	Water; barley malt; corn grits; hop; natural flavors from beer
RBc	Lager	Water; barley malt; corn grits; yeast; hop
NABd	Weissbier	Water; wheat malt; barley malt; CO <sub>2</sub> ; yeast; hop
RBd	Weissbier	Water; wheat malt; barley malt; yeast; hop
NABe	Lager	Water; barley malt; barley; hop; natural flavor
RBe	Lager	Water; barley malt; CO <sub>2</sub> ; hop
NABf	Pils	Water; barley malt; hop
RBf	Pils	Water; barley malt; hop
NABg	Lager	Water; barley malt; corn grits; hop; natural flavors from beer
RBg	Lager	Water; barley malt; corn; hop
NABh	Pils	Water; barley malt; maize; hops; natural flavor
RBh	Pils	Water; barley malt; maize; hop

eight Italian commercials NAB from their RB counterparts and (ii) identify the potential chemical-analytical key parameters underlying the observed sensory differences between NAB and RB.

## 2 Materials and methods

### 2.1 Chemicals and reagents

NaOH (0.1 M, Emprove<sup>®</sup>), NaCl (>99%, Emprove<sup>®</sup>), ethanol (absolute, Emsure<sup>®</sup>), 2-Octanol (>99.5%), were purchased from Merck (Darmstadt, Germany). Type 1 Ultrapure water was produced by Arium<sup>®</sup> Mini (Sartorius, Göttingen, Germany). 20 mL HS glass vials, magnetic HS vials caps, DVB/CAR/PDMS SPME fiber (divinylbenzene/carboxen/polydimethylsiloxane Smart SPME Fiber 80 μm) were purchased from Restek Italia (Cernusco sul Naviglio, Italy). Alphagaz2 ultrapure helium was purchased from Air Liquide Italia Spa (Milano, Italy).

### 2.2 Beer samples

Beers were purchased from a local supermarket and selected based on the following criteria: (i) beers from the Italian market because of the ease of availability and diffusion; (ii) non-alcoholic beers must be labelled as 0.5% (v/v) alcohol beer; and (iii) non-alcoholic beers and conventional alcoholic beers must be produced by the same industrial brewery with the same brand name. Furthermore, commercial NABs and their regular counterparts were selected to represent the Italian beer market, coming from major industrial groups accounting for most of the internal beer

market (Birritalia, 2025). Based on these criteria, we selected eight pairs of NAB (NAB<sub>a</sub>–NAB<sub>h</sub>) and RB (RB<sub>a</sub>–RB<sub>h</sub>). All beers had approximately the same residual shelf life (based on the purchase date and best before date on the label), and all replicates belonged to the same production batch. The beers were stored at 4 °C in the dark until chemical and sensory analyses were conducted. For chemical analyses, three independent replicates (three bottles) of RB and NAB from each commercial brand were used. The beer styles and ingredient list according to the producers' labels are reported in Table 1.

### 2.3 Standard chemical-analytical analyses of beer

The alcohol by volume (ABV), dry extract, net extract, and density were determined using an Anton-Paar Alcoholizer with a DMA 5000 density meter (Anton Paar Benelux, Gentbrugge, Belgium). Titratable acidity (ASBC Beer 8) and pH (ASBC Beer 9) were determined following the official method reported by the ASBC (American Society of Brewing Chemists, n.d.). CIELab measurements, a uniform three-dimensional space defined by the colorimetric coordinates L\*, a\*, b\*, and H\*, were performed using a UV-vis spectrophotometer (V-730 UV-Vis, Jasco Europe). The International Bitterness Unit (IBU) values of the beers were analysed according to the method defined by the European Brewery Convention (Method 9.6). Moreover, the absorbance of beer was measured at a wavelength of 430 nm in a 10-mm cuvette, and the colour in European Brewing Convention (EBC) units was obtained by multiplying the absorbance by a given factor (Analytica-EBC, Method 9.6).

## 2.4 Quantification of aromatic compounds by HS-SPME-GCxGC-MS

The free aroma compounds were analysed following Zhang et al. (2020) with minor modifications. A preliminary design of the experiments (DoE) was performed to optimise the HS-SPME extraction protocol. The considered variables were investigated according to the Central Composite Design (CCD), considering five levels ( $\alpha$ , 1, 0,  $-1$ , and  $-\alpha$ ). Extraction time (10, 20, and 30 min), extraction temperature (40, 45, and 50 °C), and sample dilution (1:6.65, 1:2, and 1:1.17) were tested, while NaCl concentration (500 g/L) and fiber type (DVB/CAR/PDMS; Divinylbenzene/Carboxen/Polydimethylsiloxane) were maintained constant according to Saison et al. (2009). The experimental trials were performed in a randomised order twice on two different days. A calibration pool composed of equal parts of all the NAB and RB samples was used to perform the DoE analysis. The optimal conditions, namely, 1:2 dilution and 30 min of extraction at 50 °C, were selected as the best conditions, considering the response in terms of total chromatographic area, chromatographic quality, and number of resolved peaks. Finally, 4 mL of diluted beer was spiked with 40  $\mu$ L of internal standard (2-octanol in ethanol) into 20 mL headspace glass vials preloaded with 2 g NaCl to increase the ionic strength of the solution, thus improving volatility. Extraction was performed using an AOC-6000 autosampler (Shimadzu Italia, Milan, Italy) equipped with a DVB/CAR/PDMS fiber (Restek Italia, Cernusco sul Naviglio, Italy). Samples were equilibrated for 5 min at 50 °C and subsequently extracted by fiber exposure for 30 min at 50 °C, under constant stirring (250 rpm). The analytes were thermally desorbed for 2 min at 220 °C in splitless mode, and the fibre was reconditioned at 260 °C for 5 min between runs. Comprehensive volatile separation was performed using a Nexis GC-2030 GC  $\times$  GC system coupled to a TQ8040 NX MS detector (Shimadzu Italia, Milan, Italy). The column configuration comprised a non-polar first-dimension SLB-5ms column (fused silica; Supelco, 20 m  $\times$  0.18 mm i.d.  $\times$  0.18  $\mu$ m film) coupled to a polar second-dimension Supelco WAX column (Supelco, 5 m  $\times$  0.32 mm i.d.  $\times$  0.25  $\mu$ m film) via a physical flow modulator operated with a 4.0 s accumulation time and a 0.4 s modulation pulse. The oven program (applied to both columns and the modulator) was as follows: 40 °C held for 2 min, then ramped at 4 °C  $\text{min}^{-1}$ –220 °C. Ultrapure helium was used as the carrier gas. Mass spectrometric acquisition was performed in single-quadrupole mode, and both the transfer line and ion source were maintained at 260 °C. The spectra were collected over 41–360 m/z at an acquisition rate of approximately 60 Hz. Compound identification followed a three-step approach: (i) comparison of mass spectra and retention times with those of authentic standards, when available; (ii) tentative identification by spectral matching against commercial libraries (NIST 2020/Wiley 12; similarity > 80%); and (iii) confirmation using published linear retention indices obtained under comparable conditions on first-dimension columns ( $\Delta$ LRI < 15). Volatiles were semi-quantified by comparing the peak areas to the internal standard (2-octanol) in the total ion current (TIC). Two-dimensional chromatograms were generated using Chrome Square 2.1 (Chromaleont Srl, Messina, Italy), and the target peaks were integrated using the same software with a custom method (noise setting; minimum area ratio 1:9). A detailed list of all the aroma compounds detected in each beer sample is provided in Supplementary Table S1, along with their respective LRI.

## 2.5 Sensory evaluation

All the beer samples were served at 15.0 °C  $\pm$  2.0 °C during the trials. Each sample (20 mL beer) was coded with a three-digit random number and poured into a tulip-shaped glass covered with a Petri dish to preserve volatiles and presented sequentially and monadically in a randomised order at a 15-min interval with approximately the same level of foam, thus avoiding a potential source of bias in flavour perception (Donadini et al., 2011).

The descriptive analysis (DA) (Stone and Sidel, 2004) of the beers was conducted in duplicate in a laboratory that met the general guidelines for the design of test rooms provided by ISO 8589 (ISO 8589, 2007), using a trained gender-balanced panel ( $n = 8$ , four females and four males, all above the age of 18) and an established sensory language (Donadini and Fumi, 2010). The included descriptors ( $n = 15$ ) were: perceived level of body, perceived level of carbonation, perceived level of alcohol, bitter, astringent, overall flavour persistence (PAI), bitter aftertaste, sweet, malty, worty, honey-like, fruity, sour, solvent-like, and phenolic (Meilgaard et al., 1979). DA was conducted using the typical format reported in previous publications (Donadini et al., 2013). Alcoholic and non-alcoholic samples were served in different sessions, and duplicate samples were assessed on different days. The intensity of each attribute was scored on a nine-point horizontal Likert scale anchored at “not perceived at all” and “extremely intense” at the left and right ends, respectively (Donadini et al., 2011a). The assessors were provided with mineral water, unsalted breadsticks, and white napkins to avoid carryover effects between samples (Lucak and Delwiche, 2009).

## 2.6 Statistical analysis

Statistical analysis was performed in three subsequent blocks. The first comprised ANOVA on physical-chemical/volatile parameters (Table 2 and Supplementary Table S1) and Mixed Models on sensory data to assess differences in the different parameters (Table 3). Three exploratory principal component analysis (PCA) were performed on the physicochemical, volatile, and sensory datasets (Figures 1, 2). Finally, to appropriately describe the relationship between sensory data and other parameters, partial least square regression (PLS) was performed, combined with a Clustered Image Map (CIM, Figure 3). Finally, to improve the prediction of the sensory attributes and reduce the dimension of the physical-chemical/volatile dataset, an Elastic Net (EN) selection of variables was performed, obtaining better prediction performance (Figure 4).

### 2.6.1 Descriptive analysis on physical-chemical parameters, volatile compounds and sensory description

Statistical analysis of the physical-chemical parameters and volatile composition of NAB and RB was performed for each beer, with three independent samples from the same batch of production. First, the compositions of NAB and RB were compared using one-way analysis of variance (ANOVA) (R-Studio environment; *Agricolae* package), and Duncan's *post*

TABLE 2 Technological parameters and chromatic properties of non-alcoholic beers (NABs) and regular beers (RBs).

Code	Titration acidity <sup>1</sup>	pH	Ethanol	Total extract <sup>2</sup>	Net extract <sup>2</sup>	L*	a*	b*	H*	C*	S*	EBC color	IBU
NABa	1.2 ± 0.1 h	4.5 ± 0.0 bc	0.2 ± 0.0 e	54.4 ± 0.1 de	6.8 ± 0.0 gh	97.8 ± 0.0 j	1.6 ± 0.0 g	25.5 ± 0.0 c	86.4 ± 0.0 d	25.6 ± 0.0 c	0.3 ± 0.0 c	7.2 ± 0.0 c	17.8 ± 0.4 g
RBa	1.9 ± 0.0 bc	4.3 ± 0.0 g	4.7 ± 0.3 ab	35.5 ± 1.0 hi	10.8 ± 0.4 abc	99.3 ± 0.0 c	2.3 ± 0.0 o	20.2 ± 0.1 h	83.4 ± 0.0 j	20.4 ± 0.1 h	0.2 ± 0.0 i	5.3 ± 0.0 efg	18.6 ± 0.4 g
NABb	1.7 ± 0.0 e	4.4 ± 0.0 efg	0.3 ± 0.1 e	53.0 ± 0.7 de	6.7 ± 0.3 gh	98.0 ± 0.0 i	1.8 ± 0.0 j	22.6 ± 0.0 f	85.4 ± 0.0 e	22.7 ± 0.0 f	0.2 ± 0.0 f	6.4 ± 0.0 d	14.5 ± 0.7 h
RBb	1.7 ± 0.0 ef	4.3 ± 0.0 fg	4.7 ± 0.0 abc	33.5 ± 0.2 ij	10.6 ± 0.1 abc	98.5 ± 0.0 g	1.7 ± 0.0 h	19.6 ± 0.0 j	85.0 ± 0.0 h	19.6 ± 0.0 k	0.2 ± 0.0 j	5.3 ± 0.0 efg	20.8 ± 1.0 ef
NABc	1.6 ± 0.0 g	4.4 ± 0.0 de	0.1 ± 0.0 e	43.2 ± 0.3 f	5.8 ± 0.1 h	100.1 ± 0.0 a	2.3 ± 0.0 o	17.7 ± 0.0 n	82.5 ± 0.0 L	17.8 ± 0.0 o	0.2 ± 0.0 n	4.4 ± 0.0 hi	19.4 ± 0.3 fg
RBc	1.6 ± 0.0 efg	4.6 ± 0.0 b	4.2 ± 0.3 bcd	38.2 ± 1.6 gh	10.3 ± 0.5 bcd	98.6 ± 0.0 f	2.2 ± 0.0 n	19.5 ± 0.0 j	83.4 ± 0.0 j	19.7 ± 0.0 j	0.2 ± 0.0 j	5.0 ± 0.0 fgh	29.5 ± 0.3 a
NABd	1.9 ± 0.1 cd	4.8 ± 0.0 a	0.2 ± 0.0 e	87.5 ± 0.8 a	9.3 ± 0.2 de	93.1 ± 0.0 p	0.0 ± 0.0 a	40.3 ± 0.0 a	90.0 ± 0.0 a	40.3 ± 0.0 a	0.4 ± 0.0 a	13.6 ± 0.0 a	13.0 ± 0.6 h
RBd	2.0 ± 0.1 b	4.5 ± 0.0 bc	5.0 ± 0.7 a	41.0 ± 2.5 fg	11.6 ± 0.1 a	93.9 ± 0.0 o	0.3 ± 0.0 b	39.1 ± 0.0 b	89.5 ± 0.0 b	39.1 ± 0.0 b	0.4 ± 0.0 b	12.8 ± 0.0 b	14.5 ± 0.8 h
NABe	1.8 ± 0.1 de	4.6 ± 0.0 b	0.4 ± 0.0 e	67.5 ± 2.3 b	8.4 ± 0.5 ef	97.5 ± 0.0 k	1.4 ± 0.0 d	22.0 ± 0.0 g	86.4 ± 0.0 d	22.0 ± 0.0 g	0.2 ± 0.0 g	6.3 ± 0.0 d	20.5 ± 1.4 ef
RBe	2.2 ± 0.0 a	4.4 ± 0.0 ef	3.8 ± 0.2 d	31.9 ± 2.4 j	9.9 ± 1.0 cd	98.1 ± 0.0 h	1.8 ± 0.0 k	22.9 ± 0.0 e	85.4 ± 0.0 e	23.0 ± 0.0 e	0.2 ± 0.0 e	6.4 ± 0.0 d	24.9 ± 1.1 c
NABf	1.6 ± 0.0 fg	4.3 ± 0.0 fg	0.3 ± 0.1 e	60.4 ± 0.7 c	7.7 ± 0.3 fg	95.6 ± 0.0 L	0.6 ± 0.0 c	24.9 ± 0.0 d	88.7 ± 0.0 c	24.9 ± 0.0 d	0.3 ± 0.0 d	7.8 ± 0.0 c	26.5 ± 0.7 b
RBf	2.0 ± 0.0 bc	4.3 ± 0.0 g	4.1 ± 0.3 cd	32.2 ± 1.1 j	9.8 ± 0.4 cd	99.6 ± 0.0 b	2.1 ± 0.0 m	18.0 ± 0.0 m	83.2 ± 0.0 k	18.2 ± 0.0 n	0.2 ± 0.0 m	4.6 ± 0.0 ghi	27.7 ± 0.7 b
NABg	1.9 ± 0.0 bcd	4.3 ± 0.0 g	0.4 ± 0.1 e	51.5 ± 0.1 e	6.8 ± 0.1 gh	99.2 ± 0.0 d	2.0 ± 0.0 L	18.6 ± 0.0 k	84.0 ± 0.0 i	18.7 ± 0.0 L	0.2 ± 0.0 k	4.2 ± 1.1 i	21.2 ± 0.2 e
RBg	1.7 ± 0.1 e	4.3 ± 0.0 fg	4.2 ± 0.4 bcd	32.4 ± 1.2 j	9.9 ± 0.5 cd	98.7 ± 0.0 e	1.6 ± 0.0 f	18.3 ± 0.0 L	85.0 ± 0.0 g	18.3 ± 0.0 m	0.2 ± 0.0 L	5.0 ± 0.0 fgh	19.5 ± 0.1 fg
NABh	0.9 ± 0.0 i	4.3 ± 0.0 fg	0.1 ± 0.1 e	55.7 ± 0.7 d	6.8 ± 0.2 gh	95.4 ± 0.0 m	1.5 ± 0.0 e	17.7 ± 0.0 n	85.3 ± 0.0 f	17.7 ± 0.0 p	0.2 ± 0.0 L	5.5 ± 0.4 ef	26.9 ± 0.3 b
RBh	0.8 ± 0.1 j	4.5 ± 0.1 cd	5.1 ± 0.1 a	36.0 ± 0.2 hi	11.3 ± 0.1 ab	95.1 ± 0.0 n	1.8 ± 0.0 i	20.1 ± 0.0 i	85.0 ± 0.0 gh	20.2 ± 0.0 i	0.2 ± 0.0 h	5.9 ± 0.3 de	23.2 ± 0.5 d
ANOVA <sup>3</sup>	***	***	***	***	***	***	***	***	***	***	***	***	***
t-test NAB/RB <sup>4</sup>	ns	*	***	***	***	ns	ns	ns	ns	ns	ns	ns	*

For each sample, the average ± standard deviation (SD) (n = 3) is reported.

<sup>1</sup>As g/L of lactic acid.

<sup>2</sup>As g/L.

<sup>3</sup>As ANOVA with Duncan's *post hoc* (95%) test was performed, different letters within the column represent different homogeneous groups of samples.

<sup>4</sup>t-test between all the NABs and RBs is also reported.

Significance levels are denoted as \*(p < 0.05), \*\*(<0.01), and \*\*\*(<0.001).

*hoc* comparison test was used to assess the statistical significance among the different samples (p < 0.05).

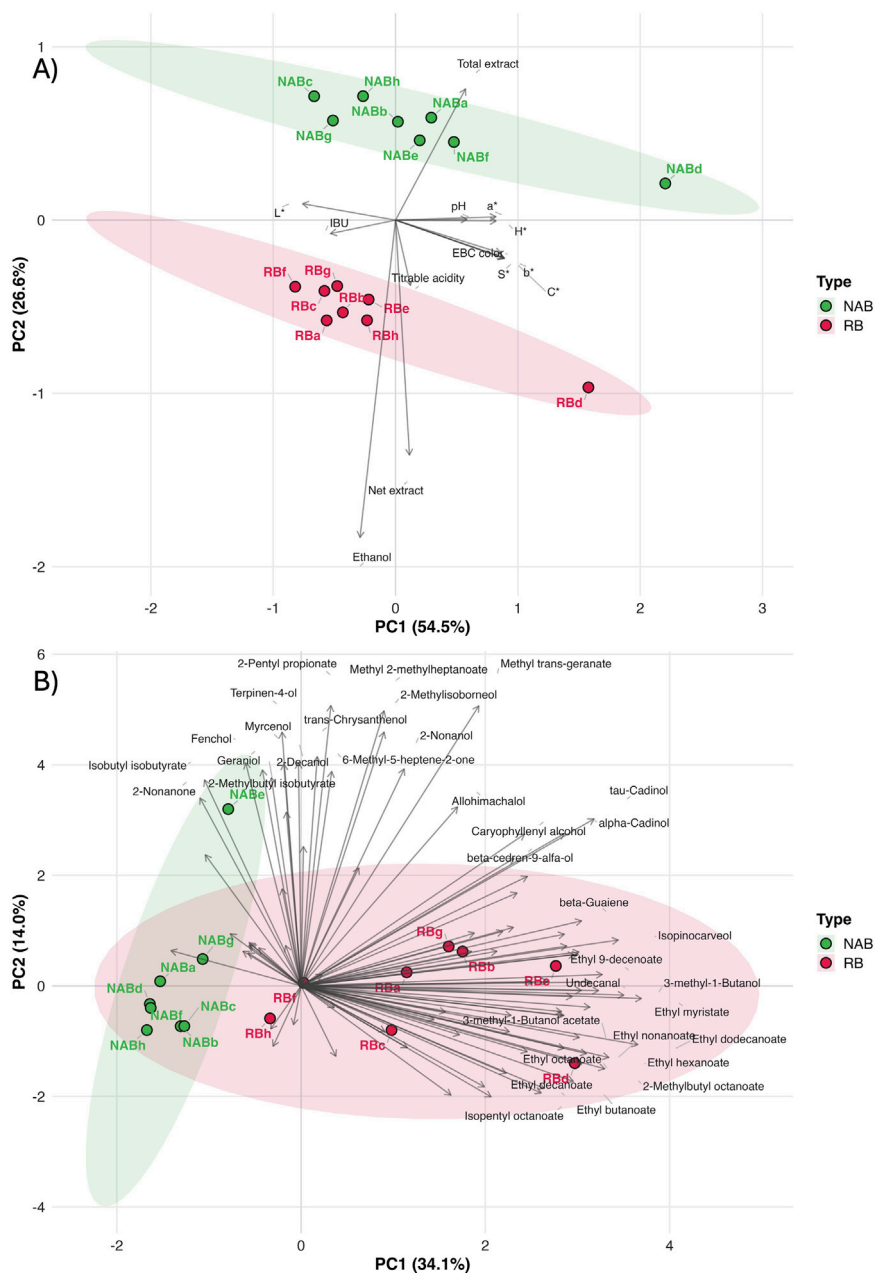
Sensory descriptive data were analysed using linear mixed-effects models (LMMs) to account for the variability associated

with individual assessors, as recommended for descriptive sensory data (Næs et al., 2010). All analyses were performed in RStudio using the *lme4* and *lmerTest* packages (Kuznetsova et al., 2017). For each sensory attribute, the product was included as a fixed effect, while

TABLE 3 Linear mixed-effects model results for sensory descriptors, reporting product effects, and assessor-related variability.

Code	Body	CO <sub>2</sub>	EtOH	Bitter	Astringent	PAI	Bitter after taste	Sweet	Worty	Malty	Honey	Fruity	Sour	Solvent-like	Phenolic
RBa	5.13 def	4.81 defgh	5.06 d	4.75 ef	3.12 cde	2.13 de	3.62 def	4.62 ef	2.50 c	3.38 bcd	1.19 cde	2.56 b	3.25 bcde	2.88 bcd	1.00 a
NABa	3.31 a	2.31 a	1.94 a	2.38 a	2.12 a	2.19 a	2.75 a	7.75 a	8.13 a	2.50 a	3.44 a	2.31 a	2.19 a	1.06 a	1.00 a
RBb	4.94 def	4.44 efgh	5.06 de	3.25 f	2.12 cde	2.13 ef	3.81 def	4.50 efg	1.69 d	4.06 cde	1.38 def	4.00 c	2.38 cde	3.06 bcde	1.00 a
NABb	2.19 ab	4.00 ab	1.25 ab	2.12 ab	1.37 ab	1.00 ab	2.94 ab	4.69 ab	5.31 a	2.25 ab	2.88 ab	2.62 ab	4.31 ab	1.00 a	1.00 a
RBc	4.25 efg	3.69 fgh	3.69 ef	3.00 g	1.69 de	2.63 ef	2.50 efg	3.69 fgh	1.75 de	2.75 cde	1.75 efg	1.69 c	2.75 cde	2.00 cdef	1.00 a
NABc	4.13 bc	3.50 bc	2.81 ab	4.88 abc	2.87 ab	4.00 ab	4.50 abc	4.56 abc	2.44 ab	2.94 ab	2.06 abc	4.12 ab	2.81 abc	2.38 a	1.00 a
RBd	5.38 efg	5.19 fgh	5.62 ef	2.19 g	1.94 def	1.63 f	4.50 efg	4.81 gh	2.06 ef	4.56 def	2.06 fg	5.88 c	4.50 de	3.06 def	1.31 a
NABd	3.31 bc	3.00 bcd	2.25 abc	2.06 abcd	1.81 ab	2.31 bc	4.06 abcd	7.38 abcd	6.81 ab	2.44 abc	5.88 abc	3.81 ab	2.56 abcd	2.13 a	6.56 a
RBe	5.06 efg	4.75 gh	5.12 ef	5.00 g	3.00 ef	3.00 f	4.81 efg	4.19 gh	1.69 efg	3.00 def	2.00 g	2.81 c	2.81 ef	4.00 ef	1.00 a
NABe	3.44 bc	4.88 cde	1.88 bc	2.69 abcde	1.62 ab	1.69 bc	4.06 bcde	6.00 bcde	4.81 abc	3.50 abc	3.56 abcd	5.81 ab	2.88 abcd	2.13 b	1.00 a
RBf	4.81 fg	4.69 gh	5.12 f	5.31 g	3.88 fg	5.38 f	5.06 fgh	3.12 h	1.25 fg	3.88 efg	1.56 g	2.50 c	3.06 ef	2.56 ef	1.00 a
NABf	3.31 bcd	5.13 cdef	2.19 bc	5.19 bcdef	4.19 abc	4.56 bcd	4.19 bcde	5.56 cde	6.06 abc	2.06 abcd	2.50 abcd	4.19 ab	2.75 abcd	1.00 b	1.00 a
RBg	4.31 fg	3.88 gh	4.25 f	3.69 g	3.06 g	3.81 fg	3.62 gh	3.50 i	1.00 g	3.13 fg	1.00 h	2.00 d	2.00 fg	2.69 f	1.00 b
NABg	3.06 bcd	4.00 cdef	2.13 bc	3.06 cdef	2.94 abc	4.06 bcd	3.25 cde	5.56 de	5.94 bc	2.19 abcd	2.94 bcd	4.06 ab	3.63 bcd	1.00 bc	1.00 a
RBh	4.88 g	4.31 h	4.88 f	3.50 g	2.25 g	3.81 g	3.88 h	3.81 i	1.75 h	3.13 g	1.75 h	2.81 d	3.06 g	3.25 g	1.00 c
NABh	3.50 cde	4.94 cdefg	2.00 c	4.88 def	4.56 bcd	4.50 cd	5.25 de	5.50 de	6.25 bc	2.88 bcd	5.38 cde	2.38 b	3.63 bcd	2.00 bc	1.00 a
F-val <sub>product</sub>	25.03	22.00	86.07	46.13	31.22	54.96	21.04	56.74	231.17	18.05	68.02	44.12	19.23	45.86	552.80
p-value <sub>product</sub>	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
F-val <sub>NAB/RB</sub>	168.6	10.07	559.2	3.84	0.09	0.4	0.01	116.2	338.4	56.68	119.9	7.76	0.69	124.7	7.89
p-value <sub>NAB/RB</sub>	***	**	***	ns	ns	ns	ns	***	***	***	***	**	ns	***	**

The product was modelled as a fixed effect and the assessor as a random effect to account for the between-assessor variability. Different letters within the column represent different homogeneous groups of samples. Significance levels are denoted as \* ( $p < 0.05$ ), \*\* ( $< 0.01$ ), and \*\*\* ( $< 0.001$ ), ns: not significant.

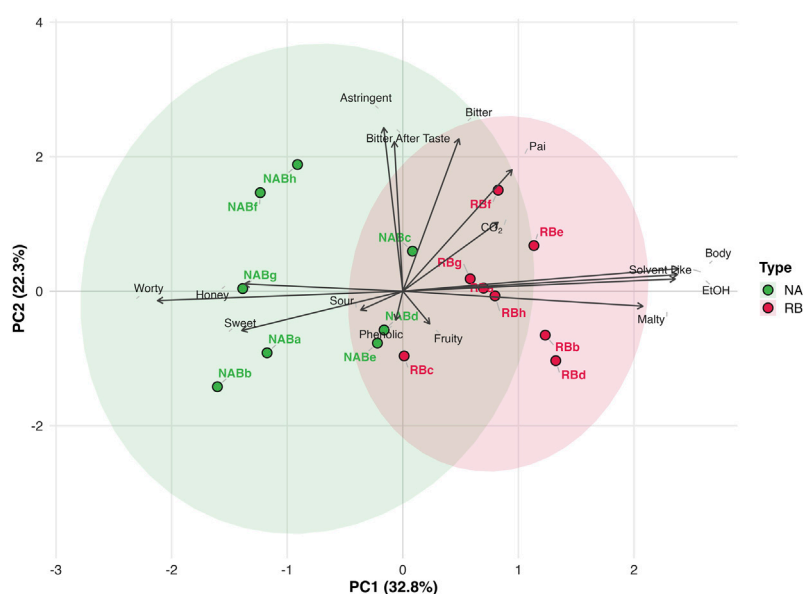


**FIGURE 1** Principal components analysis score plots (left) and loading plots (right) for (A) technological parameters, (B) volatile composition. Score plots show 95% confidence ellipses per sample group; loading plots show 95% confidence ellipses for non-alcoholic (NAB, pink) and regular (RB, green) beers, with arrows representing variable contributions to principal component 1 (PC1) and 2 (PC2).

the panellist was treated as a random effect to model between-assessor variability in scale use and response behaviour. The adoption of these models allows for a focus on product differences while accounting for assessor-related variability (Lawless and Heymann, 2010). According to Kuznetsova et al. (2015), fixed effects were evaluated using Type III analysis of variance, with F-tests and denominator degrees of freedom calculated via Satterthwaite’s (1946) approximation, which provides reliable inference in mixed-effects models. Statistical significance was set at  $p < 0.05$ .

### 2.6.2 Exploratory visualization of physico-chemical parameters, volatile compounds and sensory description

An exploratory multivariate statistical visualisation of the physicochemical parameters, volatile compounds, and sensory descriptors was obtained using three PCAs. All analyses were performed on RStudio according to the workflow reported by Rocchetti et al. (2021). The PCA outcomes were interpreted only for visualisation purposes to explore similarities and differences



**FIGURE 2**  
Principal components analysis score plots (left) and loading plots (right) for sensory descriptors. Score plots show 95% confidence ellipses per sample group; loading plots show 95% confidence ellipses for non-alcoholic (NAB, pink) and regular (RB, green) beers, with arrows representing variable contributions to principal component 1 (PC1) and 2 (PC2).

among samples, without inferring sensory relevance directly from these unsupervised models.

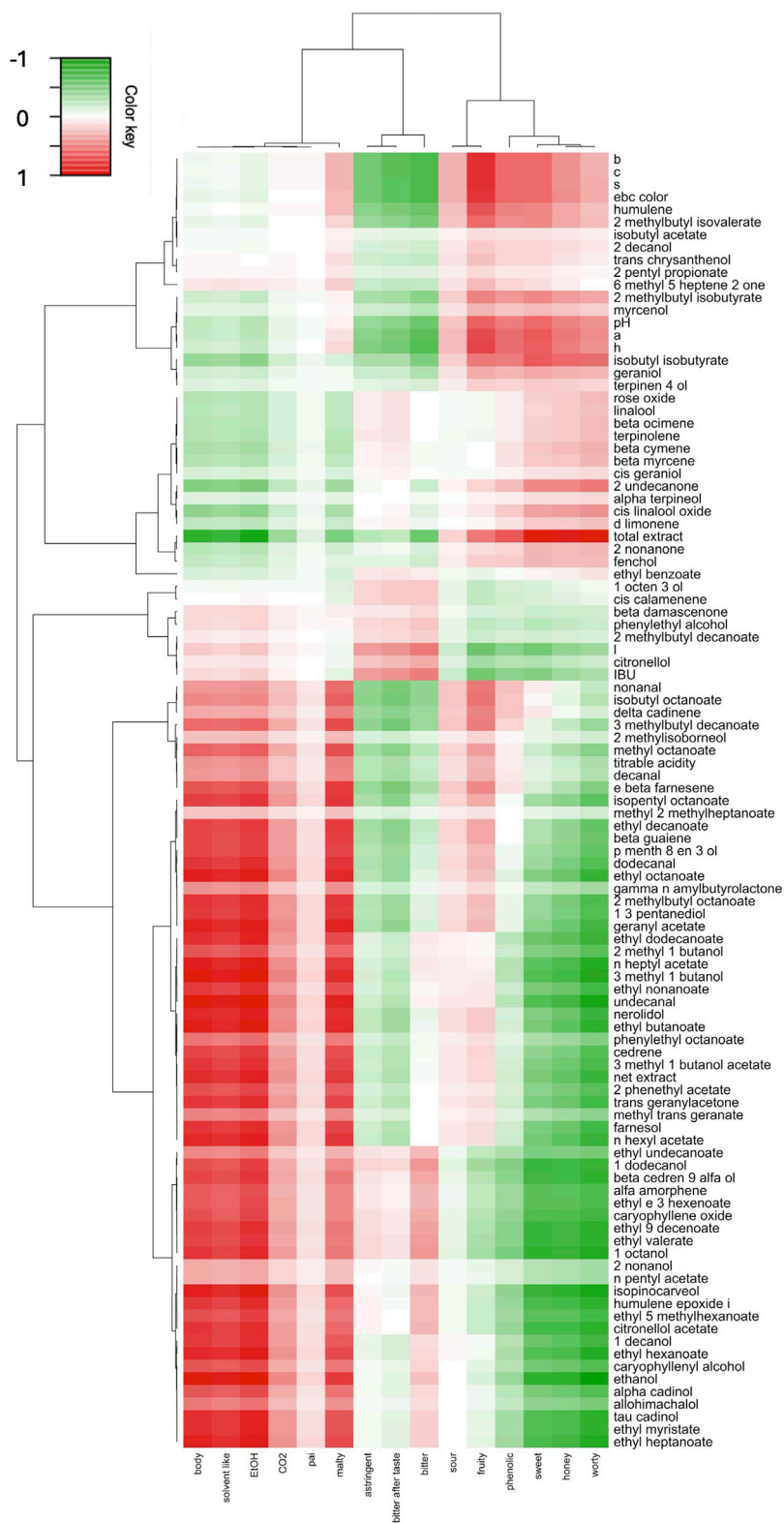
For the physicochemical parameters and volatile compounds, data pretreatment using range-scaling transformations to display the greatest variations in the analytical dataset of the NAB and RB samples was adopted. To visualise the sensory attributes among samples and identify major perceptual gradients, a third exploratory PCA was applied to the sensory dataset. This PCA was performed after adopting a *varimax* rotation with Kaiser normalisation, to maximise the interpretability of extracted components by reducing cross-loadings and achieving simpler factor structures (Borgognone et al., 2001; Watson, 2017). The extracted components were retained if they accounted for more than 1.0 units of variance (eigenvalue  $\lambda > 1$ ) (Jolliffe, 2002).

### 2.6.3 Integrative chemometric analysis and putative identification of chemical drivers of sensory perception

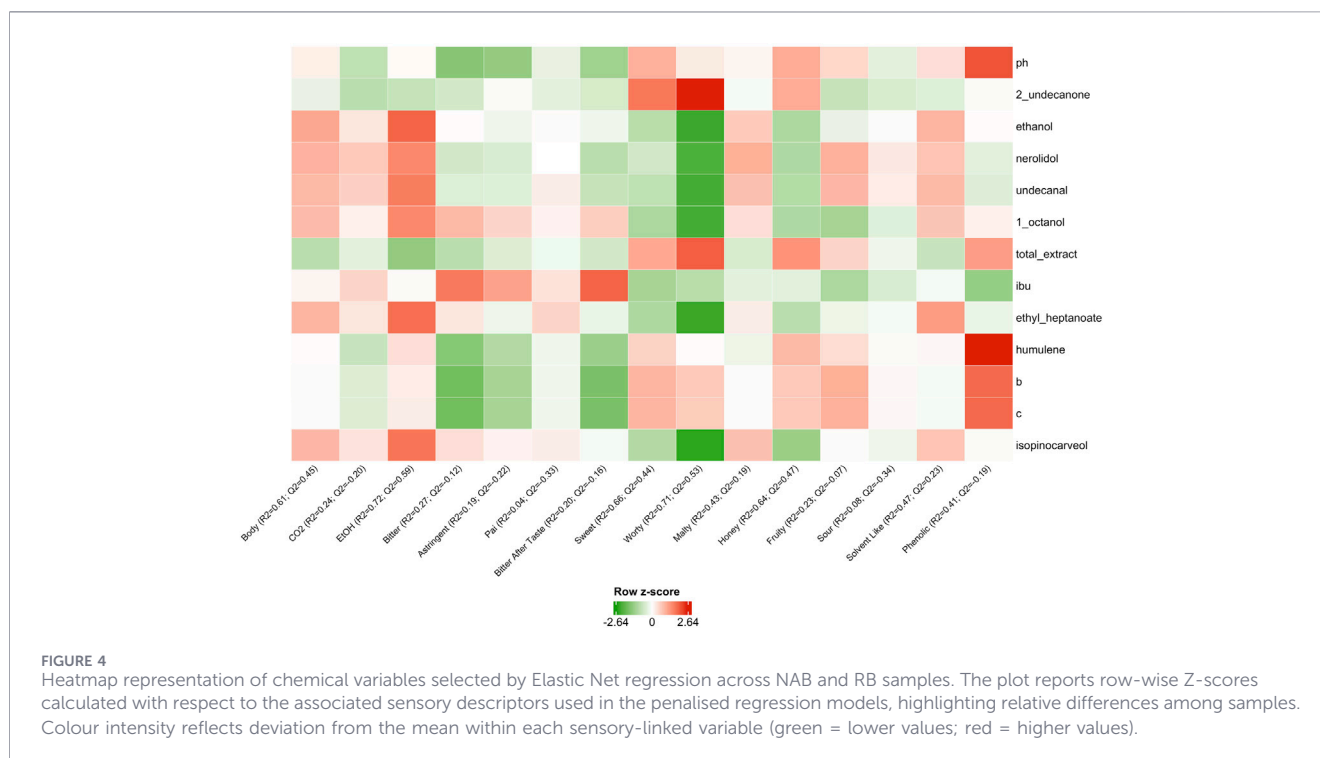
To investigate the relationship between chemical composition and sensory perception, Partial Least Squares (PLS) regression was used to model the sensory descriptors (Y-block,  $n = 15$ ) as a function of the combined physicochemical parameters and volatile compounds (X-block,  $n = 103$ ). PLS is suited to highly collinear predictors and multi-response settings and is widely applied in chemometrics and food-related multivariate analyses (Martens and Naes, 1992). Variable Importance in Projection (VIP) scores were computed to summarise the overall contribution of each chemical predictor within the  $X \rightarrow Y$  model and to rank the variables in terms of their relevance for explaining sensory variability (Supplementary Table S3). To complement the PLS analysis and better visualise how chemical variables relate to individual sensory descriptors, a

Clustered Image Map (CIM) was generated. The CIM was constructed from a matrix of pairwise correlations between all X-block and Y-block variables. In the CIM, each cell reports the strength and direction of the association between a given chemical variable and a given sensory attribute, expressed as a correlation coefficient. The pls analysis was performed on R-studio.

Given the high dimensionality of the chemical predictor block with respect to the number of sensory descriptors (103 vs. 15 variables), the PLS-CIM analysis was complemented by a second, regularised modelling step based on Elastic Net regression. Elastic Net was adopted to reduce model instability in the presence of strong multicollinearity and X-block  $\gg$  Y-block conditions, which are common in combined physicochemical and volatile datasets, in which many chemical variables are correlated to few sensory attributes (Zou and Hastie, 2005; Menéndez et al., 2012). Specifically, Elastic Net regression was applied to identify a reduced subset of chemical variables most strongly associated with sensory attributes while explicitly controlling for correlations among predictors. Briefly, the Elastic Net combines two complementary, well-established penalty methods: the L1 (LASSO) term, which shrinks less informative coefficients to exactly zero and thus performs variable selection, and the L2 (ridge) term, which stabilises coefficient estimates under correlated predictors. Accordingly, the Elastic Net provides a parsimonious number of X variables and a more stable estimate of the chemical drivers of sensory variation than unpenalised regression in high-dimensional, collinear settings (Tibshirani, 1996; Hoerl and Kennard, 1970). This combination is particularly suitable for complex chemical datasets characterised by high dimensionality and strong multicollinearity (Friedman et al., 2010). Model parameters were optimised by cross-validation, resulting in a near-LASSO solution ( $\alpha = 0.9$ ) and selection of the regularisation parameter at the minimum cross-



**FIGURE 3** Clusters Image Map (CIM) showing pairwise associations between chemical variables (physicochemical parameters and volatile compounds) and sensory descriptors in NAB and RB samples. The heatmap reports correlation coefficients, with hierarchical clustering applied to both rows and columns to highlight structured chemical–sensory association patterns.



validated error ( $\lambda_{\min} = 1.285$ ). The Elastic Net produced a sparse and stable model in which only the meaningful contributions to the prediction of sensory attributes were retained. A final heatmap summarising the model-based correlation relationships between the selected variables and sensory descriptions derived from the Elastic Net was produced. PLS and Elastic Net were implemented using respectively *mixOmics* and *glmnet* packages in R-studio (Friedman et al., 2010; Rohart et al., 2017).

### 3 Result and discussion

#### 3.1 Physicochemical characterization of NAB and RB

The alcohol content (ABV, % v/v), pH, titratable acidity, IBU, dry extract, total extract, and chromatic features of regular beers (RB) and non-alcoholic beers (NAB) investigated in this study are shown in Table 2. The ABV (%) of the NABs varied from  $0.1\% \pm 0.0\%$  to  $0.4\% \pm 0.0\%$ . All the selected NAB had an ABV lower than 0.5%, falling within the Italian and European legal limit (Italian Law No. 1354/1962, Reg. (EU) No. 1169/2011; Gliszczyńska-Świątło et al., 2025). In contrast, RB showed an ABV from  $3.8\% \pm 0.2\%$  to  $5.1\% \pm 0.1\%$  according to the beer style declared by the producer (Table 1). Overall, NAB exhibited significantly ( $p < 0.001$ ) higher total extract content (from  $43.2 \pm 0.3$  to  $87.5 \pm 0.8$  g/L) and pH values (from  $4.3 \pm 0.0$  to  $4.8 \pm 0.0$ ), together with lower net extract (from  $5.8 \pm 0.1$  to  $9.3 \pm 0.2$  g/L) and bitterness levels (IBU, from  $13.0 \pm 0.6$  to  $26.9 \pm 0.3$ ) compared with RB. No statistically significant differences were observed in titratable acidity, EBC colour, or CIE Lab colour parameters, whereas the bitterness (IBU) was significantly higher ( $p < 0.05$ ) in RB than in non-alcoholic beers, as reported in Table 2.

PCA was performed to further elucidate the contributions of the physicochemical parameters (Figure 1). The first two principal components (PC1 and PC2) explained 81.1% of the total variance, with PC1 accounting for 54.5% and PC2 for 26.6% of the variance. As shown in Figure 1A, PC1 mainly described colour parameters (i.e.,  $a^*$ ,  $b^*$ ,  $H^*$ ,  $S^*$ ,  $C^*$ , and EBC colour) and pH on the positive side, whereas on the negative side, contributions were associated with  $L^*$  and bitterness units (IBU). This suggests that the brewing style has a greater impact than other parameters on beer classification. PC1 can discriminate between NAB<sub>d</sub> and RB<sub>d</sub> samples, which are Weiss beers, independently of the presence of alcohols. Moreover, these beers are characterised by a notable yellow colour, as described by EBC units and  $b^*$  (blue/yellow) and  $C^*$  (colour fullness) chromatic coordinates. In contrast, on PC2, the effect of alcohol presence is described: all the RB are not only characterised by a higher presence of alcohol but also by a higher net extract value, whereas NAB samples achieve higher values for total extract. It is well established that the total extract in beer is largely composed of residual sugars (e.g., dextrans, maltose, glucose, maltotriose, and maltotetraose) that are not fermented and therefore remain in the final beer (Iñón et al., 2006). Consequently, NABs are characterised by higher sugar levels than their regular counterparts, which contributes to their sweeter taste (Moss et al., 2022). The different levels of residual sugars exhibited by NAB samples could be attributable to the different dealcoholization or production techniques applied in the brewing process (Bellut and Arendt, 2019).

#### 3.2 Aroma profile of NAB and RB

In this study, a broad spectrum of volatile compounds, including fermentative esters (33), monoterpenes (20), sesquiterpenes (16),

higher alcohols (9), carbonyl compounds (7), and norisoprenoids (2), were analysed (Supplementary Table S1). Comparing RB samples with their alcohol-free counterparts, the concentrations of total volatile compounds were significantly reduced (from 54% to 99%), except for NAB<sub>e</sub>, which exhibited a 72% increase in the total amount of aroma compounds. Sesquiterpenes, fermentative esters, higher alcohols, and carbonyl derivatives were strongly affected by dealcoholization, with average percentage reductions of 79%, 72%, 79%, and 41%, respectively. In contrast, terpene compounds showed the opposite behaviour, with a higher average concentration in NAB than in regular beer. Notably, NAB<sub>a</sub>, NAB<sub>e</sub>, NAB<sub>g</sub>, and NAB<sub>h</sub> exhibited significantly higher concentrations of total terpene compounds than their regular counterparts. These data could suggest that these NABs could be added with natural aromas to replace aroma compounds lost during the dealcoholisation process as declared by the producer in Table 1.

As the next step, starting from the HS-SPME-GC × GC-MS targeted quantification of volatile compounds in beer samples, multivariate statistical methods were applied to highlight potential aroma marker compounds associated with NAB and RB samples. By first examining the overall aromatic profiles of both NAB and RB, an unsupervised principal component analysis (PCA) was performed to explore patterns among non-alcoholic beers and their regular counterparts. The score plot obtained from the first principal components (PC1 and PC2) is shown in Figure 1B. PC1 and PC2 explained 34.1% and 14.0% of the total variance, respectively. As can be observed, the PCA effectively distinguished between the RB and NAB. The NAB cluster consisted of closer samples, whereas the RB was much more dispersed. Almost all the RB samples were located in the right quadrant of the PCA bi-plot, together with ethyl esters (i.e., ethyl octanoate, decanoate, and dodecanoate), higher alcohols (i.e., 3-methyl-1-butanol) and terpenoids compounds (i.e., humulene epoxide I, caryophyllenyl alcohol, and citronellol acetate). This means that RB generally contains higher levels of esters (RB: 691.5–4427.4 µg/L; NAB: 12.3–1581.6 µg/L), higher alcohols (RB: 480.2–1051.1 µg/L; NAB: 8.3–459.3 µg/L), and sesquiterpenes (RB: 7.2–28.1 µg/L; NAB: 0.44–15.24 µg/L) compared to their NAB counterparts (Supplementary Table S1). The reduction of ethyl and acetate esters ranged between 64.2%–99.2% and 41.2%–99.9%, respectively, while the higher alcohols and sesquiterpenes showed a reduction from 22.5% to 99.2% and from 45.6% to 97.1%, respectively. The only exception to these trends was NAB<sub>g</sub>, which showed a 74% increase in acetate esters. The fermentative esters and higher alcohols are the most abundant families of compounds found in young alcoholic beers, produced during alcoholic fermentation, and their flavours play an important role in the overall profile of the beer (Shopska et al., 2022). Our results demonstrated that the RB samples contained significantly higher concentrations of these compounds, especially ethyl hexanoate, ethyl octanoate, ethyl decanoate, and isoamyl acetate, which positively affect the aroma of beer with fruity notes owing to their low perception threshold (Xu et al., 2017; Verstrepen et al., 2003).

In contrast, the non-alcoholic beer samples were much more dispersed on PC2 and clustered into two groups. Notably, the NAB<sub>e</sub> were located in the upper right quadrant of the PCA biplot, together with monoterpenes (i.e., myrcenol, cis-geraniol, Terpinen-4-ol, Fenchol), suggesting a distinctive trend in the accumulation of these compounds compared to the other NAB samples.

Interestingly, hop-derived flavour-active monoterpenes (i.e., linalool, alpha-terpineol, and beta-myrcene) were present in higher concentrations in NAB<sub>g</sub> and NAB<sub>e</sub> than in their alcoholic counterparts. Most notably, the NAB<sub>g</sub> sample contained a linalool (lavender-like aroma) concentration (1521.5 µg/L) than that of the RB<sub>g</sub> samples (28.2 µg/L), as reported in Supplementary Table S1. Linalool concentrations above the range of 5–10 µg/L are not expected in conventional kettle-hopped beers, but in late- and dry-hopped beers (Van Opstaele et al., 2010; Van Opstaele et al., 2020; Takoi et al., 2016; Brendel et al., 2020; Forster and Gahr, 2012). Conversely, the other non-alcoholic beers contained lower levels of monoterpene compounds, which explains their shift in position to the middle of the PCA bi-plot. Non-alcoholic beers generally exhibit lower concentrations of fermentation-derived volatile compounds (i.e., higher alcohols, ethyl and acetate esters) and hop-derived aroma constituents (i.e., terpenes, sesquiterpenes, and norisoprenoids) than conventional beers. However, the observed differences in aroma profiles among the NAB samples could be attributable to the different dealcoholization techniques employed, as these processes differentially affect the retention, removal, and transformation of volatile aroma compounds (Piornos et al., 2023; Müller et al., 2021).

### 3.3 Sensory differences between NABs and RBs

Sensory descriptive data were analysed as described in Section 2.6 to account for assessor-related variability and the repeated-measures structure of the experimental design. The sensory results are shown in Table 3. The analysis revealed significant product effects ( $p < 0.05$ ) for all sensory descriptors considered, indicating clear and systematic differences among the beers under study. When samples were grouped according to alcohol content, regular beers (RBs) were perceived as significantly fuller-bodied, more carbonated, richer in alcoholic warmth, maltier, and richer in solvent-like notes. In contrast, NABs were described as significantly sweeter, fruitier, richer in wortiness, and richer in honey-like notes. Other sensory attributes, including sourness, overall flavour persistence (PAI), astringency, bitterness, and bitterness aftertaste, did not differ significantly between the two groups. Comparable sensory trends between alcoholic and non-alcoholic beers have been widely reported, with alcohol reduction affecting the global flavour balance rather than individual attributes alone (Bauwens et al., 2021; Donadini and Fumi, 2010; Saison et al., 2009).

To visualise the sensory relationships among samples and identify the main perceptual dimensions driving product differentiation, PCA was applied. PCA contributions for each descriptor are summarised in Supplementary Table S2, while score and loading plots are reported in Figure 2. Four principal components with eigenvalues greater than one were retained, explaining a substantial proportion of the total variance in the sensory dataset.

The first principal component (PC1), which explained 32.8% of the total variance, represented the main sensory dimension separating beers according to the perceived alcohol presence and body. PC1 showed strong positive contributions from perceived alcohol intensity, body, solvent-like notes, and maltiness, and strong negative contributions from wortiness. Along this axis, RB samples

were generally distributed on the positive side, whereas NAB samples were positioned on the negative side, reflecting a higher perception of worthiness and reduced body in NABs. This pattern is consistent with the masking role of ethanol and fermentation-derived volatiles in conventional beers, which has been shown to reduce the perceptibility of wort-derived sweetness and aldehydic notes (Saison et al., 2009; Lafontaine et al., 2020).

The second principal component (PC2), which accounted for 22.3% of the variance, differentiated the samples primarily according to bitterness-related attributes. Bitter taste, bitter aftertaste, and astringency contributed positively to this component, along with perceived carbonation and overall flavour persistence. Samples with higher scores along PC2 were characterised by a more bitter and persistent sensory profile. Bitterness perception in beer has previously been shown to depend on both hop-derived compounds and matrix effects related to alcohol content and carbonation (Schmelzle et al., 2013). Moreover, the NABs part of this study were perceived as being less carbonated than RBs. Previous literature gave evidence that NABs had low bubble formation largely due to differences in surface tension and composition compared to alcoholic beers which is primarily driven by the presence of alcohol in standard beer (Bossaerts et al., 2025). In the first two PCs, the NABs consistently clustered on the side of the map associated with a less structured and lower-intensity sensory profile, and are commonly described as flatter, watery, and less intense, in line with previous evidence (Müller et al., 2021). Consequently, achieving a just-about-right carbonation level appears crucial to improve consumer liking: when carbonation is properly dosed, slightly higher non-alcoholic notes can be perceived as more refreshing and can help mask undesirable off-flavours, while also improving fruity notes, finally making these NABs more preferred than under-carbonated NABs (Lafontaine et al., 2020).

The third principal component (PC3) described a sweetness-related sensory dimension, with positive contributions from sweetness and honey-like notes and moderate contributions from fruitiness and wortiness. NAB samples tended to score positively along this axis, consistent with their higher perceived sweetness. Wortiness exhibited meaningful contributions to both PC1 and PC3, indicating that this descriptor was relevant across multiple perceptual dimensions. Cross-loading of wortiness and sweetness has been previously linked to incomplete fermentation and residual sugar effects in NABs (Myncke et al., 2026; Saison et al., 2009). The fourth principal component (PC4) captured the variability related to freshness and beer style, with contributions from sourness, perceived carbonation, and fruitiness. Phenolic notes also contributed to this component and were primarily associated with wheat-based beers, contributing to their separation from the remaining samples. These attributes are typical of top-fermented wheat beers and have been described as style-defining rather than alcohol-dependent sensory markers (Beer Judge Certification Program, 2015; Donadini and Fumi, 2010; Parker, 2012).

Overall, sensory PCA revealed that the differences between NABs and RBs were organised along multiple orthogonal perceptual dimensions related to alcohol presence and body (PC1), bitterness and persistence (PC2), sweetness–wortiness balance (PC3), and beer style-related characteristics, including phenolic perception (PC4). These results provide a first descriptive framework for the sensory space and form the basis

for the integrative and regression-based analyses presented in Sections 3.4, 3.5.

### 3.4 Integrative analysis of chemical composition and sensory perception

To investigate how differences in physicochemical parameters and volatile composition were reflected in sensory perception, an integrative multivariate analysis based on Partial Least Squares (PLS) regression was applied. This approach allowed the sensory differences described in Section 3.3 to be interpreted in the context of coordinated chemical variations rather than as the effects of isolated compounds or individual physicochemical parameters. The PLS-based integration confirmed a coherent separation between RBs and NABs markers, consistent with the patterns observed in the individual PCA analyses of physicochemical, volatile, and sensory data, in agreement with previous integrative studies on alcoholic and non-alcoholic beers (Bauwens et al., 2021; Rettberg et al., 2022). The full table of Variable Importance in Projection (VIP) is reported in Supplementary Table S3. To further explore how chemical variables were associated with specific sensory descriptors differentiating RBs and NABs, a Clustered Image Map (CIM) was constructed using all chemical variables retained in the PLS X-block (Figure 3), based on pairwise correlations between chemical and sensory variables. The full correlation matrix between X and Y is presented in Supplementary Table S4. The CIM revealed a highly structured organisation of chemical–sensory associations, with sensory descriptors grouped into coherent blocks reflecting the major perceptual dimensions identified in the sensory PCA.

The PLS model was built using 103 chemical predictors (X-block = physicochemical + volatile variables) to explain 15 sensory descriptors (Y-block). In calibration, the model showed high goodness-of-fit (mean  $R^2 = 1.000$  across the 15 sensory responses), whereas cross-validated predictability was limited (mean  $Q^2 = -0.293$ ). At the individual descriptor level,  $Q^2$  values ranged from 0.434 to  $-1.110$ , with five of the 15 descriptors showing  $Q^2 \geq 0$ . The highest  $Q^2$  values were observed for solvent-like ( $Q^2 = 0.434$ ), body ( $Q^2 = 0.434$ ), and perceived EtOH ( $Q^2 = 0.394$ ), followed by malty ( $Q^2 = 0.122$ ) and worty ( $Q^2 = 0.004$ ) descriptors. The lowest  $Q^2$  values were observed for phenolic ( $Q^2 = -1.110$ ) and sour ( $Q^2 = -1.001$ ), followed by honey ( $Q^2 = -0.649$ ), astringent ( $Q^2 = -0.511$ ), and sweet ( $Q^2 = -0.499$ ). Although negative  $Q^2$  values were obtained for several aroma- and style-dependent descriptors, this reflects the intrinsic complexity of these sensory dimensions and their limited amenability to linear prediction (Wold et al., 2001), rather than a lack of structured chemical–sensory relationships. Therefore, the PLS–CIM analysis is intended to provide a descriptive and coordinated view of chemical–sensory relationships, which was subsequently refined through a sparse descriptor-specific regression approach in the following section. Descriptors related to beer alcohol content (RB vs. RB), such as body, perceived alcohol (reported as EtOH in Figure 3), malty, and solvent-like, formed a closely associated sensory cluster. These descriptors showed strong positive associations with ethanol concentration, net extract, and a wide range of fermentation-derived volatiles, consistent with the known role of ethanol and yeast metabolism in enhancing mouthfeel, flavour integration, and aroma release in beer (Saison

et al., 2009; Ramsey et al., 2020). Within this cluster, ethanol emerged as the most influential chemical variable at the multivariate level, exhibiting the highest Variable Importance in Projection (VIP > 1.8). Ethanol showed strong positive correlations with perceived alcohol (cor ~ 0.95), body (cor ~ 0.88), and solvent-like notes (cor ~ 0.76), and strong negative correlations with sweetness (cor ~ -0.69) and wortiness-related descriptors (cor ~ -0.89). This confirms the central role of ethanol not only as a direct sensory stimulus but also as a matrix component capable of masking wort-derived aldehydes and modulating flavour balance (Saison et al., 2009; Lafontaine et al., 2020). Net extract also displayed high multivariate relevance (VIP ~ 1.5) and a similar, although less pronounced, pattern of associations, supporting its contribution to body and mouthfeel perception. Several fermentation-derived volatile compounds aligned with this sensory block and exhibited elevated VIP values, including ethyl hexanoate, ethyl octanoate, ethyl decanoate (VIPs ~ 1.3–1.5), together with 3-methyl-1-butanol (VIP ~ 1.2). These compounds were positively associated with body, perceived alcohol, and malty or solvent-like notes, and negatively associated with sweet and warty descriptors. This behaviour is consistent with the known contribution of esters and higher alcohols to fruity, alcoholic, and solvent-like impressions in fully fermented beers and their reduced presence in NABs due to restricted fermentation or volatile losses during dealcoholisation process (Verstrepen et al., 2003; Xu et al., 2017; Piornos et al., 2023).

A second major sensory block in the CIM was defined by sweet, honey-like, and warty descriptors. These attributes showed strong positive associations with total extract, which also exhibited high multivariate relevance (VIP ~ 1.4), and with pH (VIP ~ 1.2). Total extract was strongly correlated with sweetness (cor ~ 0.82), honey-like perception (cor ~ 0.87), and wortiness (cor ~ 0.82), and negatively correlated with body and perceived alcohol, confirming its central role in shaping the sensory profile of NABs. This pattern is consistent with the higher levels of residual sugars typically observed in NABs produced by restricted fermentation or biological dealcoholisation methods (Iñón et al., 2006; Moss et al., 2022; Rettberg et al., 2022). Carbonyl compounds associated with wort-derived notes, such as undecanal and 2-undecanone, also showed relatively high VIP values (VIP ~ 1.2–1.4) and were positioned within this cluster, supporting their involvement in sweetness- and wortiness-related sensory impressions. These compounds have been reported as key contributors to warty off-flavours in NABs and are known to be less efficiently reduced in the absence of complete yeast metabolism (Saison et al., 2009; Lafontaine et al., 2020; Blanco et al., 2016). In addition, selected hop-derived compounds, including geranyl acetate and humulene epoxide (VIP ~ 1.1–1.3), displayed meaningful associations with fruity descriptors, suggesting that late- or dry-hopping strategies may have contributed to modulating aroma perception in some NAB samples. Similar compensation strategies have been documented as effective approaches to enhance aroma intensity and mask sensory deficiencies in NABs, however, in the absence of detailed production protocols, this interpretation remains speculative (Brendel et al., 2020; Forster and Gahr, 2012).

Bitterness-related descriptors formed a partially distinct sensory block. These attributes were positively associated with IBU, which

showed moderate multivariate relevance (VIP ~ 1.0–1.1), and with selected hop-derived volatiles, but exhibited weaker associations with residual extract-related variables. These results are consistent with previous findings indicating that bitterness perception is influenced by both hop chemistry and matrix effects and is not solely dependent on alcohol concentration (Schmelzle et al., 2013). Phenolic perception displayed a more specific and style-dependent association pattern in the CIM. Rather than contributing to the general separation between NABs and RBs, phenolic descriptors were associated with a limited subset of volatile compounds and colour-related parameters, supporting their role as markers of beer style, particularly in wheat beers, rather than as primary drivers of alcohol-related sensory differences (Beer Judge Certification Program, 2015; Donadini and Fumi, 2010; Jackowski et al., 2024).

Overall, the integrative PLS–CIM analysis demonstrated that the sensory differences between NABs and RBs arise from coordinated and multidimensional chemical effects involving ethanol concentration, extract composition, bitterness, and aroma-active volatiles. The CIM provides a comprehensive map of chemical–sensory associations, whereas VIP values highlight the chemical variables with the highest global relevance within this structure. However, this analysis remains descriptive and does not define a minimal set of chemical drivers for individual sensory attributes. The identification of these key contributors, which account for redundancy and collinearity among predictors, is addressed in the following section using a sparse regression-based approach.

### 3.5 Identification of putative chemical drivers of sensory attributes by elastic net regression

As last step to refine the integrative associations described in Section 3.4 and to identify a reduced and interpretable set of chemical predictors for individual sensory attributes, Elastic Net regression was applied. Model performance was evaluated in terms of explained variance ( $R^2$ ) and predictive ability under cross-validation ( $Q^2$ ), while the robustness of the chemical predictors was assessed through bootstrap-based selection frequency. This approach is particularly suited for complex beer matrices characterised by high collinearity among chemical variables and heterogeneous sensory responses (Friedman et al., 2010; Emmert-Streib and Dehmer, 2019). The 13 selected physicochemical variables were Nerolidol, Humulene, Isopinocarveol, 1-octanol, Ethyl-heptanoate, Undecanal, 2-undecanone, pH, ethanol, Total extract,  $b^*$ ,  $C^*$ , and IBU.

The sensory descriptors directly related to the presence of alcohol and mouthfeel were best explained by the Elastic Net models with respect to the full PLS, as reported by means of  $Q^2$  in Supplementary Table S5, where  $Q^2$  of PLS and EN are paired. Perceived alcohol intensity showed the highest performance ( $R^2 = 0.72$ ;  $Q^2 = 0.59$ ), followed by body ( $R^2 = 0.61$ ;  $Q^2 = 0.45$ ). For both attributes, ethanol emerged as the dominant predictor, being consistently retained across bootstrap iterations, whereas the net extract showed a secondary contribution with a positive coefficient. These results confirm that alcohol-related sensory perception is strongly affected by the fermentation step and matrix composition, in agreement with previous studies

describing the role of ethanol in enhancing viscosity, flavour integration, and aromatic persistence in beer (Ramsey et al., 2020; Gliszczynska-Świąło et al., 2025). Several sweetness-related descriptors were also satisfactorily described by the models. Sweetness ( $R^2 = 0.66$ ;  $Q^2 = 0.44$ ), honey-like perception ( $R^2 = 0.64$ ;  $Q^2 = 0.47$ ), and wortiness ( $R^2 = 0.71$ ;  $Q^2 = 0.53$ ) showed good explanatory and predictive performances. Across these models, the total extract was the most stable positive predictor, supporting the role of residual non-fermented carbohydrates in shaping sweetness-driven sensory attributes in non-alcoholic beers. Ethanol showed a consistent negative association with wortiness, reinforcing the inverse relationship between fermentation completeness and wort-derived sensory notes previously reported for NABs (Saison et al., 2009; Rettberg et al., 2022).

Intermediate performance was observed for malty perception ( $R^2 = 0.43$ ;  $Q^2 = 0.19$ ) and solvent-like notes ( $R^2 = 0.47$ ;  $Q^2 = 0.23$ ). Although these descriptors were less well predicted than alcohol- or sweetness-related attributes, their models identified fermentation-derived volatiles and ethanol as recurrent predictors. However, predictive performance remained limited overall, indicating that these sensory attributes are only partially explained by fermentation-related chemical markers (Müller et al., 2017; Bauwens et al., 2021).

In contrast, several sensory descriptors were poorly described by the Elastic Net models. Bitterness ( $R^2 = 0.27$ ;  $Q^2 = -0.12$ ), astringency ( $R^2 = 0.19$ ;  $Q^2 = -0.22$ ), bitter aftertaste ( $R^2 = 0.20$ ;  $Q^2 = -0.16$ ), CO<sub>2</sub> perception ( $R^2 = 0.24$ ;  $Q^2 = -0.20$ ), fruitiness ( $R^2 = 0.23$ ;  $Q^2 = -0.07$ ), sourness ( $R^2 = 0.08$ ;  $Q^2 = -0.34$ ), phenolic perception ( $R^2 = 0.41$ ;  $Q^2 = -0.19$ ), and overall flavour persistence (PAI) ( $R^2 = 0.04$ ;  $Q^2 = -0.33$ ) showed limited or negligible predictive ability. For these attributes, variable selection was unstable and no chemical predictor displayed consistently high selection frequency. This suggests that these sensory dimensions are either weakly linked to the measured chemical parameters or are influenced by complex perceptual interactions, style-specific effects, or non-linear mechanisms, as previously discussed for aroma-driven and style-dependent beer attributes (Schmelzle et al., 2013; Brendel et al., 2020; Bauwens et al., 2021). The evaluation of predictor stability across sensory attributes highlighted a small core set of chemical parameters recurring across multiple models. Ethanol and total extracts showed the highest overall stability, followed by the net extract and pH. Among the volatile compounds, fermentation-derived esters and selected carbonyl compounds were more frequently retained in models describing alcohol- and sweetness-related attributes, whereas hop-derived compounds were selected in a more descriptor-specific and unstable manner.

## 4 Conclusion

From the brewers' perspective, non-alcoholic beers (NABs) are increasingly designed to closely replicate the sensory characteristics of conventional beer styles, both in terms of typicality and overall drinking experience (Bauwens et al., 2021). Achieving this objective requires advanced brewing and dealcoholisation strategies aimed at preserving flavour integrity while minimising alcohol content, as the absence of ethanol necessitates precise adjustments to restore

mouthfeel, body, flavour integration, and sensory complexity. Within the European and International lager NAB styles, which represent the majority of commercially available NABs, pronounced differences in chemical and sensory profiles compared with alcoholic counterparts have been previously reported (Lafontaine et al., 2020).

The results of the present study are consistent with these observations. Sensory descriptive analysis and sensory PCA of the analysed NAB samples highlighted a systematic reduction in body, alcoholic warmth, and flavour integration, alongside an increased perception of sweetness, honey-like notes, and wortiness. Integrative PLS-CIM analysis further demonstrated that ethanol and net extract act as central coordinating variables for body- and alcohol-related sensory dimensions, while total extract and residual matrix components are strongly associated with sweetness- and wortiness-driven perceptions. These patterns were subsequently confirmed by Elastic Net regression, which identified ethanol, total extract, and net extract as the most stable chemical predictors of these sensory attributes.

In line with previous literature, quality defects in NABs were therefore primarily associated with a lack of body, reduced fermentative fruitiness, and an excessive perception of sweetness and wort-derived notes. Overall, these findings suggest that despite reported improvements in recent commercial formulations, the optimisation of NABs sensory quality remains an open and technologically challenging issue for brewers. While noticeable progress has been achieved for several style-dependent attributes, the present results indicate that substantial sensory limitations persist for fundamental matrix-related dimensions (i.e., absence of alcohol, presence of sugars), particularly for perceived alcohol intensity and sweetness. This highlights the need for improved and integrated control of fermentation process, residual extract, and aroma integration.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical approval was not required for the studies involving humans because ethical review and approval were waived for this study due to the nature of the research involving humans, which posed negligible risk to trained assessors who participated in sensory trials, since this activity did not involve invasive or potentially harmful procedures. Generally, descriptive studies in the field of sensory analysis can be classified as involving minimal risk and not requiring ethical approval. This can also apply to studies involving chemical analysis of beers and focusing on descriptive analysis of beer, as that carried out in this study, since we did not include medical interventions, sampling of human tissue, or invasive procedures. Furthermore, the 8 trained panellists involved were all above 18 years old, healthy, and they participated voluntarily. We excluded vulnerable subjects, and we used commercial products; we handled data anonymously. As additional care, the principles

described in the IFST Guidelines for Ethical and Professional Practices for the Sensory Analysis of Foods issued by The Institute of Food Science and Technology were given full consideration in the design and execution of sensory tests. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

GD: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. LD: Data curation, Formal Analysis, Visualization, Writing – original draft. GS: Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing. MG: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review and editing.

## Funding

The author(s) declared that financial support was received for this work and/or its publication.

## Acknowledgements

This study was supported by the PhD in Agro-Food System (Agrisystem) of the Università Cattolica del Sacro Cuore (Italy) and the Portus Project funded by Romeo and Enrica Invernizzi Foundation.

## References

- Akdoğan, A., and Baltacı, C. (2026). Non-alcoholic beer production using ohmic heating-assisted vacuum distillation method. *J. Food Sci.* 91 (1), e70790. doi:10.1111/1750-3841.70790
- American Society of Brewing Chemists (ASBC) (n.d.). Methods of analysis. Available online at: <https://www.asbcnet.org/Pages/default.aspx> (Accessed January, 2024).
- Anderson, P., Kokole, D., and Llopis, E. J. (2021). Production, consumption, and potential public health impact of low- and no-alcohol products: results of a scoping review. *Nutrients* 13 (9), 3153. doi:10.3390/nu13093153
- Andrés-Iglesias, C., Blanco, C. A., García-Serna, J., Pando, V., and Montero, O. (2016). Volatile compound profiling in commercial lager regular beers and derived alcohol-free beers after dealcoholization by vacuum distillation. *Food Anal. Methods* 9 (11), 3230–3241. doi:10.1007/s12161-016-0513-7
- Andrés-Iglesias, C., Blanco, C. A., and Montero, O. (2019). Sugar, hop  $\alpha$ -acid, and amino acid contents contribute to the differential profile between nonalcoholic and alcoholic beers. *Food Anal. Methods* 12 (1), 59–68. doi:10.1007/s12161-018-1338-3
- AssoBirra (2024). Annual report. Available online at: <https://www.assobirra.it/annual-report-assobirra/> (Accessed December, 2025).
- Bauwens, J., van Opstaele, F., Eggermont, L., Weiland, F., Jaskula-Goiris, B., De Rouck, G., et al. (2021). Comprehensive analytical and sensory profiling of non-alcoholic beers and their pale lager beer counterparts. *J. Inst. Brew.* 127 (4), 385–405. doi:10.1002/jib.664
- Bauwens, J., van Opstaele, F., Karatairis, C., Weiland, F., Eggermont, L., Jaskula-Goiris, B., et al. (2022). Assessing the ageing process of commercial non-alcoholic beers in comparison to their lager beer counterparts. *J. Inst. Brew.* 128 (4), 109–123. doi:10.1002/jib.698
- Beer Judge Certification Program (BJCP) (2015). Style guidelines. Available online at: <https://www.bjcp.org/style/2015/2/international-lager/> (Accessed March, 2026).
- Beer Judge Certification Program (BJCP) (2021). *Style Guidelines*. Available online at: <https://www.bjcp.org/style/2021/4/> (Accessed March, 2026).
- Bellut, K., and Arendt, E. K. (2019). Chance and Challenge: non-Saccharomyces yeasts in nonalcoholic and low alcohol beer brewing – a review. *J. Am. Soc. Brew. Chem.* 77 (2), 77–91. doi:10.1080/03610470.2019.1569452
- BirrItalia (2025). Beer industry XXX edizione. (2025–2026). Available online at: <https://www.beverfood.com/birritalia-2025-26-mercato-birrario-italiano/> (Accessed December, 2026).
- Blanco, C. A., Andrés-Iglesias, C., and Montero, O. (2016). Low-alcohol beers: flavor compounds, defects, and improvement strategies. *Crit. Rev. Food Sci. Nutr.* 56 (8), 1379–1388. doi:10.1080/10408398.2012.733979
- Borgognone, M., Bussi, J., and Hough, G. (2001). Principal component analysis in sensory analysis: covariance or correlation matrix? *Food Qual. Prefer.* 12 (5), 323–326. doi:10.1016/S0950-3293(01)00017-9
- Borşa, A., Muntean, M. V., Salanță, L. C., Tofană, M., Socaci, S. A., Mudura, E., et al. (2022). Effects of botanical ingredients addition on the bioactive compounds and quality of non-alcoholic and craft beer. *Plants* 11 (15), 1958. doi:10.3390/plants11151958
- Bossaerts, L., Van Opstaele, F., Wouters, A. G. B., Courtin, C. M., and Langenaeken, N. A. (2025). Study of the influence of beer composition on the amount of bubbles in beer: CO<sub>2</sub>, alcohol, protein and iso-alpha-acid contents as primary predictors. *Food Chem.* 469, 142523. doi:10.1016/j.foodchem.2024.142523
- Brányik, T., Silva, D. P., Baszczyński, M., Lehnert, R., and Almeida e Silva, J. B. (2012). A review of methods of low alcohol and alcohol-free beer production. *J. Food Eng.* 108 (4), 493–506. doi:10.1016/j.jfoodeng.2011.09.020
- Brendel, S., Hofmann, T., and Granvogel, M. (2020). Dry-hopping to modify the aroma of alcohol-free beer on a molecular level – loss and transfer of odor-active compounds. *J. Agric. Food Chem.* 68 (32), 8602–8612. doi:10.1021/acs.jafc.0c01907
- Catarino, M., and Mendes, A. (2011). Non-alcoholic beer – a new industrial process. *Sep. Purif. Technol.* 79, 342–351. doi:10.1016/j.seppur.2011.03.020

## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frfst.2026.1840815/full#supplementary-material>

- Clark, R. A., Hewson, L., Bealin-Kelly, F., and Hort, J. (2011). The interactions of CO<sub>2</sub>, ethanol, hop acids and sweetener on flavour perception in a model beer. *Chemosens. Percept.* 4 (1), 42–54. doi:10.1007/s12078-011-9087-3
- Clark, R., Linforth, R., Bealin-Kelly, F., and Hort, J. (2011). Effects of ethanol, carbonation and hop acids on volatile delivery in a model beer system. *J. Inst. Brew.* 117 (1), 74–81. doi:10.1002/j.2050-0416.2011.tb00446.x
- Dietz, C., Cook, D., Huisman, M., Wilson, C., and Ford, R. (2020). The multisensory perception of hop essential oil: a review. *J. Inst. Brew.* 126 (4), 320–342. doi:10.1002/jib.622
- Donadini, G., and Fumi, M. D. (2010). Sensory mapping of beers on sale in the Italian market. *J. Sens. Stud.* 25 (1), 19–49. doi:10.1111/j.1745-459X.2009.00244.x
- Donadini, G., Fumi, M. D., and De Faveri, D. M. (2011). How foam appearance influences the Italian consumer's beer perception and preference. *J. Inst. Brew.* 117 (4), 523–533. doi:10.1002/j.2050-0416.2011.tb00500.x
- Donadini, G., Fumi, M., and Faveri, M. (2011a). Sensory characteristics of Romanian, polish, Albanian and former Yugoslavian beers. *J. Inst. Brew. Distill.* 117 (4), 507–515. doi:10.1002/j.2050-0416.2011.tb00498.x
- Donadini, G., Fumi, M. D., and Lambri, M. (2013). A preliminary study investigating consumer preference for cheese and beer pairings. *Food Qual. Prefer.* 30 (2), 217–228. doi:10.1016/j.foodqual.2013.05.012
- Emmert-Streib, F., and Dehmer, M. (2019). Understanding statistical hypothesis testing: the logic of statistical inference. *Mach. Learn. Knowl. Extr.* 1 (3), 945–962. doi:10.3390/make1030054
- Eurostat (2020). Sold production, exports and imports by PRODCOM list (NACE Rev. 2) – annual data. Available online at: <https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/edn-20250801-1> (Accessed April, 2026).
- Ferreira, I. M., and Guido, L. F. (2023). Advances in extraction techniques for beer flavor compounds. *Beverages* 9 (3), 71. doi:10.3390/beverages9030071
- Forster, A., and Gahr, A. (2012). Hopping of low alcohol beers. *Brew. Sci.* 65 (7/8), 72–82.
- Friedman, J. H., Hastie, T., and Tibshirani, R. (2010). Regularization paths for generalized linear models via coordinate descent. *J. Statistical Software* 33, 1–22. doi:10.18637/jss.v033.i01
- Gernat, D. C., Brouwer, E., and Ottens, M. (2020). Aldehydes as wort off-flavours in alcohol-free beers — origin and control. *Food Bioprocess Technol.* 13 (2), 195–216. doi:10.1007/s11947-019-02374-z
- Gliszczynska-Świgło, A., Klimczak, I., Klensporf-Pawlik, D., and Rybicka, I. (2025). Quality characteristics and consumer perception of non-alcoholic beers in the context of responsible alcohol consumption. *Sci. Rep.* 15 (1), 7145. doi:10.1038/s41598-025-89833-0
- Grover, N., Nehra, M., and Gahlawat, S. K. (2022). Non alcoholic beers: review and methods. *Madridge J. Food Technol.* 7 (1), 200. doi:10.18689/mjft-1000130
- Hoerl, A. E., and Kennard, R. W. (1970). Ridge regression: biased estimation for nonorthogonal problems. *Technometrics* 12 (1), 55–67. doi:10.1080/00401706.1970.10488634
- Ickes, C. M., and Cadwallader, K. R. (2017). Effects of ethanol on flavor perception in alcoholic beverages. *Chemosens. Percept.* 10 (4), 119–134. doi:10.1007/s12078-017-9238-2
- Iñón, F. A., Garrigues, S., and de la Guardia, M. (2006). Combination of mid- and near-infrared spectroscopy for the determination of the quality properties of beers. *Anal. Chim. Acta* 571 (2), 167–174. doi:10.1016/j.aca.2006.04.070
- ISO 8589 (2007). *Sensory analysis—General Guidance for the Design of Test Rooms*. Geneva, Switzerland.
- Ivanova, N., Yang, Q., Bastian, S. E. P., Wilkinson, K. L., Johnson, T. E., and Ford, R. (2023). The impact of varying key sensory attributes on consumer perception of beer body. *Food Qual. Prefer.* 112, 105004. doi:10.1016/j.foodqual.2023.105004
- Jackowski, M., Lech, M., Wnukowski, M., and Trusek, A. (2024). The influence of pervaporation on ferulic acid and Maltol in dealcoholised beer. *ChemEngineering* 8 (5), 101. doi:10.3390/chemengineering8050101
- Jolliffe, I. T. (2002). *Principal Component Analysis*. 2nd edition. New York, NY: Springer.
- Klimczak, K., Cioch-Skoneczny, M., Poreda, A., and Ciosek, A. (2025). Evaluation of commercial yeast strains to produce reduced-alcohol beer. *Eur. Food Res. Technol.* 251 (11), 3965–3979. doi:10.1007/s00217-025-04884-x
- Kozłowski, R., Dziędziński, M., Stachowiak, B., and Kobus-Cisowska, J. (2021). Non- and low-alcoholic beer—popularity and manufacturing techniques. *Acta Sci. Pol. Technol. Aliment.* 20 (3), 347–357. doi:10.17306/J.AFS.2021.0961
- Krebs, G., Müller, M., Becker, T., and Gastl, M. (2019). Characterization of the macromolecular and sensory profile of non-alcoholic beers produced with various methods. *Food Res. Int.* 116, 508–517. doi:10.1016/j.foodres.2018.08.067
- Kumar, Y., Khalangre, A., Suhag, R., and Cassano, A. (2025). Applications of reverse osmosis and nanofiltration membrane process in wine and beer industry. *Membranes* 15 (5), 140. doi:10.3390/membranes15050140
- Kuznetsova, A., Christensen, R. H., Bavay, C., and Brockhoff, P. B. (2015). Automated mixed ANOVA modeling of sensory and consumer data. *Food Qual. Prefer.* 40, 31–38. doi:10.1016/j.foodqual.2014.08.004
- Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. (2017). lmerTest package: tests in linear mixed effects models. *J. Stat. Softw.* 82, 1–26. doi:10.18637/jss.v082.i13
- Lafontaine, S., Senn, K., Dennenlöhner, J., Schubert, C., Knoke, L., Maxminer, J., et al. (2020). Characterizing volatile and nonvolatile factors influencing flavor and American consumer preference toward nonalcoholic beer. *ACS Omega* 5 (36), 23308–23321. doi:10.1021/acsomega.0c03168
- Lawless, H. T., and Heymann, H. (2010). *Sensory Evaluation of Food: Principles and Practices*. New York, NY: Springer Science & Business Media.
- Liguori, L., De Francesco, G., Russo, P., Perretti, G., Albanese, D., and Di Matteo, M. (2015). Production and characterization of alcohol-free beer by membrane process. *Food Bioprod. Process.* 94, 158–168. doi:10.1016/j.fbp.2015.03.003
- Liu, J., Vaag, P., Delgado, A., Ramsey, I., Chatzinikolaou, C., Harholt, J., et al. (2024). The impact of ethanol on the sensory perception and aroma release of alcohol-free beers. *Brew. Sci.* 77 (9/10), 102–106. doi:10.23763/BRSC24-08LIU
- Lucak, C. L., and Delwiche, J. F. (2009). Efficacy of various palate cleansers with representative foods. *Chemosens. Perception* 2 (1), 32–39. doi:10.1007/s12078-009-9036-6
- Martens, H., and Naes, T. (1992). *Multivariate Calibration*. Chichester, United Kingdom: John Wiley & Sons.
- Meilgaard, M. C., Dalglish, C. E., and Clapperton, J. F. (1979). Beer flavor terminology. *J. Am. Soc. Brew. Chem.* 37 (1), 47–52. doi:10.1094/asbcj-37-0047
- Menéndez, P., Eilers, P., Tikunov, Y., Bovy, A., and van Eeuwijk, F. (2012). Penalized regression techniques for modeling relationships between metabolites and tomato taste attributes. *Euphytica* 183 (3), 379–387. doi:10.1007/s10681-011-0374-5
- Moss, R., Barker, S., and McSweeney, M. B. (2022). An analysis of the sensory properties, emotional responses and social settings associated with non-alcoholic beer. *Food Qual. Prefer.* 98, 104456. doi:10.1016/j.foodqual.2021.104456
- Müller, M., Bellut, K., Tippmann, J., and Becker, T. (2017). Physical methods for dealcoholization of beverage matrices and their impact on quality attributes. *ChemBioEng Rev.* 4 (5), 310–326. doi:10.1002/cben.201700010
- Muller, C., Neves, L. E., Gomes, L., Guimaraes, M., and Ghesti, G. (2020). Processes for alcohol-free beer production: a review. *Food Sci. Technol. (Campinas)* 40, 273–281. doi:10.1590/fst.32318
- Müller, M., Gastl, M., and Becker, T. (2021). Key constituents, flavour profiles and specific sensory evaluation of wheat style non-alcoholic beers depending on their production method. *J. Inst. Brew.* 127 (3), 262–272. doi:10.1002/jib.663
- Myncke, E., Vandoorne, S., Huys, J., Smout, P., Laureys, D., Vermeir, P., et al. (2026). Wort optimisation for non-alcoholic beer production with maltose-negative yeasts: incorporation of malted, flaked, and unmalted adjuncts. *Food Chem.* 506, 148037. doi:10.1016/j.foodchem.2026.148037
- Narziss, L., Miedaner, H., Kern, E., and Leibhard, M. (1992). Technology and composition of non-alcoholic beer — processes using arrested fermentation. *Brauwelt Int.* 4, 396–410.
- Næs, T., Brockhoff, P. B., and Tomic, O. (2010). *Statistics for Sensory and Consumer Science*. Chichester, United Kingdom: Wiley. doi:10.1002/9780470669181
- Nurgel, C., and Pickering, G. (2006). Modeling of sweet, bitter and irritant sensations and their interactions elicited by model ice wines. *J. Sensory Studies* 21 (5), 505–519. doi:10.1111/j.1745-459X.2006.00081.x
- Parker, D. K. (2012). “Beer: production, sensory characteristics and sensory analysis,” in *Alcoholic Beverages* (Oxford/Philadelphia: Woodhead Publishing), 133–158.
- Paszkot, J., Gasiński, A., and Kawa-Rygielska, J. (2023). Evaluation of volatile compound profiles and sensory properties of dark and pale beers fermented by different strains of brewing yeast. *Sci. Rep.* 13 (1), 6725. doi:10.1038/s41598-023-33246-4
- Peeters, M., Ter Braak, J., Hagemeyer, F., Voogt, C., Kersbergen, I., Holmes, J., et al. (2025). Exploring Adolescents' consumption of alcohol-free and low-alcohol drinks: a review of the literature and a drinking profile analysis. *Int. J. Ment. Health Addict.* 1–21. doi:10.1007/s11469-025-01515
- Petelkov, I., Shopska, V., Denkova-Kostova, R., Ivanova, K., Kostov, G., and Lyubenova, V. (2021). Investigation of fermentation regimes for the production of low-alcohol and non-alcohol beers. *Period. Polytech. Chem. Eng.* 65 (2), 229–237. doi:10.3311/PPCh.15975
- Piornos, J. A., Koussissi, E., Balagiannis, D. P., Brouwer, E., and Parker, J. K. (2023). Alcohol-free and low-alcohol beers: aroma chemistry and sensory characteristics. *Compr. Rev. Food Sci. Food Saf.* 22 (1), 233–259. doi:10.1111/1541-4337.13068
- Ramsey, I., Dinu, V., Linforth, R., Yakubov, G. E., Harding, S. E., Yang, Q., et al. (2020). Understanding the lost functionality of ethanol in non-alcoholic beer using sensory evaluation, aroma release and molecular hydrodynamics. *Sci. Rep.* 10, 20855. doi:10.1038/s41598-020-77697-5
- Rettberg, N., Lafontaine, S., Schubert, C., Dennenlöhner, J., Knoke, L., Diniz Fischer, P., et al. (2022). Effect of production technique on pilsner-style non-alcoholic beer (NAB) chemistry and flavor. *Beverages* 8 (1), 4. doi:10.3390/beverages8010004
- Riu-Aumatell, M., Miró, P., Serra-Cayuela, A., Buxaderas, S., and López-Tamames, E. (2014). Assessment of the aroma profiles of low-alcohol beers using HS-SPME-GC-MS. *Food Res. Int.* 57, 196–202. doi:10.1016/j.foodres.2014.01.016

- Rocchetti, G., Michelini, S., Pizzamiglio, V., Masoero, F., and Lucini, L. (2021). A combined metabolomics and peptidomics approach to discriminate anomalous rind inclusion levels in Parmigiano Reggiano PDO grated hard cheese from different ripening stages. *Food Res. Int.* 149, 110654. doi:10.1016/j.foodres.2021.110654
- Rohart, F., Gautier, B., Singh, A., and Lê Cao, K. A. (2017). mixOmics: an R package for 'omics feature selection and multiple data integration. *PLoS Computational Biology* 13 (11), e1005752. doi:10.1371/journal.pcbi.1005752
- Rossi, F., Spigno, G., Luzzani, G., Bozzoni, M. E., Donadini, G., Rolla, J., et al. (2021). Effects of the intake of craft or industrial beer on serum homocysteine. *Int. J. Food Sci. Nutr.* 72 (1), 93–98. doi:10.1080/09637486.2020.1760219
- Saison, D., De Schutter, D. P., Uyttenhove, B., Delvaux, F., and Delvaux, F. R. (2009). Contribution of staling compounds to the aged flavour of lager beer by studying their flavour thresholds. *Food Chem.* 114, 1206–1215. doi:10.1016/j.foodchem.2008.10.078
- Salañã, L. C., Coldea, T. E., Ignat, M. V., Pop, C. R., Tofanã, M., Mudura, E., et al. (2020). Non-alcoholic and craft beer production and challenges. *Processes* 8 (11), 1382. doi:10.3390/pr8111382
- Satterthwaite, F. E. (1946). An approximate distribution of estimates of variance components. *Biom. Bulletin* 2 (6), 110–114. doi:10.2307/3002019
- Schmelzle, A., Lindemann, B., and Methner, F. J. (2013). Sensory descriptive analysis and investigation of consumer acceptance of Bavarian wheat beer. *BrewingScience* 66 (5/6), 46–54.
- Shopska, V., DenkModellingova, R., and Kostov, G. (2022). Modeling in brewing—a review. *Processes* 10 (2), 267. doi:10.3390/pr10020267
- Sohrabvandi, S., Mortazavian, A. M., and Rezaei, K. (2012). Health-related aspects of beer: a review. *Int. J. Food Prop.* 15 (2), 350–373. doi:10.1080/10942912.2010.487627
- Stefanuto, P. H., Perrault, K. A., Dubois, L. M., L'Homme, B., Allen, C., Loughnane, C., et al. (2017). Advanced method optimization for volatile aroma profiling of beer using two-dimensional gas chromatography time-of-flight mass spectrometry. *J. Chromatogr. A* 1507, 45–52. doi:10.1016/j.chroma.2017.05.064
- Stone, H., and Sidel, J. L. (2004). *Sensory Evaluation Practice*. 3rd edition. San Diego, CA: Elsevier Academic Press.
- Takoi, K., Tokita, K., Sanekata, A., Usami, Y., Itoga, Y., Koie, K., et al. (2016). Varietal difference of hop derived flavour compounds in late-hopped/dry-hopped beers. *BrewingScience* 69, 1–7.
- Tibshirani, R. (1996). Regression shrinkage and selection via the lasso. *J. R. Stat. Soc. Ser. B Stat. Methodol.* 58 (1), 267–288. doi:10.1111/j.2517-6161.1996.tb02080.x
- Van Opstaele, F., De Rouck, G., De Clippeleer, J., Aerts, G., and De Cooman, L. (2010). Analytical and sensory assessment of hoppy aroma and bitterness of conventionally hopped and advanced hopped pilsner beers. *J. Inst. Brew.* 116, 445–458. doi:10.1002/j.2050-0416.2010.tb00796.x
- Van Opstaele, F., De Rouck, G., Janssens, P., and Montandon, G. G. (2020). An exploratory study on the impact of the yeast strain on hop flavour expressions in heavily hopped beers: new England IPA. *BrewingScience* 73, 26–40. doi:10.23763/BRSC20-04OPSTAELE
- Verstrepen, K. J., Derdelinckx, G., Dufour, J. P., Winderickx, J., Thevelein, J. M., Pretorius, I. S., et al. (2003). Flavor-active esters: adding fruitiness to beer. *J. Biosci. Bioeng.* 96, 110–118. doi:10.1016/S1389-1723(03)90112-5
- Watson, J. C. (2017). Establishing evidence for internal structure using exploratory factor analysis. *Meas. Eval. Couns. Dev.* 50, 232–238. doi:10.1080/07481756.2017.1336931
- Wold, S., Sjöström, M., and Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. *Chemom. Intelligent Laboratory Systems* 58 (2), 109–130. doi:10.1016/S0169-7439(01)00155-1
- Xu, Y., Wang, D., Li, G., Hao, J., Jiang, W., Liu, Z., et al. (2017). Flavor contribution of esters in lager beers and an analysis of their flavor thresholds. *J. Am. Soc. Brew. Chem.* 75 (3), 201–206. doi:10.1094/ASBCJ-2017-3007-01
- Zhang, P., Carlin, S., Lotti, C., Mattivi, F., and Vrhovsek, U. (2020). On sample preparation methods for fermented beverage VOCs profiling by GC×GC-TOFMS. *Metabolomics* 16 (10), 102. doi:10.1007/s11306-020-01718
- Zhang, P., Piervigiovanni, M., Franceschi, P., Mattivi, F., Vrhovsek, U., and Carlin, S. (2023). Application of comprehensive 2D gas chromatography coupled with mass spectrometry in beer and wine VOC analysis. *Analytica* 4 (3), 347–373. doi:10.3390/analytica4030026
- Zou, H., and Hastie, T. (2005). Regularization and variable selection via the elastic net. *J. R. Stat. Soc. Ser. B Stat. Methodol.* 67 (2), 301–320. doi:10.1111/j.1467-9868.2005.00503.x