Florian Lehnhardt, Tobias Kössel, Sarina Lindtner, Fabian Schumacher, Luis Raihofer and Martina Gastl

Flavour instability and aroma profiles of non-alcoholic beers across production principles and beer styles

Flavour instability is a major quality challenge in non-alcoholic beers (<0.5 vol.% alcohol), as their reduced ethanol content alters aroma retention, antioxidative capacity, and ageing pathways compared with conventional beer. Consequently, non-alcoholic beers are often more susceptible to flavour deterioration during storage.
In this study, the aroma composition, sensory profile, and ageing behaviour of 45 commercial non-alcoholic beers from 30 breweries were investigated. Samples were grouped into physically dealcoholised, stopped fermentation, alternative yeast, and hybrid beers. Aroma compounds and ageing-relevant aldehydes were analysed in fresh and forced-aged samples, complemented by trained-panel sensory evaluation. In addition, ageing potential was assessed through alkaline-induced release of aldehydes from bound states.
Distinct differences between production principles were observed. Biologically produced non-alcoholic beers, particularly stopped-fermentation beers, exhibited higher wort-like character, elevated concentrations of Strecker aldehydes, and larger pools of releasable aldehydes. In contrast, physically dealcoholised beers generally showed lower initial aldehyde concentrations but often experienced the strongest increases in ageing-related compounds during forced ageing. Across all production principles, Strecker aldehydes and furfural increased markedly during ageing and were identified as major contributors to flavour deterioration. The alkaline release approach revealed a substantial aldehyde-related ageing potential exceeding the aldehyde increases observed during forced ageing, indicating the presence of both bound aldehydes and matrix-dependent formation pathways. Hybrid beers displayed the most favourable ageing behaviour, combining comparatively low aldehyde concentrations with the smallest sensory deterioration after ageing.
Overall, flavour instability was influenced more strongly by production principle than by beer style, demonstrating that technology selection is a key determinant of long-term sensory quality in non-alcoholic beers. These findings highlight the importance of production-specific strategies to improve flavour instability and shelf life.

Descriptors: Non-alcoholic beer, aroma profile, beer ageing, flavour instability, ageing potential

1 Introduction

Non-alcoholic beers (NABs) represent one of the fastest-growing segments of the brewing industry, with global market volumes increasing significantly in recent years. Rather than merely replicating the sensory profile of traditional beers, NABs are increasingly positioned as a distinct beverage category in their own right, driven by changing consumer preferences for mindful drinking (1). However, they are prone to undesired flavour alterations after packaging, making freshness a key determinant of product quality and flavour instability a key challenge (2).

Although beer flavour instability has been extensively studied, NABs present distinct challenges due to their altered production processes, highly different matrix composition, reduced ethanol content, and potentially lower antioxidative capacity. Chemical and sensory ageing is generally driven by the same fundamental processes as in conventional beer, including oxidation, *de novo* formation of aroma-active compounds, and the release of bound aldehydes. However, the low or absent ethanol content (< 0.5 vol. %) can substantially alter the extent and dynamics of these reactions, thereby accelerating flavour deterioration, promoting the formation and release of ageing-related compounds, and intensifying the perceived loss of freshness during storage (3, 4).

Oxidative reactions are central to aroma degradation in beer, with oxygen and light promoting the formation of reactive oxygen species and flavour changes (5). In NABs, the absence of ethanol as a radical sink may shift radical pathways toward reactions with polyphenols, hop-derived compounds, lipids, sugars, or amino acids, although

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direct experimental evidence and suitable ESR-based detection strategies for these matrices remain limited (6).

Further, aldehyde accumulation is a major driver of sensory degradation in NABs, resulting from elevated initial levels, oxidation and *de novo* formation during storage, and the release of bound aldehydes from non-volatile intermediates (7–11). This is particularly relevant for biologically (predominantly stopped fermentation or alternative yeasts) produced NABs, where limited fermentation activity, incomplete yeast-mediated aldehyde reduction, yeast strain effects, and lower SO_2 levels can increase ageing potential and promote wort-like, malty, cooked-potato, and cardboard-like off-flavours (12–15). Interestingly, Rettberg et al. did not report strong correlations between aldehydes and wort-like off-flavours or overall harmony in a study with several pilsner NABs (15).

Product composition, aroma profiles and ageing pathways in NABs strongly depend on the production method: biologically produced beers such as stopped or cold-contact fermentations tend to show high aldehyde levels, high residual sugars, limited SO_2 formation, and increased *de novo* ageing potential, whereas thermal and membrane dealcoholisation mainly differ in thermal stress, aroma losses, and retention of ageing-relevant compounds. Also, further ageing-relevant compounds can be of interest, especially when considering different production techniques (15–17). In addition, NABs are more prone to colloidal instability, as altered protein–polyphenol–polysaccharide interactions promote haze formation and sedimentation, making raw material selection and stabilisation measures such as PVPP or silica gel treatment important for shelf-life control (6, 15, 18).

Regarding the matrix, the absence or strong reduction of ethanol alters the polarity of the beer matrix and reduces the retention of non-polar aroma compounds such as aldehydes, resulting in increased volatility and stronger perception of wort-like off-flavours in NABs (3, 4, 8, 14). This effect is further intensified by reduced masking from esters and higher alcohols, as well as by residual sugars that promote aldehyde release into the headspace through salting-out effects (3, 19).

Compared to conventional beer, NABs often show accelerated ageing due to reduced ethanol-related antioxidative buffering, altered radical pathways, and faster degradation of hop bittering compounds and polyphenols (15, 20). This can lead to a more rapid loss of freshness and stronger ageing impressions during storage, particularly under elevated temperatures, where compounds such as methional and furfural increase markedly (13).

Therefore, it was hypothesised that commercial NABs differ in their aroma profiles and flavour instability depending on the applied production principle and that production principle represents a major determinant of both fresh aroma character and the extent of sensory and chemical changes during ageing. Furthermore, it was hypothesised that bound-state aldehydes contribute to the ageing potential of NABs and that their chemically induced release provides complementary information on bound state-driven ageing pathways beyond free aldehyde analysis alone. As biological, physical, and hybrid production strategies differ in fermentation performance, aldehyde reduction, thermal load, and matrix composition, these differences were expected to allow the identification of a production approach with more favourable ageing behaviour, characterised by reduced sensory deterioration and lower formation or release of ageing-related aldehydes during storage.

Thus, the aims of this study were therefore: (i) chemical and sensory description of NABs from different production techniques in regard to aroma profiles and ageing behaviour, (ii) determine the most stable production technique regarding flavour instability, (iii) apply the concept of bound aldehydes to NABs.

2 Materials and Methods

2.1 Samples and breweries

The dataset comprises 45 non-alcoholic beer samples from 30 distinct breweries. The sample set consisted of 16 lager (L), 6 other beer-styles (O; including Bock, India Pale Ale, Alt, Kölsch, and beer-mix beverages), 8 Pilsner (P), and 15 Wheat beer samples (W) from different production setups. Regarding geographical origin, the dataset is predominantly German, with 41 samples from Germany. In addition, 2 samples originate from Italy, 1 sample from Switzerland, and 1 sample from the Netherlands. Thus, the dataset primarily reflects the German market while including selected international references (Table 1). A survey on the respective production technique was completed on a voluntary basis. Table 1 summarises of all relevant brewery information provided.

The samples were grouped into four categories: see Table 1.

Regarding production technology, the dataset includes 20 physically dealcolised beers (p), 7 stopped fermentation (sf), 10 alternative yeast (y) samples, and 8 hybrid products (h). Physical approaches were predominantly based on thermal dealcoholisation techniques. Biological methods mainly relied on stopped fermentation or the application of alternative yeast strains. Hybrid products combined or blended biological and physical approaches. In some cases original alcohol-containing beer was blended to NABs.

The samples were analysed and tasted in fresh and forced aged conditions. Forced ageing was achieved after 24 h shaking and 96 h storage (40 °C, dark) as described in the literature (21). The analyses took place within 2 weeks after shipping resp. 3 weeks after filling.

2.2 Analyses

2.2.1 Instrumental analyses

All standard analyses were performed in technical duplicate measurements. The following analyses were performed according to the resp. methods: original gravity, extract, attenuation, alcohol (B-590.10.181 [2020-10]), and pH value (B-590.00.040 [2020-10]).

Furthermore, fermentation by-products and aroma-active compounds were quantified according to MEBAK methods. Ethyl butanoate, 2-phenylethyl acetate, ethyl hexanoate, ethyl octanoate, ethyl decanoate, 2-phenylethanol, isovaleric acid, hexanoic acid, octanoic acid and decanoic acid were analysed by GC-FID analysis

Table 1 **Sample setup; p = physical dealcoholisation, h = hybrid production, sf = stopped fermentation, y = alternative yeast, - = no answer**

Code	Beer style	Production principle	Production method	Processing notes	Stabilisation technology	Pasteurisation units [PU]
L1	Helles	p	Thermal	–	–	–
L2	Helles	p	Thermal	–	–	–
L3	Helles	h	Stopped fermentation / Membrane	–	–	–
L4	Helles	p	Thermal	Addition of original beer	No	–
L5	Helles	p	Thermal	–	–	–
L6	Helles	y	Alternative yeast	–	Pasteurisation	–
L7	Helles	p	Thermal	Addition of original beer	–	–
L8	Helles	p	Thermal	–	Flash pasteurisation	70
L9	Helles	y	Alternative yeast	–	Pasteurisation	30
L10	Helles	sf	Stopped fermentation	Unique hopping	Flash pasteurisation, pasteurisation	27+50
L11	Helles	p	Thermal	–	–	–
L12	Helles	sf	Stopped fermentation	–	–	–
L13	Helles	y	Alternative yeast	*S. ludwigii*	–	–
L14	Helles	sf	Stopped fermentation	–	Pasteurisation	–
L15	Helles	h	Alternative yeast / stopped fermentation / thermal	Addition of original beer	Sterile filtration	–
L16	Naturally cloudy	y	Alternative yeast	Non filtered	Flash pasteurisation, pasteurisation	80+55
O1	Altbier	y	Alternative yeast	Specialty malt, whirlpool hopping	Flash pasteurisation, pasteurisation	–
O2	Kölsch	p	Thermal	–	–	–
O3	Kölsch	sf	Stopped fermentation	–	Pasteurisation	36
O4	Bock	p	Thermal	–	–	–
O5	IPA	y	Alternative yeast	–	–	–
O6	Radler	p	Thermal	–	–	–
P1	Pils	h	Alternative yeast / thermal	Addition of special hop extract, low-attenuating yeasts	Pasteurisation	25
P2	Pils	sf	Stopped fermentation	–	–	–
P3	Pils	p	Thermal	–	Flash pasteurisation	–
P4	Pils	p	Thermal	Aroma addition (isoamyl acetate)	–	–
P5	Pils	p	Thermal	Dosage of aroma recovery	Flash pasteurisation	70
P6	Pils	h	Membrane	Addition of original beer	–	–
P7	Pils	h	Stopped fermentation / thermal	Dosage of aroma recovery	Flash pasteurisation	40
P8	Pils	y	Alternative yeast	–	Pall filtration, pasteurisation	35
W1	Wheat beer	p	Thermal	Addition of original beer	-	–
W2	Wheat beer	h	Alternative yeast / thermal	–	Flash pasteurisation, pasteurisation	70+25

Code	Beer style	Production principle	Production method	Processing notes	Stabilisation technology	Pasteurisation units [PU]
W3	Wheat beer	y	Alternative yeast	–	Flash pasteurisation, pasteurisation	80+55
W4	Wheat beer	h	Alternative yeast / stopped fermentation	Unique hopping	Flash pasteurisation, pasteurisation	80+55
W5	Wheat beer	p	Thermal	–	–	–
W6	Dark wheat beer	p	Thermal	Addition of original beer	no	–
W7	Dark wheat beer	y	Alternative yeast	–	Pasteurisation	23
W8	Wheat beer	p	Thermal	–	–	–
W9	Wheat beer	p	Thermal	–	Flash pasteurisation	–
W10	Wheat beer	h	Stopped fermentation / thermal	Addition of original beer	Flash pasteurisation	300
W11	Wheat beer	p	Thermal	–	–	–
W12	Wheat beer	sf	Stopped fermentation	–	–	–
W13	Wheat beer	sf	Stopped fermentation	–	–	–
W14	Wheat beer	y	Alternative yeast	–	–	–
W15	Wheat beer	p	Cold contact	–	–	–

Continued Table 1

according to B-420.25.151 [2020-10]. Acetaldehyde, ethyl acetate, n-propanol, isobutanol, isobutyl acetate, isoamyl acetate and amyl alcohols were quantified by HS-GC-FID in accordance with B-420.16.157 [2020-10]. Total diacetyl, total 2,3-pentanedione and acetoin were analysed by HS-GC-ECD according to B-420.21.157 [2020-10] resp. B-420.22.157 [2025-01].

Free dimethyl sulfide was determined by HS-GC-FPD in accordance with B-400.35.153 [2020-10]. For wheat beers only, 4-vinylguaiacol was determined by HPLC-UV according to B-420.20.131 [2025-04].

Analysis of free aldehydes by OFD-HS-SPME-GC-MS/MS was conducted as previously described in literature (21, 22) using a triple quadrupole GC-MS (Trace 1610/TSQ 9610, Thermo Fisher Scientific). In short, samples were derivatised with O-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine (10 min, 40 °C) prior to SPME arrow extraction (DVB/Carbon-WR/PDMS, 15 min, 1,000 rpm, 40 °C) and analyzed on a TraceGOLD TG-5MS column (30 m × 0.25 mm × 0.25 µm) with a temperature gradient from 80–300 °C.

Additionally, bound aldehydes were measured as free aldehydes – resp. ageing potential – upon addition of 100 µL NaOH (1 N) into the headspace vial (already containing 5 mL sample and 50 µL internal standard solution). The vials were then incubated for 10 h until analysis in a cooled tray (15 °C). A strict sequence design and procedure were maintained consisting of a fixed number of analysed samples, blank runs and delay times in order to achieve the desired incubation time.

2.2.2 Sensory analyses

The sensory testing of the fresh and aged beers was carried out in a fully randomised setup by trained 5 DLG-certified tasters in a consensus rating. Still water was used as a palate cleanser between samples. The samples were tasted in 10 separate sessions. All panelists underwent continuous training (once per week) – consisting of different matching, descriptive and rating exercises with diverse testing material including TUM Flavour Kits to train specific descriptors at different intensity levels. Samples were swirled gently 15 min prior to testing to ensure sample homogeneity. Their temperature was controlled at 10 °C. The tasting setup consisted of a DLG 5-point scheme® and an Eichhorn ageing scheme as previously described (23, 24).

In addition, a quantitative descriptive analysis (QDA) approach with pre-selected descriptors was applied. These descriptors include malt aroma, DMS, wort-like, bready, popcorn, hop aroma, fruity, herbal, yeast aroma, estery, phenolic, sulfury, off-flavour, diacetyl, metallic, bitterness intensity, bitterness quality, sweetness, sourness, palate fullness intensity, watery, mouth coating, and slimy. Furthermore, the ageing-related descriptors sweetish, bready, cardboard, honey, and sherry were evaluated. Free-text comments were additionally recorded for each sample. The resp. intensity was rated on a monadic scale covering 0 (not present), 1 (very low), 2 (low), 3 (medium), 4 (high) and 5 (very high).

All sensory evaluations were conducted in accordance with the ethical principles of the Declaration of Helsinki. Participation was voluntary, and all panelists provided informed consent prior to the study. No personally identifiable data were collected. This research did not involve any animal experiments.

2.2.3 Data analysis

All data analysis was performed in JMP Pro 19 (SAS Institute Inc., Cary, NC, USA) and visualisation in R Studio (2026.06.0 Build 242,

R Core Team). Values below the limit of quantification (LOQ) were treated as 50 % of the LOQ for statistical evaluation. Changes in sensory attributes or other parameters are expressed as Δ values, defined as the difference between forced aged and fresh samples or as otherwise indicated.

Initially, normal distribution of the data was assessed for each group (production principle) using the Shapiro-Wilk test. For normally distributed data, a parametric test (one-way ANOVA expressed as p values) and for non-normally distributed data, a nonparametric test (Kruskal-Wallis test expressed as χ^2 incl. degrees of freedom and p values) were used to reveal statistical differences between the groups. An overall significance level of $\alpha = 0.05$ was used. If these resulted in $p < 0.05$, further pairwise tests were applied (Tukey Kramer HSD Test and Dunns Test, respectively). Significance levels are indicated as follows: * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$.

Hierarchical cluster analysis was performed on the ageing-related changes of all 14 aldehydes, expressed as Δ values for both approaches (forced − fresh and released (fresh) − fresh; 28 variables, 45 samples). A pairwise Pearson correlation matrix was calculated and clustered in rows and columns using Euclidean distance and Ward's linkage (ward.D2), visualised as a heatmap with a diverging colour scale centred at r = 0.

3 Results

In the following sections, the observed differences in physicochemical parameters and aroma compounds, sensory analyses, as well as free and released aldehydes are presented in relation to the applied production principle (in fresh or forced aged conditions or expressed as Δ = difference between forced and fresh samples). For this purpose, the dataset was grouped into physically dealcoholised (p), stopped fermentation (sf), alternative yeast (y), and hybrid process (h) beers, allowing for a comparison of the technological influences on the resulting beer composition. All data can be found in the supplementary material.

3.1 Differences between production principles – Aroma compounds

In comparison between production principles, original gravity was significantly lower in physically dealcoholised beers (mean h: 6.5 °P, mean p: 4.9 °P, mean y: 6.5 °P, mean sf: 6.7 °P, $p < 0.001$).

The pH value was significantly higher in beers produced by biological approaches, with the highest values observed for stopped fermentation samples (mean h: 4.3, mean p: 4.4, mean y: 4.5, mean sf: 4.6, $p = 0.03$).

Aroma compounds showed various trends reflecting the influence of the different production technologies. For instance, isovaleric acid concentrations were significantly higher in physically dealcoholised beers (mean h: 0.57 mg/L, mean p: 1.21 mg/L, mean y: 0.70 mg/L, mean sf: 0.72, $p = 0.02$). A similar trend was observed for hexanoic acid, which was also significantly elevated in physically dealcoholised samples (mean h: 1.09 mg/L, mean p: 1.65 mg/L, mean y: 0.45 mg/L, mean sf: 0.95, $\chi^2(3) = 20.8$, $p < 0.001$).

Accordingly, octanoic acid concentrations were significantly lower in beers produced with alternative yeast and stopped fermentation (mean h: 3.27 mg/L, mean p: 3.08 mg/L, mean y: 0.87 mg/L, mean sf: 2.29, $\chi^2(3) = 13.8$, $p < 0.01$). A similar tendency was observed for other medium-chain fatty acids such as decanoic acid ($p = 0.06$). Hybrid beers showed a comparatively high variability, appearing to form two distinct subgroups.

Ethyl acetate concentrations were mostly below the limit of quantification; nevertheless, trends of higher levels were observed in physically dealcoholised beers (mean h: 1.99 mg/L, mean p: 3.05 mg/L, mean y: 0.69 mg/L, mean sf: 0.71, $\chi^2(3) = 4.48$, $p = 0.21$).

For isoamyl acetate, the lowest concentrations were found in stopped fermentation and alternative yeast beers, while hybrid beers exhibited the highest values. However, this was largely driven by two individual samples (mean h: 0.46 mg/L, mean p: 0.41 mg/L, mean y: 0.07 mg/L, mean sf: 0.05, $\chi^2(3) = 9.18$, $p = 0.03$).

Ethyl hexanoate concentrations were generally low (close to LOQ of 0.01 mg/L) but slightly elevated in physically dealcoholised and hybrid beers, although no significant differences were observed (mean h: 0.02 mg/L, mean p: 0.02 mg/L, mean y: 0.01 mg/L, mean sf: 0.01, $p = 0.16$).

No significant differences were detected for amyl alcohols, although the lowest levels were found in stopped fermentation samples (mean h: 5.99 mg/L, mean p: 6.56 mg/L, mean y: 8.37 mg/L, mean sf: 3.90, $\chi^2(3) = 4.29$, $p = 0.23$), or for diacetyl ($\chi^2(3) = 1.88$, $p = 0.60$).

In contrast, dimethyl sulfide concentrations were significantly higher in beers produced with alternative yeast and stopped fermentation (mean h: 29 µg/L, mean p: 1 µg/L, mean y: 102 µg/L, mean sf: 31 µg/L, $\chi^2(3) = 15.88$, $p < 0.01$).

2-Phenylethanol levels were highest in physically dealcoholised beers, followed by hybrid samples, while the lowest concentrations were found in stopped fermentation and alternative yeast beers (mean h: 15.1 mg/L, mean p: 23.8 mg/L, mean y: 5.0 mg/L, mean sf: 6.2 mg/L, $\chi^2(3) = 22.46$, $p < 0.001$).

For 4-vinylguaiacol, significantly higher concentrations were observed in physically dealcoholised beers compared to biologically produced samples (mean h: 0.8 mg/L, mean p: 1.3 mg/L, mean y: 0.3 mg/L, mean sf: 0.3 mg/L, $\chi^2(3) = 8.87$, $p = 0.03$).

3.2 Differences between production principles – Sensory analysis

For the DLG overall rating, no differences between production groups were observed in fresh samples ($\chi^2(3) = 1.3$, $p = 0.72$). After forced ageing, first trends became apparent, with hybrid beers showing slightly increased ratings compared to the other groups. This is also reflected in the mean Δ values between forced and fresh samples, indicating a comparatively smaller decline for hybrid beers (mean h: -0.24, mean p: -0.35, mean y: -0.33, mean sf: -0.38, $p = 0.42$).

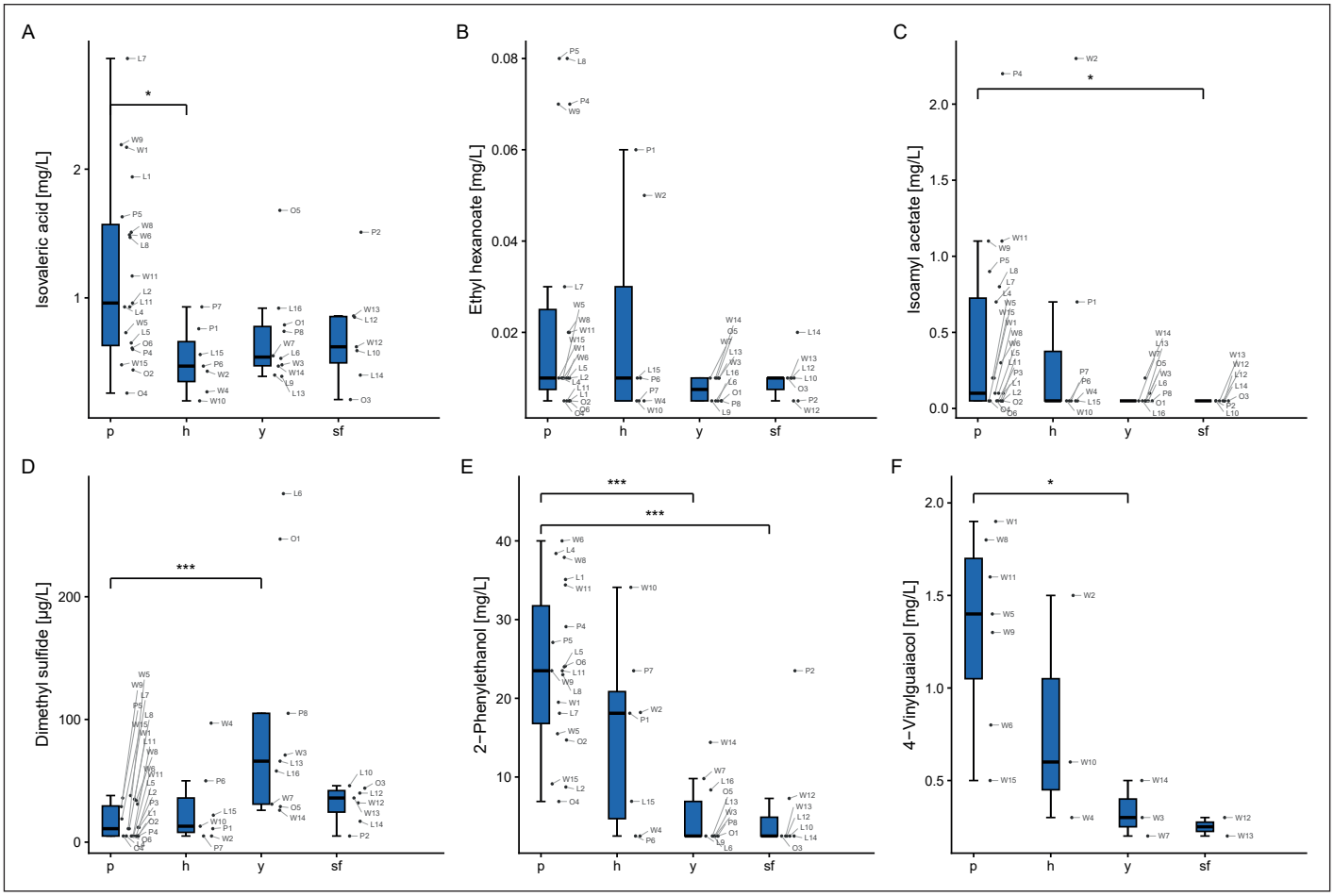

Fig. 1 Boxplots of chosen aroma compounds separated by production principle; p = physical dealcoholisation, h = hybrid production, sf = stopped fermentation, y = alternative yeast

For the Eichhorn scheme, Δ scores for the descriptor smell tended to increase less in hybrid samples compared to the other production types (mean h: 0.9, mean p: 1.2, mean y: 1.1, mean sf: 1.1, $\chi^2(3) = 1.9$, $p = 0.60$). A similar pattern was observed for Δ taste and the Δ DLG overall rating.

In terms of overall acceptance, a general decline was observed for all sample groups upon forced ageing. This loss of acceptance was most pronounced in physically dealcoholised beers, followed by alternative yeast samples (mean h: -26.9 %, mean p: -33.5 %, mean y: -31.0 %, mean sf: -27.1 %, $\chi^2(3) = 2.5$, $p = 0.48$).

Considering individual sensory descriptors in fresh samples, wort-like was rated highest in stopped fermentation and hybrid samples, with significantly lower intensities in physically dealcoholised beers (mean h: 1.63, mean p: 0.58, mean y: 2.1, mean sf: 2.4, $\chi^2(3) = 16.4$, $p < 0.001$). The same pattern was observed after forced ageing.

The Δ wort-like values indicated the strongest increases for stopped fermentation and physically dealcoholised samples, while a decrease was observed for alternative yeast beers (mean h: 0.0, mean p: 0.1, mean y: -0.5, mean sf: 0.1, $\chi^2(3) = 8.4$, $p = 0.04$).

The descriptor bready showed a comparable tendency, with higher intensities in stopped fermentation samples, although differences were not statistically significant (mean h: 0.4, mean p: 0.6, mean y: 0.6, mean sf: 1.3, $\chi^2(3) = 6.4$, $p = 0.09$).

For honey-like, Δ values revealed higher increases in stopped fermentation and alternative yeast samples compared to hybrid and physically dealcoholised beers (mean h: 0.5, mean p: 0.6, mean y: 1.1, mean sf: 1.3, $\chi^2(3) = 5.6$, $p = 0.13$). The descriptor sweetish showed a comparable behaviour.

Cardboard-like flavour tended to increase more in biologically produced beers, while hybrid samples exhibited the lowest increase (mean h: 0.6, mean p: 0.7, mean y: 1.1, mean sf: 1.3, $\chi^2(3) = 2.6$, $p = 0.45$).

Sweetness was rated significantly higher in stopped fermentation and hybrid beers compared to physically dealcoholised samples, both in fresh (mean h: 2.6, mean p: 1.4, mean y: 3.1, mean sf: 2.9, $\chi^2(3) = 14.7$, $p < 0.01$) and forced aged samples (mean h: 2.7, mean p: 1.5, mean y: 2.6, mean sf: 2.6, $\chi^2(3) = 11.5$, $p < 0.01$).

Sourness tended to be higher in physically dealcoholised samples and lowest in stopped fermentation and alternative yeast beers (mean h: 2.3, mean p: 2.6, mean y: 1.7, mean sf: 1.9, $p = 0.15$). Sourness increased during ageing, while maintaining the same relative group differences (mean h: 2.6, mean p: 3.1, mean y: 2.2, mean sf: 2.3, $p = 0.08$).

Palate fullness was significantly increased in alternative yeast samples and lowest in physically dealcoholised beers in fresh samples (mean h: 2.8, mean p: 2.2, mean y: 3.2, mean sf: 2.9, $\chi^2(3) = 8.9$, $p =$

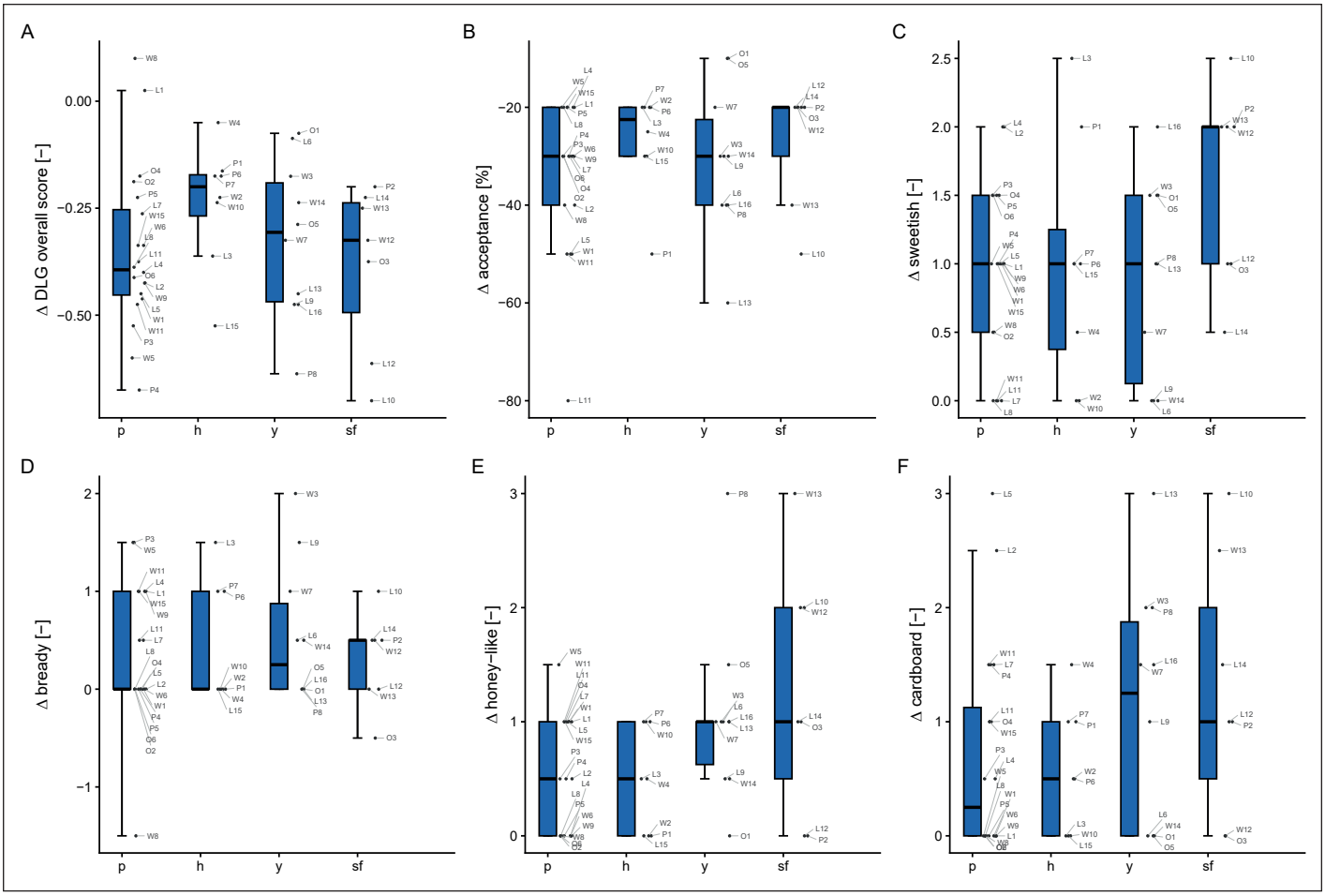

Fig. 2 **Boxplots of chosen sensory attributes and descriptors separated by production principle with a focus on changes during ageing; Δ = difference between forced and fresh samples; p = physical dealcoholisation, h = hybrid production, sf = stopped fermentation, y = alternative yeast**

0.03), with a similar pattern after forced ageing (mean h: 2.6, mean p: 1.9, mean y: 2.8, mean sf: 2.7, $\chi^2(3) = 10.1$, p = 0.02).

Accordingly, the descriptor watery was rated higher in physically dealcoholised beers compared to the other groups, both in fresh (mean h: 0.8, mean p: 0.9, mean y: 0.3, mean sf: 0.3, $\chi^2(3) = 6.9$, p = 0.08) and forced aged samples (mean h: 1.1, mean p: 1.3, mean y: 0.2, mean sf: 0.6, $\chi^2(3) = 10.2$, p = 0.02).

In contrast, physically dealcoholised beers tended to exhibit lower scores for the descriptor slimy in fresh samples compared to the other groups (mean h: 1.0, mean p: 0.5, mean y: 1.1, mean sf: 0.9, $\chi^2(3) = 2.7$, p = 0.44).

3.3 Differences between production principles – Ageing behaviour

In fresh beers, distinct differences in aldehyde profiles were already observed, particularly for Strecker aldehydes. For example, 2-methylpropanal showed elevated concentrations in stopped fermentation samples and slightly increased levels in alternative yeast beers, while hybrid and physically dealcoholised samples exhibited lower concentrations. However, these differences were not statistically significant (mean h: 10.0 µg/L, mean p: 12.1 µg/L, mean y: 18.2 µg/L, mean sf: 26.2 µg/L, $\chi^2(3) = 5.6$, p = 0.13). A comparable pattern was observed for 3-methylbutanal.

Furfural followed a similar trend, with the lowest concentrations detected in physically dealcoholised samples, although differences between groups did not reach statistical significance (mean h: 71.6 µg/L, mean p: 68.3 µg/L, mean y: 70.2 µg/L, mean sf: 110.8 µg/L, p = 0.05).

For (E)-2-nonenal, concentrations were highest in biologically produced samples and lowest in hybrid beers, although no significant differences were observed (mean h: 0.04 µg/L, mean p: 0.07 µg/L, mean y: 0.12 µg/L, mean sf: 0.10 µg/L, p = 0.14).

After forced ageing, stopped fermentation samples still exhibited the highest concentrations for Strecker aldehydes; however, differences between production principles became less pronounced overall. This is exemplified for 3-methylbutanal (mean h: 16.1 µg/L, mean p: 18.7 µg/L, mean y: 18.6 µg/L, mean sf: 34.2 µg/L, p = 0.01).

Accordingly, the most prominent increases during forced ageing were generally observed in physically dealcoholised beers, particularly for Strecker aldehydes such as 2-methylpropanal (mean Δ h: 6.2 µg/L, mean Δ p: 9.3 µg/L, mean Δ y: 4.1 µg/L, mean Δ sf: 8.2 µg/L, p = 0.24).

Interestingly, in forced aged samples, furfural concentrations no longer differed between production principles (mean h: 152.3 µg/L, mean p: 147.6 µg/L, mean y: 136.7 µg/L, mean sf: 172.9 µg/L, p =

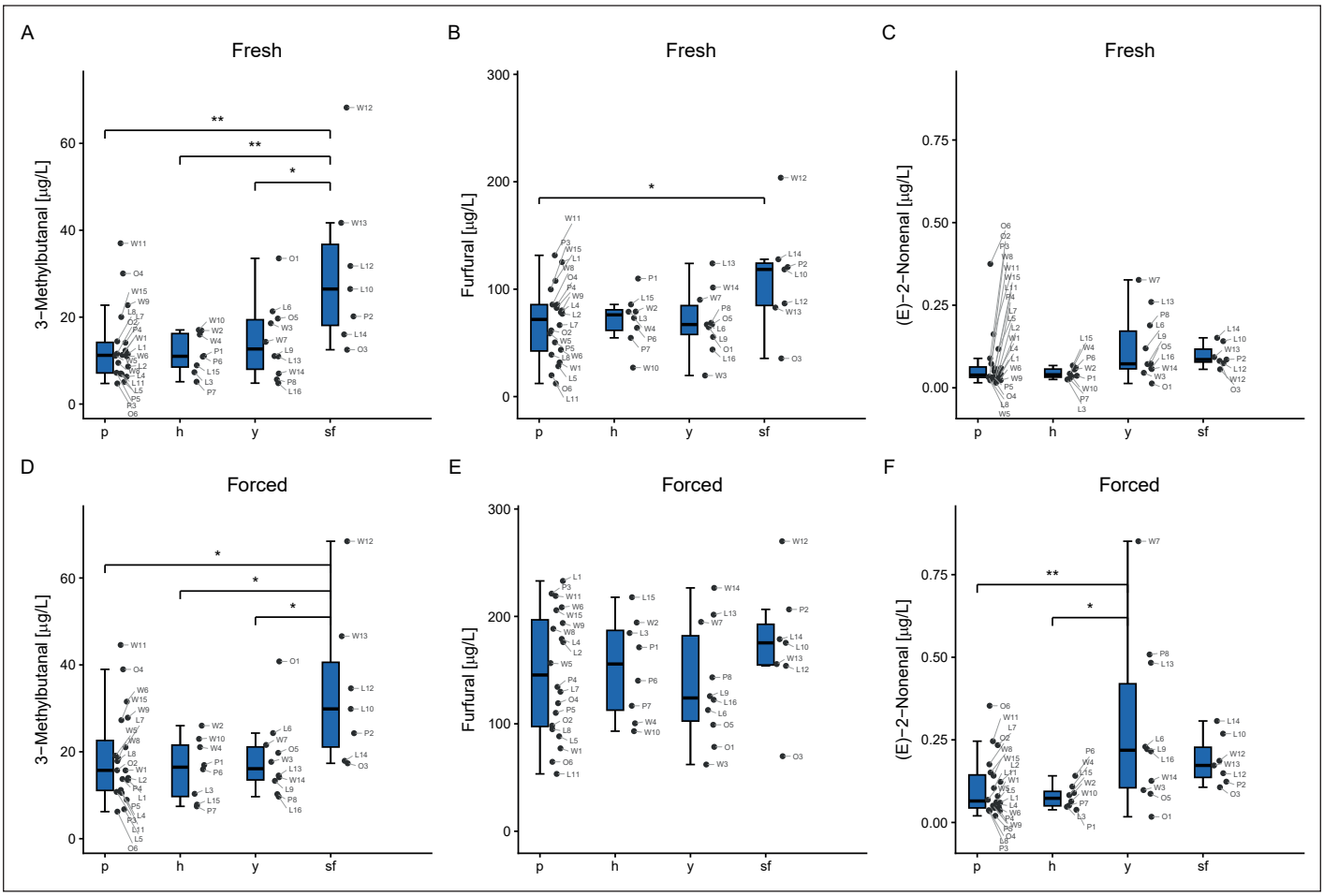

Fig. 3 **Boxplots of chosen aldehydes in fresh and forced samples separated by production principle; p = physical dealcoholisation, h = hybrid production, sf = stopped fermentation, y = alternative yeast**

0.62). In line with this, furfural showed the lowest increase during forced ageing in stopped fermentation samples (mean Δ h: 80.7 µg/L, mean Δ p: 79.3 µg/L, mean Δ y: 66.5 µg/L, mean Δ sf: 62.1 µg/L, p = 0.50).

Among the analysed lipid oxidation aldehydes, only (E)-2-nonenal exhibited significant differences between production groups after ageing, with the highest concentrations observed in alternative yeast and stopped fermentation samples (mean h: 0.08 µg/L, mean p: 0.11 µg/L, mean y: 0.28 µg/L, mean sf: 0.19 µg/L, $p < 0.01$). Additionally, these groups also showed the strongest increases during forced ageing.

3.4 Determination of ageing potential – Chemical release of bound state aldehydes with different reagents

Currently, no universally accepted analytical method exists for the determination of bound aldehydes in beer. Different approaches have been proposed, including direct analysis by LC–MS techniques (25) as well as indirect methods based on chemical release using various reagents and reaction conditions. These range from the assessment of (E)-2-nonenal potential in wort (26) to the release of aldehydes in fresh beer matrices (9, 27). Despite these efforts, the analysis of bound aldehydes remains an unresolved challenge in brewing science.

Therefore, the release of aldehydes was investigated in more detail in the present study. The selection of a suitable reagent for the determination of bound aldehydes in NABs revealed a clear methodological trade-off between analytical efficiency and chemical selectivity (data not shown). Five different reagents were initially evaluated, of which NaOH, acetaldehyde, and 4-vinylpyridine (4-VP) showed the most promising performance. In contrast, HCl and glyoxal did not yield satisfactory results.

Acetaldehyde and glyoxal are typically applied due to their ability to interact with amino groups and thereby shift the equilibrium of imine formation. By competing with bound aldehydes for reaction partners, they destabilise imine structures, leading to the decomposition of Schiff bases and subsequent release of free aldehydes (28).

In a series of preliminary experiments, NaOH consistently resulted in the highest release rates for all investigated aldehydes and exhibited a stable and continuously increasing release profile over time. Although acetaldehyde and 4-VP are established reagents for the selective release of bound aldehydes via competitive binding mechanisms, both compounds showed lower release efficiencies and practical limitations regarding stability, handling, and storage. Due to its robustness, ease of use, and superior analytical response, NaOH was therefore selected as the release reagent for subsequent analyses.

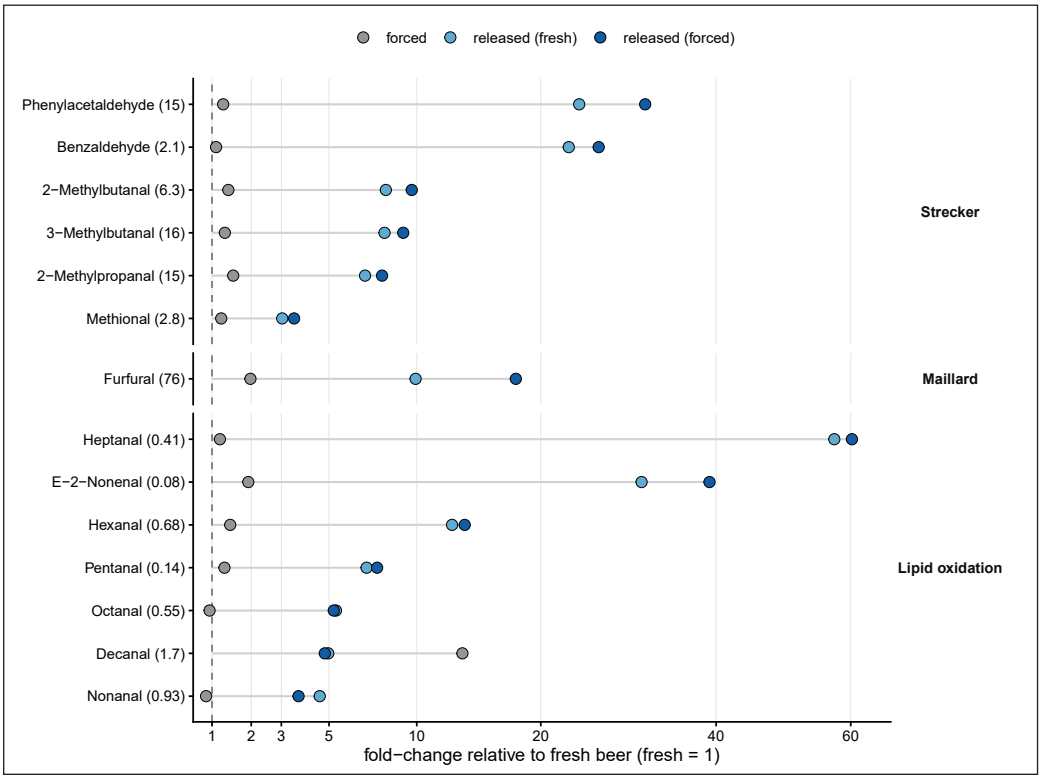

Fig. 4 **Relative changes from fresh using forced ageing and release assays/ageing potential; Values in parentheses represent mean fresh concentration [µg/L]**

However, the use of NaOH introduced methodological limitations as well. The strongly alkaline conditions not only promoted the cleavage of aldehyde binding forms but likely also induced secondary formation reactions. This assumption was supported by observable colour changes in the sample vials during incubation, indicating enhanced Maillard-type reactions and amino acid degradation processes. Literature reports further confirm that alkaline conditions can artificially increase aldehyde concentrations through Strecker degradation and related pathways. Consequently, the concentrations obtained after NaOH treatment cannot be interpreted solely as released bound aldehydes. Instead, they reflect a combined effect of aldehyde release, matrix-dependent reaction mechanisms, and potential *de novo* formation during incubation.

Furthermore, the extent of aldehyde release was strongly dependent on the sample matrix and varied considerably between beer styles and individual compounds. While aldehydes such as methional and nonanal showed little or no apparent release, others, including phenylacetaldehyde, benzaldehyde, and decanal, exhibited substantial increases following NaOH treatment. Compared to literature data obtained using more selective reagents such as 4-VP or acetaldehyde, the NaOH-derived release factors were markedly higher, further emphasizing the broader yet less selective chemical action of alkaline conditions.

3.5 Ageing potential of different production principles

In fresh samples, the release of bound aldehydes (expressed as free aldehydes after alkaline treatment) – or rather: the ageing potential – showed a general trend towards higher values in stopped fermentation beers, particularly for Strecker aldehydes.

An exception was observed for methional, which exhibited the highest concentrations in hybrid samples and the lowest levels in alternative yeast beers (mean h: 13.0 µg/L, mean p: 8.5 µg/L, mean y: 6.1 µg/L, mean sf: 7.6 µg/L, $\chi^2(3) = 4.98$, $p = 0.17$). This behaviour corresponds to the volatility based behaviour observed for 2-phenylethanol, with phenylacetaldehyde showing comparable levels in physically dealcoholised and stopped fermentation samples ($\chi^2(3) = 3.10$, $p = 0.38$).

For furfural, the lowest release of bound fractions was found in hybrid samples, while stopped fermentation beers showed the highest values (mean h: 526 µg/L, mean p: 673 µg/L, mean y: 809 µg/L, mean sf: 1164 µg/L, $\chi^2(3) = 1.57$, $p = 0.67$).

No differences between production principles were observed for (E)-2-nonenal in fresh alkaline-treated samples (mean h: 2.1 µg/L, mean p: 2.5 µg/L, mean y: 2.5 µg/L, mean sf: 2.6 µg/L, $\chi^2(3) = 3.23$, $p = 0.36$).

In forced aged samples, similar trends were observed for all aldehydes; however, no statistically significant differences between production groups were detected.

4 Discussion

The four production principles as grouped in this study were represented by unequal and, in part, small sample numbers limiting the statistical power of the between-group comparisons, particularly for the biologically produced beers.

A further constraint concerns the composition of these groups with respect to beer style. As the dataset was assembled from commercially available products, beer style and production principle were not balanced against one another. Lager, Pilsner, and wheat beers were present in all four groups, so that no single style was fully confounded with a single production principle. The distribution was nevertheless uneven. The physically dealcoholised group spanned the entire range of beer styles, whereas the stopped fermentation and hybrid groups were more strongly weighted toward lager and wheat beers, and several hybrid beer style-production combinations were represented by only one or no sample. Beer style-related and production-related effects can therefore not be fully separated in this dataset. This is of particular relevance for beer style-defining parameters, such as the volatile phenols of wheat beer, where an apparent effect of production principle may in part reflect the style composition of the respective group.

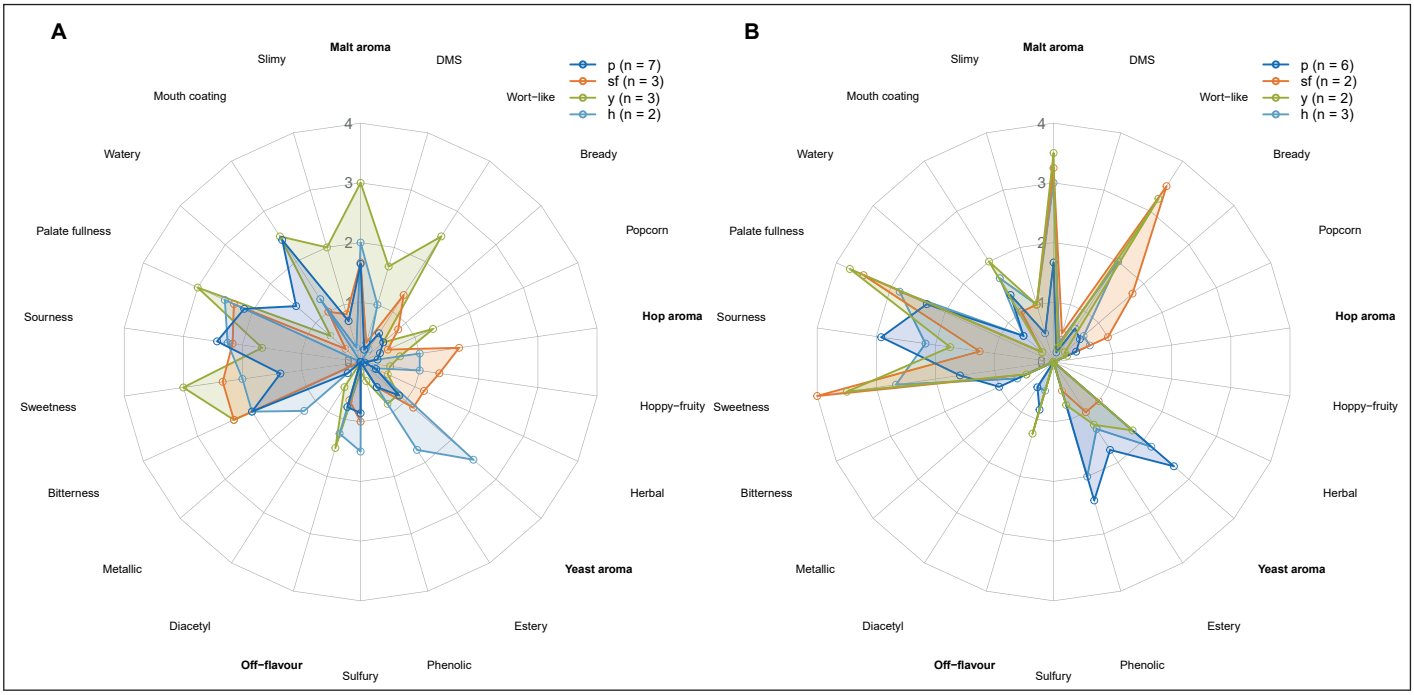

Fig. 5 **Aroma profiles of NABs for different beer styles; A: lager; B: wheat beer; p = physical dealcoholisation, h = hybrid production, sf = stopped fermentation, y = alternative yeast; aroma categories are printed bold**

Given the limited and unequal number of samples per group, together with this partial overlap of style and production principle, the reported differences should be regarded as exploratory rather than confirmatory, indicating trends that would require confirmation in a balanced, style-controlled design.

4.1 Aroma profiles of NABs

The aroma profiles of the fresh beers varied drastically by beer style and production principle. In Figure 5, the sensory profiles 2 main beer styles (lager and wheat beer) are each represented in an individual radar plot.

Notably, for several descriptors the sensory variation introduced by the production principle within a beer style was greater than the difference between the two beer styles. For chosen descriptors, the spread introduced by the production principle exceeded the difference across beer styles. This was most pronounced for wort-like, where the production principle spanned up to 2.8 scale points within a single style (e.g. p = 0.7 vs. sf = 3.5 in wheat beers), compared with only ~0.7 points between lager and wheat beer overall. Comparable patterns were observed for sweetness and malt aroma, with physically dealcoholised beers consistently scoring lowest and the biologically produced variants (stopped fermentation and alternative yeast) highest, irrespective of beer style.

Two attributes showed the opposite pattern. Bitterness intensity was clearly beer style driven as expected. Lager samples were rated as substantially more bitter than wheat beers (mean 2.1 vs. 0.8), whereas the production principle had almost no effect within either style (range ≤ 0.5 scale points). Likewise, phenolic behaved as a classic style marker, being essentially absent in lagers (mean 0.1) but pronounced in wheat beers (mean 1.8), consistent with the yeast-derived 4-vinylguaiacol typical of wheat beer. Notably, among the wheat beers the phenolic intensity still varied considerably with production principle (from 0.5 in alternative yeast and 0.8 in stopped-fermentation beers up to 2.0–2.4 in the physically produced samples), indicating that even for a beer style-defining attribute the production route modulates the outcome. These cases confirm that the dominance of production over beer style is attribute-specific rather than universal, and that both factors need to be considered jointly when interpreting the sensory profiles. This suggests that choices regarding production can outweigh the beer style-related distinction resulting in the final sensory profile.

These findings are consistent with the literature and can be explained by the formation, degradation and volatility (losses, retention) of the respective aroma compounds (16, 29). Kienitz et al. observed the same differences in two beer styles – lager and wheat beer – in regard to the intensities of malt-, hop- and yeast-related aromas (29).

In regard to the wort-like off-flavour, in both beer styles, the alternative yeast group stood out indicating a low reduction of aldehydes during fermentation. This highlights the potential of development of alternative yeasts as other authors pointed out recently (30).

4.2 Sensory profiles during ageing

In the fresh state, the production principles did not differ in the intensity of the ageing-related descriptors, and the overall DLG ratings were statistically not different. In contrast, upon forced ageing, the sensory quality (DLG-overall) declined only moderately and without significant differences between groups (Δ −0.24 to −0.38), whereas the hedonic acceptance decreased more markedly in every group (Δ −26.9 to −33.5 %). In comparison with the literature, the DLG-overall score of NABs was of a similar to that reported for pale lager (mean ≈ −0.26; range +0.23 to −1.0) and German wheat beer (≈ −0.4 under forced ageing). However, the acceptance rat-

ings, were distinctly larger than the −20.5 % reported for wheat beer under the same forced ageing regime (21, 23). A comparable sensory deterioration therefore translated into a greater hedonic decline in the NABs. This can be explained by the sensory qualities of NABs, which often lack masking capacity in comparison to their alcoholic counterparts. A comparable heightened ageing sensitivity of commercial NABs relative to their lager counterparts was reported by Bauwens et al. (20).

Lafontaine et al. (1) similarly found that honey-like aroma in NABs – positively correlated with furfural, methional, and (E)-2-nonenal – negatively impacted consumer acceptance, even in fresh products, highlighting the particular sensitivity of NAB consumers to ageing-associated volatiles. Beyond that, the same authors further reported that malty, skunky, and stale notes, together with thin and bitter taste, were the attributes most strongly associated with consumer dissatisfaction, and these were positively correlated with (E)-2-nonenal, 3-methylbutanal, ethyl nicotinate, and phenylacetaldehyde. Consumer disliking in NABs therefore does not appear to be driven by a single marker compound but rather reflects a broader spectrum of ageing-associated volatiles, several of which overlap with those identified as relevant in the present study.

Regarding the suitability of individual descriptors as ageing descriptors and differentiators between production principles, honey and cardboard showed the strongest increases in the present dataset, whereas bready changed only weakly (≈ 0.5). Honey showed the highest potential to e. g. differentiate between p and sf beers. This pattern differs from that of German wheat beer, where cardboard was found to be largely irrelevant and buttermilk, sherry, sweetish, and sour were the strongest descriptors (23). For pale lager beers, the descriptors partly overlap with the observed honey and sweetish changes (21). These differences indicate that ageing indicators are matrix- and beer style-dependent and cannot be transferred uncritically between beer styles.

The wort-like descriptor followed the fresh aldehyde profile: it was rated highest in the stopped fermentation and hybrid beers and lowest in the physically dealcoholised samples. This is consistent with the established association between wort-like character and unreduced Strecker aldehydes (8).

4.3 Aldehydes during ageing

Across all production principles, the investigated aldehydes increased from fresh to forced aged samples, confirming that the investigated NABs carry a substantial ageing potential realised under thermal load. Notably, the absolute levels of the Strecker aldehydes in the fresh NABs were of the same order of magnitude as those reported for conventional beers. This indicates that, contrary to the common assumption that NABs are inherently rich in Strecker aldehydes (22), the biologically and physically produced NABs studied here enter storage at aldehyde levels broadly comparable to fully fermented beers. Rather than the group means, the between-group variance was the more informative parameter. The stopped fermentation beers consistently showed higher concentrations approximately twofold the levels determined in the physically dealcoholised (p) beers. This is the expected consequence of a stopped fermentation, in which the yeast-mediated reduction of wort aldehydes is interrupted before completion, leaving both elevated free aldehydes and an intact bound state pool (8, 13).

This directly points to the reductive capacity of the yeast as a key impact factor, and its magnitude is well documented by the recent comparative work of Myncke et al. (12). In their study of nine commercial maltose- and maltotriose-negative yeasts, the wort aldehyde load (sum ≈ 383 µg/L) was reduced to 19–42 µg/L in the finished beers, corresponding to reduction rates of 87–95 %. Importantly, this reduction was strongly strain-dependent. The maltose-negative strains achieved 91–95 %, clearly exceeding common literature values of ~70 % (8). Thus, the reductive capacity of alternative yeasts is evidently sufficient to reduce wort aldehydes to lager-like levels when fermentation is allowed to proceed as described in this study. Further, because this capacity varies markedly between strains, strain selection largely influences the residual aldehyde concentrations and ageing potential.

A contrasting pattern emerged for the change in Strecker-aldehyde concentration upon forced ageing. Despite exhibiting the highest fresh Strecker-aldehyde levels, the stopped fermentation beers showed the smallest rise during forced ageing (median Δ 2-methylpropanal: 3.4 µg/L in sf vs. 8.2 µg/L in p; phenylacetaldehyde: 2.3 vs. 4.7 µg/L), whereas the physically dealcoholised (p) beers combined low fresh levels with the highest increase. This inverse relationship between the initial concentration and the extent of formation during ageing has also been observed in other studies (31).

Taken together, these findings indicate that mitigating aldehyde-driven ageing in NABs requires two complementary approaches: maximising reductive aldehyde removal through targeted yeast-strain selection and, where possible, more complete fermentation to lower the Strecker-aldehyde and bound state pool and strict control of thermal load, oxygen exposure, and storage temperature to limit the *de novo* formation of furfural and lipid oxidation markers (12).

4.4 Release of aldehydes vs. ageing potential

The release of bound aldehydes using NaOH was evaluated as a proof of concept across all analysed NABs, considering only the mean concentrations per aldehyde irrespective of production principle or beer style. At this aggregated level, alkaline treatment produced a consistent and plausible increase for every aldehyde investigated—with the exception of octanal, nonanal, and decanal—with concentrations rising in the expected order from fresh, forced, released (fresh), to released (forced). This monotonic behaviour across chemically diverse aldehydes indicates that the release captures a genuine, releasable ageing potential rather than a compound-specific artefact, supporting the fundamental viability of estimating ageing potential through chemical release in the investigated matrix. At the same time, the findings show that NaOH provides access to a large fraction of the potentially releasable aldehyde pool, albeit at the expense of increased susceptibility to side reactions. The results obtained in this study should therefore not be interpreted strictly as a quantification of “released bound aldehydes”; rather, the NaOH-induced concentrations are considered to reflect the overall aldehyde-related “ageing potential” of the investigated NABs.

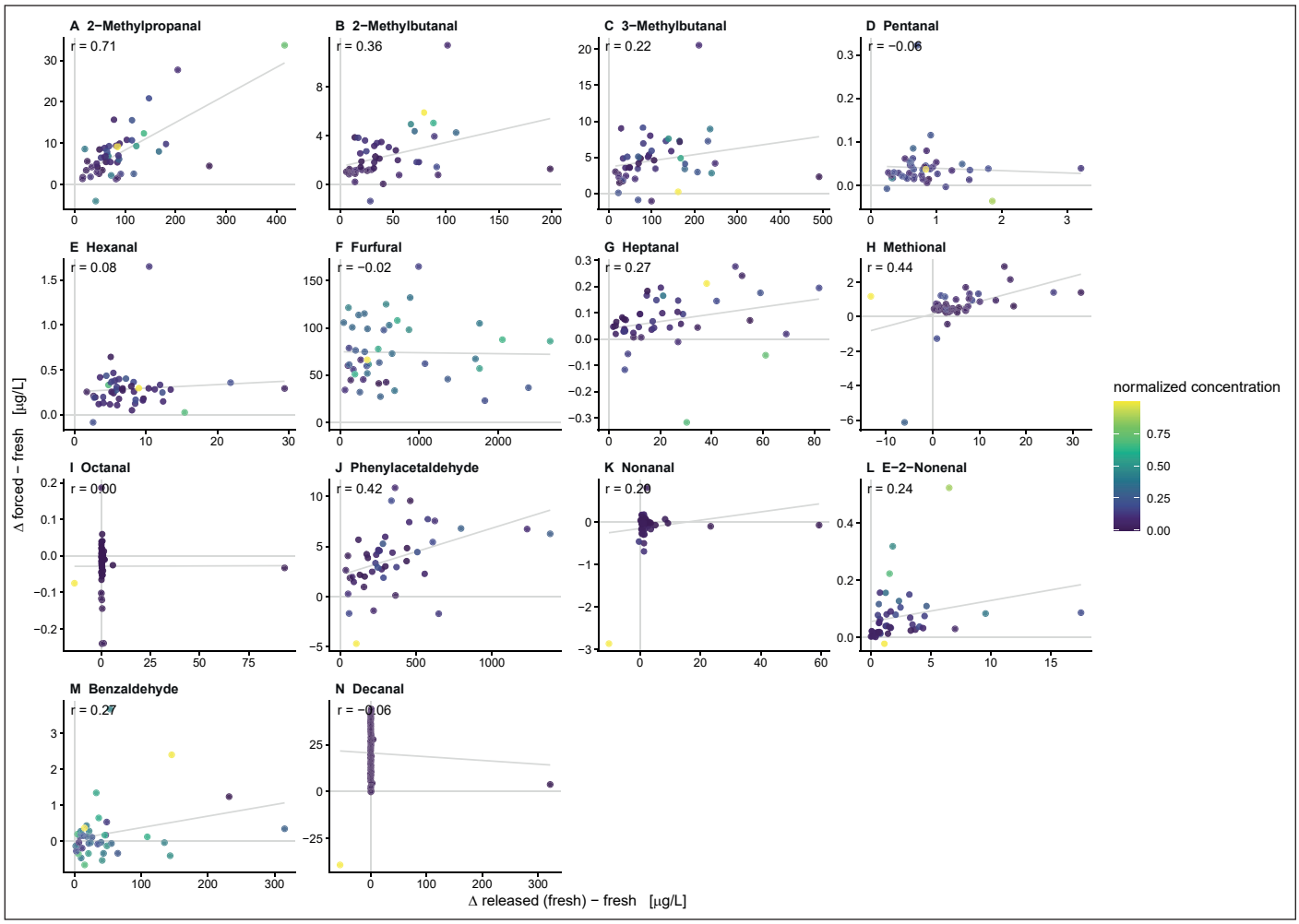

Fig. 6 Scatter plots of chosen released and forced aldehydes for the investigated NABs

At the same time, this proof of concept must be interpreted as a preliminary approach. As outlined above, the strongly alkaline conditions required for efficient release also promote secondary reactions – Strecker degradation, Maillard-type chemistry and related amino acid degradation – so that part of the measured increase reflects *de novo* formation during incubation rather than release from a bound state. Still, it can be assumed that the actual *de novo* is secondary to the release based on the minor observed colour changes (of max. 5 EBC units). Although the magnitude of this contribution appears acceptable for a comparative, potential-oriented approach, it prevents a strict quantitative interpretation of the values as "released bound aldehydes" and represents the main limitation of the current approach. Consequently, while the present data establish the general feasibility of the release concept in NABs, further work – in particular a systematic separation of true release from alkaline-induced formation, and validation against more selective reagents – will be required.

4.5 Forced ageing vs. release of aldehydes

To assess whether the release assay applied to fresh beer can predict aldehyde formation during forced ageing, the forced ageing increment (Δ forced − fresh) was correlated with the release potential of the corresponding fresh sample (Δ released (fresh) − fresh) for each aldehyde individually (Fig. 6). The use of relative increments eliminated the influence of different initial concentrations, while the colour coding of the individual data points reflects the normalised (from 0 to 1) concentration of each aldehyde. It should be noted that forced ageing has its own limitations and does not necessarily predict changes during natural ageing (32).

Compound-specific correlations revealed a clear dependence on aldehyde class. The strongest relationship was observed for the Strecker aldehyde 2-methylpropanal (r = 0.71), whereas methional (r = 0.44) and phenylacetaldehyde (r = 0.42) likewise showed moderate agreement between release potential and forced ageing response. In contrast, aldehydes associated predominantly with lipid oxidation exhibited little or no correspondence between both approaches. Hexanal and octanal showed essentially no correlation (r = 0.08 and 0.00, respectively), while (E)-2-nonenal reached only r = 0.24. These results suggest that the release approach can predict similar changes as forced ageing – at least for chosen aldehydes.

To investigate whether this relationship was also reflected in the overall covariance structure of the dataset, a hierarchical clustering analysis based on the combined release and forced ageing increments was performed (Fig. 7A).

In contrast to the compound-wise correlations shown in Fig. 6, hierarchical clustering separated most variables primarily accord-

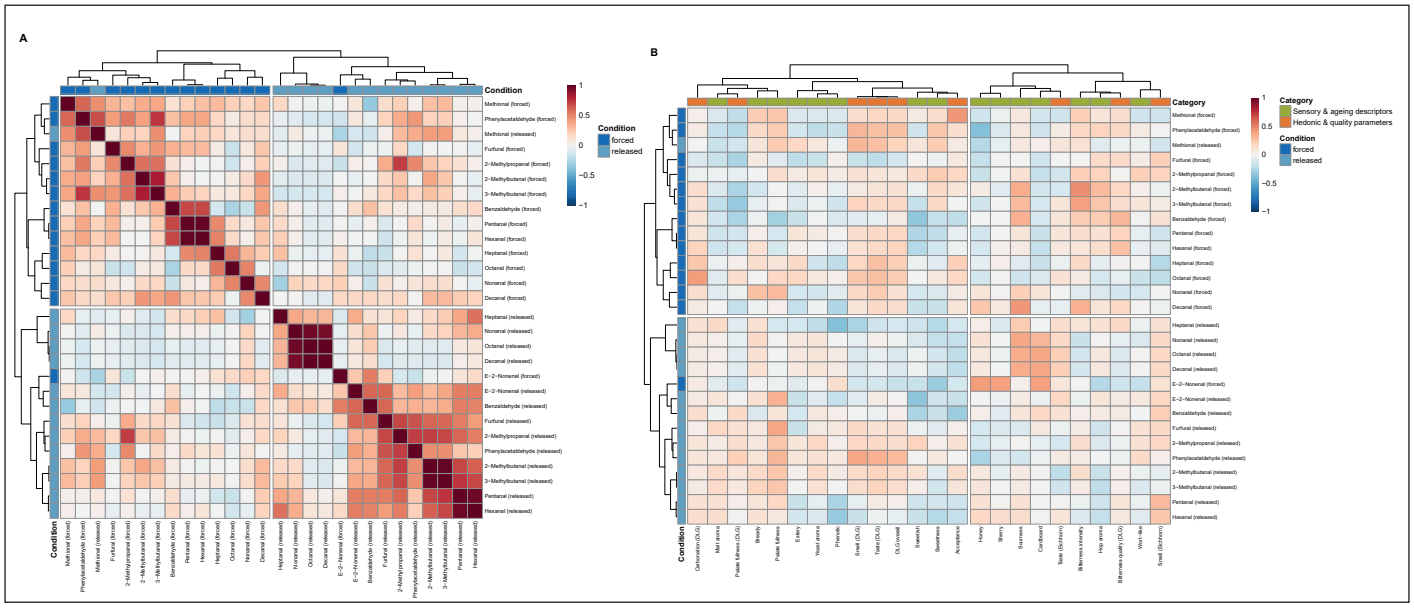

Fig. 7 Pearson correlation matrices of ageing-related aldehyde changes and sensory changes (Δ values) in NABs. (A) Pairwise correlations among 14 aldehydes each (forced ageing and NaOH-induced release); (B) Correlations between 14 aldehydes each (forced ageing and NaOH-induced release) and 24 sensory parameters, grouped into sensory and ageing descriptors and hedonic and quality parameters; colour indicates Pearson r (red: positive, blue: negative; scale −1 to 1); Variables are ordered by hierarchical clustering (Ward's method).

ing to measurement mode rather than aldehyde identity. Forced ageing and NaOH-induced ageing potential formed two major branches, indicating that both approaches generally capture different sources of variation across samples. Consequently, the release approach cannot be regarded as a direct surrogate for forced ageing but should be regarded as a different prediction tool.

Nevertheless, several mechanistically meaningful exceptions were evident. Methional exhibited the strongest agreement between both approaches, with methional (released) clustering directly within the forced ageing branch and adjacent to methional (forced), reflected by a forced–released correlation of r = 0.44 ($p < 0.01$). More broadly, the Strecker aldehydes methional, phenylacetaldehyde, 2-methylpropanal, 2-methylbutanal, and 3-methylbutanal formed a tightly interconnected group and displayed the clearest coupling between release and forced ageing behaviour, with particularly strong pairwise correlations between 2-methylbutanal and 3-methylbutanal (r = 0.82, $p < 0.001$) and between 3-methylbutanal and phenylacetaldehyde (r = 0.73, $p < 0.001$). This pattern is consistent with the presence of releasable bound states, such as imine- and bisulfite-bound forms, which contribute both to aldehyde release in fresh beer and to aldehyde formation during ageing, and thus explains the mechanistically coherent co-clustering of forced and released fractions for this aldehyde class.

By contrast, lipid-derived aldehydes showed strong inter-method associations but little correspondence between release and forced ageing approaches. In particular, nonanal, octanal and decanal formed a highly coherent cluster within the release branch, while pentanal, hexanal, heptanal and (E)-2-nonenal also clustered closely together. However, these compounds exhibited only weak links to their respective forced ageing counterparts. The isolated position of (E)-2-nonenal (forced) further highlights shows that it is not adequately represented by the release assay. Similarly, furfural showed little correspondence between release and forced ageing data, consistent with its *de novo* formation.

The relationship between aldehyde dynamics and sensory changes was further explored in Fig. 7B, which correlates the 28 aldehyde variables with ageing-relevant sensory and quality parameters (DLG and Eichhorn). Overall, correlations were moderate in magnitude, reflecting the inherent complexity of sensory perception in beer matrix. The strongest associations were observed for (E)-2-nonenal (forced), which positively correlated with the ageing descriptors honey (r = 0.40, $p < 0.01$), sherry (r = 0.40, $p < 0.01$), and cardboard (r = 0.40, $p < 0.01$). In contrast, phenylacetaldehyde (forced) was negatively associated with honey perception (r = −0.40, $p < 0.01$), suggesting that this descriptor is modulated by competing aroma interactions within the matrix. Among quality parameters, 2-methylbutanal (forced) was positively associated with perceived bitterness intensity (r = 0.44, $p < 0.01$) and sourness (r = 0.35, $p < 0.05$), while methional (forced) showed a positive correlation with acceptance (r = 0.44, $p < 0.01$), a counterintuitive finding that may reflect its co-occurrence with quality-associated compounds. Released aldehydes showed generally weaker and less consistent sensory associations than their forced counterparts.

Taken together, Figs. 6, 7A, and 7B provide complementary evidence that the predictive value of the release assay in the current state is highly compound-dependent. While the assay is a useful indicator of ageing behaviour for Strecker aldehydes — particularly 2-methylpropanal and methional — it under-represents certain aldehydes. The release assay should therefore be regarded as a selective predictor of bound state-driven ageing pathways rather than a general surrogate for forced ageing. From a sensory perspective, in this study, changes during forced ageing proved to be slightly more informative of sensory change.

5 Conclusion

This exploratory study showed that the aroma profiles and ageing behaviour of commercial NABs is often governed more by the underlying production principle than by beer style alone and revealed differences between the principles. Although ageing generally raised aldehyde concentrations, its extent and composition differed markedly between production principle so that ageing instability in NABs requires a differentiated, production-specific assessment rather than a generalised, beer style-based one.

In practice, brewers can remedy production-related disadvantages by other technological means, such as adjusted raw material selection and recipe adjustment as demonstrated by Myncke et al. (33).

Methodologically, the alkaline release assay agreed with forced ageing for several Strecker aldehydes but diverged for furfural and lipid oxidation aldehydes, following largely different covariance patterns. It is therefore not a surrogate for forced ageing – which is itself only an accelerated model with its own limitations – but a complementary measure that, with further validation, may develop into a rapid tool for estimating NAB flavour instability. Its transferability to natural storage remains to be demonstrated. Future work should combine controlled brewing and storage trials with methods addressing the underlying radical chemistry directly and inherent ageing potential.

In parallel, blending of production methods emerged as a practical lever for reduced instability, consistent with the more stable ageing of the hybrid beers. Ultimately, safeguarding NAB flavour instability is both a scientific and a commercial imperative. As the segment grows, sustained consumer acceptance depends on a consistent sensory profile throughout shelf life. A perceptible quality loss during storage risks undermining the very expectation driving this expansion. A deeper mechanistic understanding, supported by validated analytical methods, is therefore essential to keep pace with rising production without compromising quality.

Declarations

Conflict of Interest

The authors declare no conflicts of interest.

Credit authorship contribution statement

Florian Lehnhardt: conceptualisation, methodology, formal analysis, visualisation, writing – original draft; Tobias Kössel: methodology, investigation, formal analysis; Sarina Lindtner: methodology, investigation, writing – review & editing; Fabian Schumacher: methodology, investigation, writing – review & editing; Luis Raihofer: conceptualisation, writing – review & editing; Martina Gastl: methodology, writing – review & editing.

Use of AI

AI-assisted tools were used to refine language, including grammar and readability, of the text written by the authors. The scientific content, data analysis, and conclusions are solely the responsibility of the authors.

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Supplementary material

Code	Beer style	Production principle	Production method	Original gravity	Alcohol content	Apparent extract	Real extract	Apparent attenuation	Real attenuation	ph value
				[v%]	[v%]	[v%]	[v%]	[%]	[%]	[-]
L1	Helles	p	Thermal	4,41	0,01	4,39	4,39	0,6	0,5	4,44
L2	Helles	p	Thermal	4,49	0,17	4,15	4,21	7,6	6	4,56
L3	Helles	h	Membrane	6,98	0,37	6,25	6,39	10,5	8,3	4,16
L4	Helles	p	Thermal	4,71	0,35	4,01	4,15	14,9	11,8	4,25
L5	Helles	p	Thermal	4,42	0,04	4,34	4,36	1,8	1,4	4,41
L6	Helles	y	Special yeast	7,28	0,34	6,59	6,72	9,5	7,5	4,5
L7	Helles	p	Thermal	5,92	0,49	4,94	5,13	16,5	13	4,57
L8	Helles	p	Thermal	4,95	0,45	4,04	4,22	18,4	14,6	4,45
L9	Helles	y	Special yeast	6,42	0,36	5,7	5,84	11,2	8,8	4,6
L10	Helles	sf	Arrested fermentation	5,95	0,36	5,22	5,36	12,3	9,7	4,76
L11	Helles	p	Thermal							
L12	Helles	sf	Arrested fermentation	6,31	0,4	5,5	5,66	12,8	10	4,46
L13	Helles	y	Special yeast	5,93	0,28	5,35	5,47	9,7	7,6	4,87
L14	Helles	sf	Arrested fermentation	6,29	0,37	5,54	5,69	11,9	9,4	4,6
L15	Helles	h	Special yeast / arrested fermentation / thermal	6,83	0,44	5,93	6,11	13,1	10,3	4,14
L16	Naturally cloudy	y	Special yeast	5,57	0,34	4,89	5,02	12,2	9,6	4,78
O1	Altbier	y	Special yeast	6,39	0,21	5,97	6,06	6,5	5,1	4,68
O2	Kölsch	p	Thermal	3,82	0,01	3,8	3,81	0,6	0,4	4,67
O3	Kölsch	sf	Arrested fermentation	7,27	0,29	6,7	6,81	7,9	6,2	4,36
O4	Bock	p	Thermal	4,71	0,04	4,64	4,65	1,5	1,2	4,77
O5	IPA	y	Special yeast	8,45	0,4	7,64	7,8	9,6	7,4	3,98
O6	Radler	p	Thermal	4,41	0,04	4,33	4,34	1,8	1,4	4,01
P1	Pils	h	Special yeast / thermal	5,84	0,45	4,94	5,11	15,5	12,2	4,56
P2	Pils	sf	Arrested fermentation	6,08	0,01	6,05	6,06	0,4	0,3	4,63
P3	Pils	p	Thermal	4,19	0,34	3,5	3,64	16,4	13	4,46
P4	Pils	p	Thermal	5,2	0,03	5,15	5,16	1	0,8	4,48
P5	Pils	p	Thermal	4,85	0,49	3,87	4,06	20,4	16,1	4,48
P6	Pils	h	Membrane	8,22	0,05	8,11	8,14	1,3	1	4,27
P7	Pils	h	Arrested fermentation / thermal	3,68	0,02	3,65	3,66	0,9	0,7	4,35
P8	Pils	y	Special yeast	5,2	0,26	4,67	4,78	10,2	8,1	4,91
W1	Wheat beer	p	Thermal	5,09	0,32	4,44	4,57	12,7	10	4,42
W2	Wheat beer	h	Special yeast / thermal	7,44	0,42	6,59	6,76	11,4	8,9	4,36
W3	Wheat beer	y	Special yeast	8,02	0,44	7,13	7,31	11	8,6	4,53
W4	Wheat beer	h	Special yeast / arrested fermentation	8,13	0,32	7,49	7,61	8	6,2	4,47
W5	Wheat beer	p	Thermal	5,26	0,38	4,49	4,64	14,6	11,5	4,42

Code	Beer style	Production principle	Production method	Original gravity	Alcohol content	Apparent extract	Real extract	Apparent attenuation	Real attenuation	pH value
W6	Dark wheat beer	p	Thermal	5,68	0,35	4,97	5,11	12,5	9,8	4,19
W7	Dark wheat beer	y	Special yeast	6,44	0,39	5,65	5,81	12,3	9,6	4,35
W8	Wheat beer	p	Thermal	6,42	0,41	5,59	5,75	13	10,2	4,33
W9	Wheat beer	p	Thermal	6,4	0,42	5,55	5,72	13,2	10,4	4,2
W10	Wheat beer	h	Arrested fermentation / thermal	6,22	0,29	5,63	5,75	9,5	7,5	4,23
W11	Wheat beer	p	Thermal	4,24	0,3	3,63	3,75	14,5	11,5	4,29
W12	Wheat beer	sf	Arrested fermentation	8,72	0,01	8,71	8,71	0,1	0,1	5,1
W13	Wheat beer	sf	Arrested fermentation	7,42	0,37	6,67	6,82	10,1	7,9	4,52
W14	Wheat beer	y	Special yeast	7,18	0,44	6,29	6,47	12,4	9,7	4,12
W15	Wheat beer	p	Cold contact	6,17	0,45	5,26	5,44	14,8	11,6	4,39