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Technological strategies for controlling aldehyde formation in beer: a review of brewing-related flavour instability

Flavour stability is a critical quality parameter in brewing, with major implications for shelf-life, consumer satisfaction and global beer distribution. In particular lager beers are prone to flavour deterioration due to their delicate aroma profile. Essential to this deterioration is the accumulation of volatile aldehydes, which are primarily responsible for the stale flavour perceived in aged beer. These compounds originate from multiple chemical pathways, including Maillard reactions, Strecker degradation and oxidation of amino acids, humulones and lipids, all of which are influenced by raw material composition and brewing conditions. This review presents a state-of-the-art overview of aldehyde-driven flavour instability in beer, highlighting the formation mechanisms and, in particular, the impact of brewing operations across the production chain. Critical control points are examined from malt modification, mashing temperature, wort boiling and yeast metabolism, through to downstream processing and packaging. Emphasis is given to the role of heat, oxygen and transition metal ions, alongside yeast activity and sulphite dynamics. Innovative strategies such as the removal of pro-oxidative metal ions, use of antioxidant-rich ingredients are discussed. Additionally, the review outlines advances in packaging technologies aimed at minimising oxygen ingress and light exposure. This review provides an up-to-date synthesis of brewing operations that affect flavour stability, offering a practical framework for mitigating aldehyde-driven staling throughout the beer production chain.

Descriptors: staling aldehydes, flavour instability, brewing, shelf-life, review

1 Introduction

Beer is one of the world's oldest fermented beverages, with origins dating back to ancient Mesopotamia and Egypt [1, 2, 3, 4]. Over the centuries, brewing has evolved from a primitive, small-scale activity into a highly industrialised and technologically advanced process. Today, beer is produced globally in a wide range of styles, driven by variations in raw materials, fermentation methods and process design [5]. Although product diversity is high, consistent flavour and sensory quality are essential to fulfilling consumer expectations. The flavour of fresh beer is complex and highly sensitive to physical, chemical, and biological changes throughout its lifecycle, meaning from raw material processing to final consumption.

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A major quality concern in brewing is flavour instability, referring to the gradual deterioration of a beer's sensory profile during storage, which coincides with an increase in volatile aldehydes. Lager beers, which dominate global consumption, are particularly prone to staling due to their relatively subtle flavour characteristics. Over time, reactions such as oxidation, Maillard chemistry, and Strecker degradation lead to the formation of off-flavours – most notably those associated with aldehydes. These aldehyde-driven flavour changes reduce drinkability and shelf-life and are a key reason for product rejection. Although flavour stability has been studied for decades, it remains a complex challenge due to the multitude of influencing factors, including raw material composition, enzymatic activity, metal ions, oxygen ingress, and heat exposure.

Recent advances in brewing science have deepened our understanding of flavour deterioration mechanisms and introduced new strategies to mitigate these effects. Improvements in analytical tools, yeast biotechnology, antioxidant applications, and process control have all contributed to updated efforts to extend flavour stability. This review presents the current state of knowledge regarding the formation and fate of staling aldehydes, focusing on their relationship with brewing operations. Special emphasis is placed on recent findings that highlight emerging interventions and technologies aimed at controlling flavour instability. By examining the biochemical, technological, and sensory dimensions of this issue, the paper aims to provide an updated reference point for researchers and practitioners interested in maintaining beer quality throughout its shelf-life.

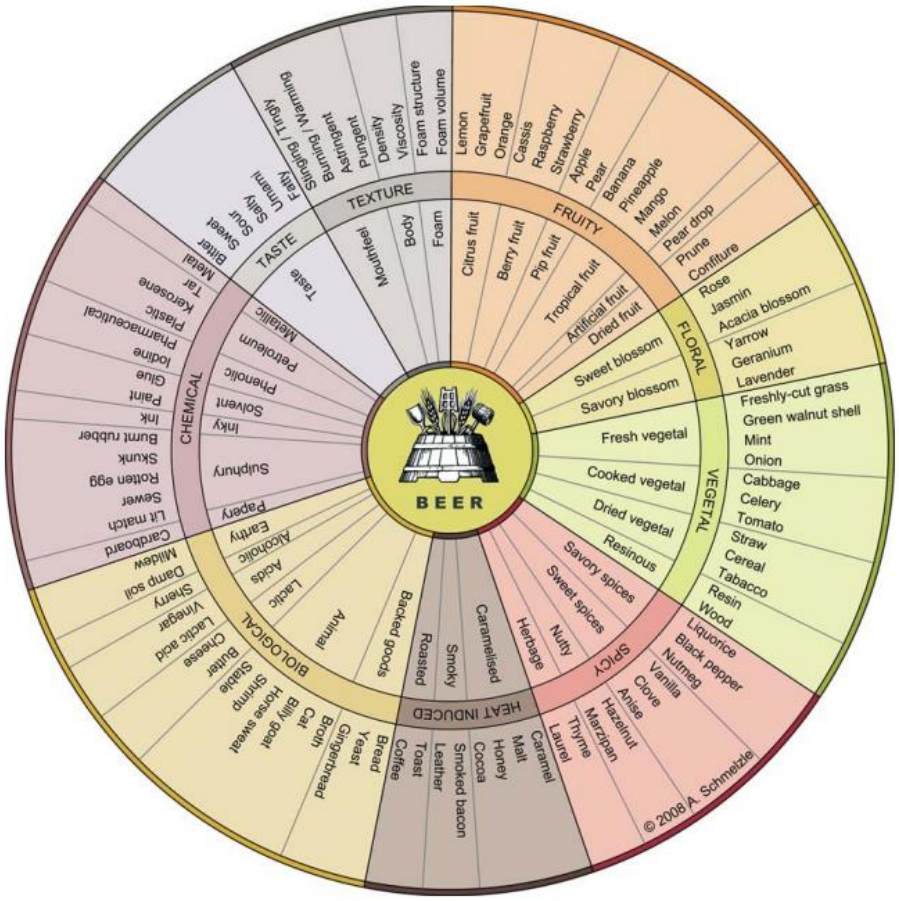


Fig. 1 **Beer flavour wheel, covering the list of flavour attributes for the description of sensory perceptions in beer [13]**

2 Beer Flavour Stability and Staling Aldehydes

2.1 The Flavour of Beer and its Stability

Flavour in beer arises from the integrated perception of taste, odour, mouthfeel and retronasal olfaction [6]. Taste sensations – such as sweet, sour, salty, bitter, and umami – are detected on the tongue, while odour and aroma are mediated by the olfactory system through both orthonasal (odour sniffing) and retronasal (aroma perception during swallowing) pathways. Mouthfeel encompasses physical sensations like carbonation, astringency, or alcohol warmth. Beer flavour is not determined by individual components alone, but by complex sensory interactions. For instance, Clark et al. [7] showed that CO_2 and ethanol significantly modulate flavour perception by influencing bitterness and sweetness sensitivity in beer. Furthermore, research by Pickering et al. [8] revealed that individuals with different thermal taster statuses (who experience taste sensations in response to temperature changes) perceive bitterness and mouthfeel differently, suggesting that genetic variability influences flavour perception. Thus, beer flavour is best understood as a multisensory phenomenon, where interactions between taste, smell and mouthfeel significantly influence how flavours are experienced [9]. To standardise descriptive language in sensory evaluation, the Beer Flavour Wheel was introduced by Meilgaard et al. [10], offering a structured lexicon that has been refined for quality assurance, product development and academic sensory science [11, 12, 13]. Such tools support both qualitative and quantitative assessments of beer, particularly in tracking the progression of flavour changes over time. The beer flavour wheel was presented in figure 1.

Fresh beer is chemically unstable and continues to evolve post-packaging due to a series of chemical and enzymatic reactions [14]. These changes diminish desirable attributes while introducing off-flavours - a process collectively referred to as flavour staling. Graphical interpretations of flavour changes during beer storage were first presented for ales by Dalgliesh [15] and later extended to pale lagers by Zufall et al. [16], which is presented in figure 2. Initial signs include the fading of sulphury and hop-derived freshness, followed by a decay in bitterness quality and the eventual appearance of cardboard-like, sweet, or oxidised notes such as honey, caramel or sherry. These transitions are strongly linked to the accumulation of staling compounds, especially aldehydes. More recently, advanced sensory analytics, including gas chromatography-olfactometry (GC-O), chemometric profiling, and forced ageing tests, have deepened the understanding of these changes and their links to aldehydes and storage conditions such as heat exposure, oxygen ingress, and light exposure [17, 18, 19, 20].

2.2 Staling Aldehydes as Markers for Beer Staling

The association between beer ageing and aldehyde formation has been well documented and continues to serve as a key area of

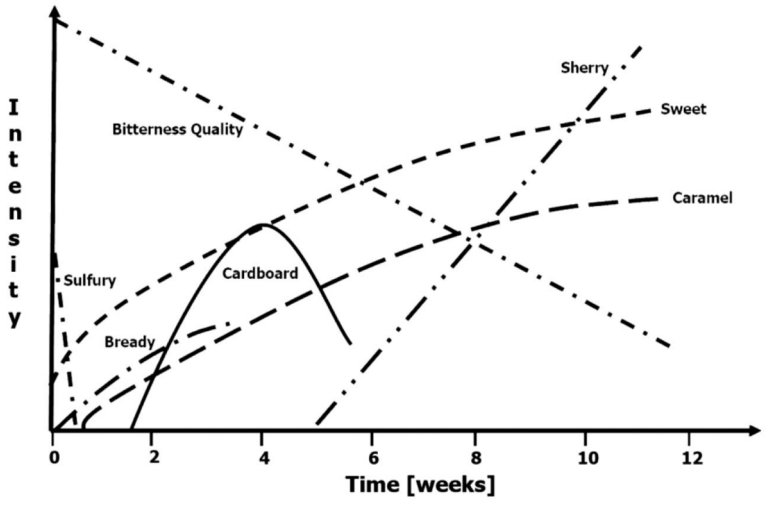
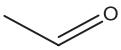
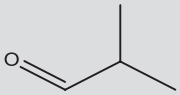
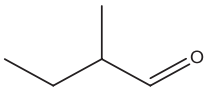
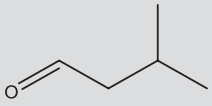
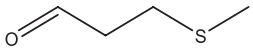
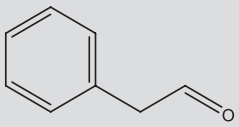
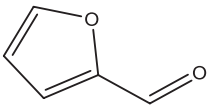
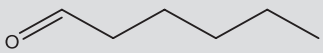
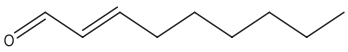


Fig. 2 **Sensory changes in beer during storage [16]**

Table 1 **Molecular, structural and sensory characteristics of aldehydes determined in stale beers. Flavour thresholds represent the minimal concentration at which compound could be perceived when spiked to fresh pale lager beers according to Saison et al. [17], Meilgaard [24] and De Clippeleer et al. [34].**

Aldehyde Type	Compound	Molecular formula	Molecular structure	Molecular mass (g/mol)	Flavour threshold (µg/L)	Flavour descriptor
'	Acetaldehyde	C_2H_4O		44.05	1,114[A] 25,000[B]	green apple, grassy
Strecker Aldehydes	2-Methylpropanal	C_4H_8O		72.11	86[A]	grainy, varnish, fruity
	2-Methylbutanal	$C_5H_{10}O$		86.13	45[A] 1,250[B]	almond, apple-like, malty
	3-Methylbutanal	$C_5H_{10}O$		86.13	56[A]	malty, cherry, almon, chocolate
	Methional	C_4H_8OS		104.17	4.2[A] 250[B]	mashed potato
	Phenylacetaldehyde	C_8H_8O		120.15	105[A] 1,600[B]	hyacinth, flowery, roses
Maillard Reactions Aldehyde	Furfural	$C_5H_4O_2$		96.10	400[C] 15,000[B]	caramel, bready, astringent
Lipid Oxidation Aldehydes	Hexanal	$C_6H_{12}O$		100.16	88[A] 350[B]	bitter, winey
	trans-2-Nonenal	$C_9H_{16}O$		140.23	0.03[A] 0.11[B]	cardboard, papery, cucumber

investigation in understanding beer flavour deterioration. Freshly packaged beers generally contain aldehydes at low or even undetectable levels [21, 22, 23, 24], but these compounds accumulate during storage and contribute to off-flavours such as cardboard, papery, or cooked vegetable notes [14, 17]. One of the earliest studies in this area was conducted by Hashimoto [25], who reported a correlation between increased aldehyde concentrations and the perception of staleness in stored beers. This relationship was further confirmed by experiments involving the addition of carbonyl scavengers, such as hydroxylamine, which led to a partial but immediate reduction in staleness perception [26]. Subsequent research confirmed similar results with other scavengers like 2,4-dinitrophenylhydrazine and semicarbazide [27], underscoring the sensory significance of volatile aldehydes.

In general, staling aldehydes are characterised by relatively small molecular masses and high volatility. A unique nature of staling aldehydes is their low flavour threshold value [17, 28]. Some are even at levels below µg/L. Table 1 lists the most relevant aldehydes and their corresponding flavour thresholds. At first, *trans*-2-nonenal, a lipid oxidation aldehyde, has been repeatedly suggested as the most relevant aldehyde in beer staling, which was attributed to the increase in its concentration during beer storage to concentrations above its extremely low flavour threshold of 0.03 µg/L [17]. With time it became apparent, that *trans*-2-nonenal is not the sole contributor to beer staleness and other volatile aldehydes, particularly Strecker and Maillard reactions aldehydes, are also important [17, 18, 23, 29]. Moreover, volatile aldehydes 2-methylpropanal and furfural have been suggested as good flavour instability markers in pale lager beers [17, 18, 23, 30, 31, 32]. Acetaldehyde ought to be considered differently, due to its importance as an intermediate in ethanol and acetate formation [33]. It may be present in beer in concentrations much higher than the longer chained aldehydes (10 – 20 mg/L) with an unpleasant grassy, green apple flavour descriptor [28].

Beyond their sensory impact, aldehydes are increasingly used as analytical markers for flavour stability. Their quantification serves both as a quality control measure and as an indicator of oxidative or thermal stress experienced by the beer. Modern analytical techniques, including gas chromatography with olfactometry (GC-O), solid-phase microextraction (SPME), and high-performance liquid chromatography (HPLC), allow for precise tracking of aldehyde levels over time. Furthermore, their presence and dynamics during storage are influenced by a wide range of factors, from malt com-

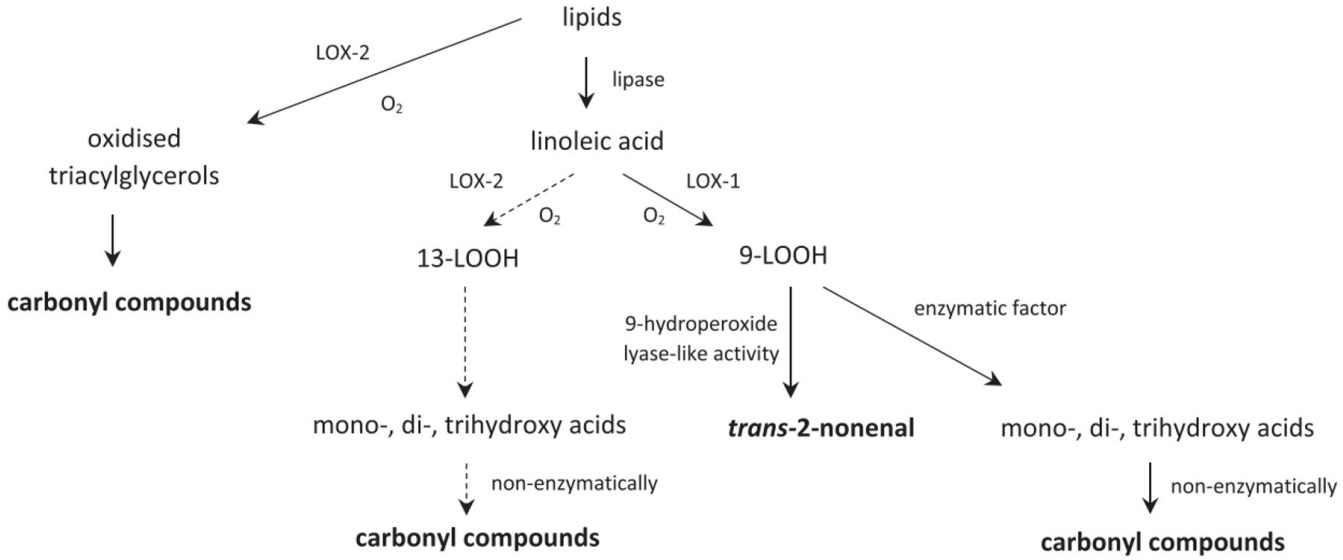


Fig. 3 An overview of enzymatic oxidation leading to the formation of hexanal and *trans*-2-nonenal, based on Baert et al [29] and Vanderhaegen et al. [14] The continuous lines refer to reactions at a high rates, whereas the dashed lines show pathways that proceed at slower rates

position and mash conditions to oxygen ingress during packaging. As such, staling aldehydes serve not only as indicators of flavour degradation but also as tracers for understanding the chemical and physical pathways that lead to it.

3 Chemical Pathways Behind Aldehyde Formation

Baert et al. [29] have made a systematic review of the potential mechanisms behind aldehyde formation. Staling aldehydes may result from two general paths: *de novo* formation and the release from the bound-state adduct forms. *De novo* formation largely refers to oxidation of unsaturated fatty acids, Maillard reactions and Strecker degradation. Strecker degradation as such can be sub-classified under Maillard reactions, which includes reactions of α-dicarbonyls, α-unsaturated carbonyls and Amadori compounds with amino acids. Formation of Strecker aldehydes have been also reported as a result of direct oxidative degradation of amino acids. On the other hand, aldehydes have been suggested to be also present in a non-volatile adduct forms (e.g. adducts with bisulphites or cysteine), which, over time can split up releasing the free aldehydes.

3.1 Unsaturated fatty acid oxidation

The oxidative degradation of unsaturated fatty acids is one of the principal sources of staling aldehydes in beer, particularly *trans*-2-nonenal and hexanal, which are associated with cardboard-like and grassy off-flavours. These compounds arise through three main mechanisms: enzymatic oxidation, spontaneous autoxidation, and photo-oxidation.

In brewing, the most abundant unsaturated fatty acids derived from malt are linoleic (C18:2) and linolenic (C18:3) acids, accounting for roughly 60 and 10 % of total malt lipids, respectively [35]. Both contain the (Z,Z)-1,4-pentadiene structure, which makes them particularly reactive to oxidation. The oxidation rate correlates with the number of double bonds: linolenic acid oxidises approximately three to four times faster than linoleic acid, which in turn oxidises significantly faster than oleic acid (C18:1) [36, 37].

During malting and mashing, these fatty acids are released from triacylglycerol structures by lipases located in the malt acrospire. These enzymes operate optimally near pH 6.8 and remain partially active during mashing. Once released, the fatty acids can undergo enzymatic oxidation via lipoxygenase (LOX) enzymes. Two LOX isoenzymes, LOX-1 and LOX-2, are found in barley [38, 39]. Both target the pentadiene structure and oxidise linoleic acid to specific hydroperoxides: LOX-1 forms 9-hydroperoxyoctadecadienoic acid (9-LOOH), while LOX-2 produces 13-LOOH. These intermediates can degrade into staling aldehydes like *trans*-2-nonenal and hexanal. LOX activity is highest during barley germination but partially survives into the final malt, especially for the more heat-stable LOX-1. Activity peaks at pH 6.5, but LOX-1 retains about 50 % activity at mash pH (~ 5.0), while LOX-2 becomes inactive [40]. Although a portion of LOX activity is lost during kilning, its residual presence in the mash contributes significantly to early aldehyde formation [41, 42, 43]. An overview of enzymatic oxidation mechanisms leading to carbonyl compound formation was presented in figure 3.

In parallel to enzymatic oxidation, unsaturated fatty acids are also prone to spontaneous autoxidation, particularly under heat, oxygen, and the presence of metal catalysts. This oxidation process is initiated by reactive oxygen species and sustained through chain reactions, ultimately leading to the breakdown of fatty acids and the resulting degradation products include volatile aldehydes [14, 29, 44, 45]. Notably, autoxidation can also involve secondary reactions, such as the further oxidation of *trans*-2-nonenal to hexanal [46], illustrating the dynamic nature of aldehyde evolution over time. The rate of autoxidation is enhanced by higher temperatures, elevated oxygen levels, and the presence of pro-oxidant metal ions [47, 48]. Although, non-enzymatic oxidation of unsaturated fatty acids, considered secondary to enzymatic pathways [49], may become increasingly relevant under specific mashing conditions such as elevated oxygen levels, the presence of transition metals, or when LOX enzymes are inactivated by low pH or high temperature

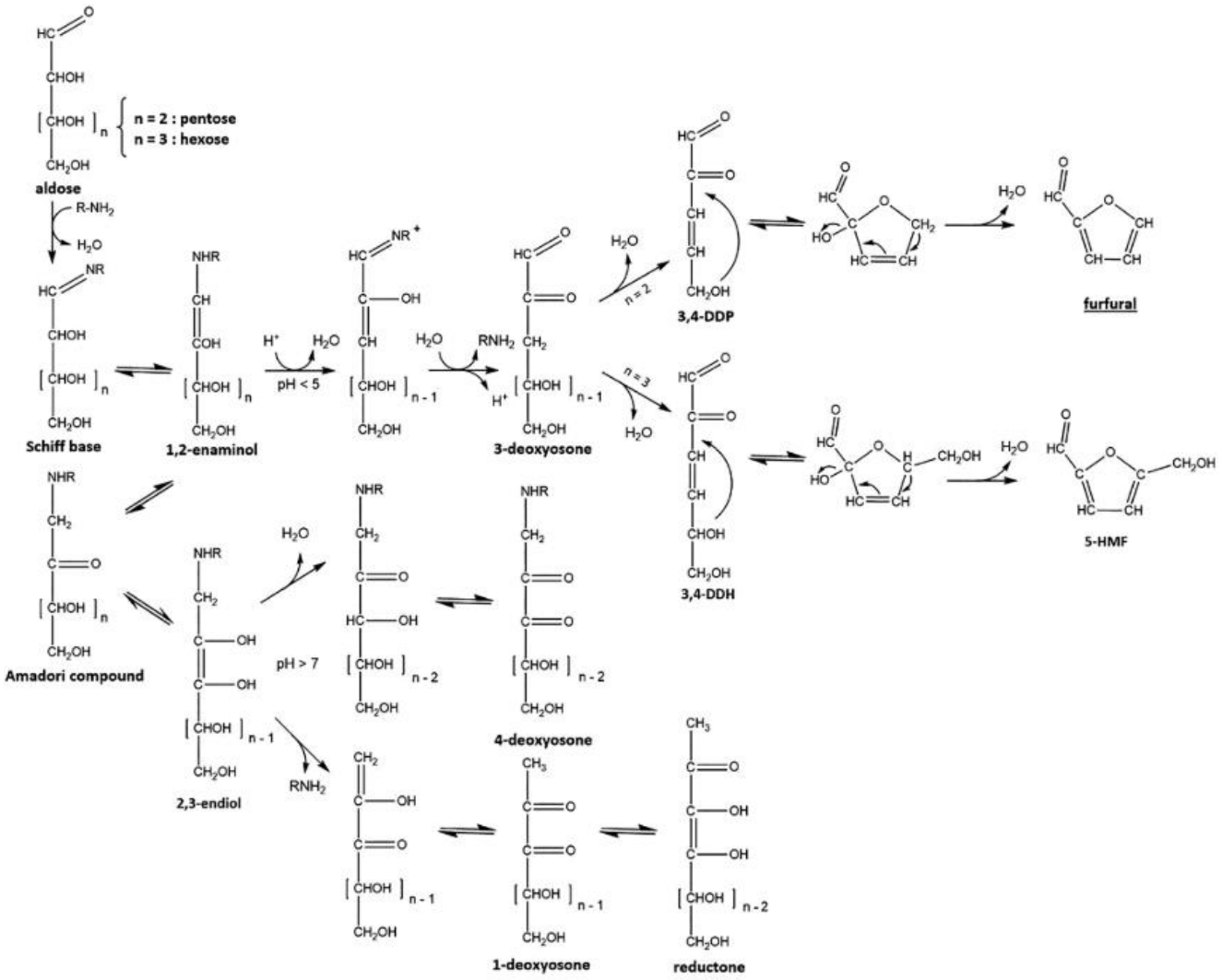


Fig. 4 An overview of Maillard reactions leading to the formation of furfural and HMF, based on Baert et al. [29]

at mashing-in. Further research is needed to clarify the relative contributions of each pathway under varying mashing conditions.

A third but distinct mechanism is photo-oxidation, which is initiated by light exposure in the presence of photosensitisers such as riboflavin. Upon light activation, riboflavin transfers energy to triplet oxygen, converting it to singlet oxygen, a highly reactive form that directly oxidises unsaturated fatty acids to hydroperoxides and aldehydes [29, 50]. Unlike enzymatic and autoxidative routes, photo-oxidation is temperature-independent, making it particularly relevant during beer storage and packaging. However, in freshly packaged beer, the concentration of dissolved oxygen is typically too low to support the formation of singlet oxygen, thereby reducing the likelihood of photo-oxidation pathways leading to aldehyde formation.

3.2 Maillard reactions

Contrary to common belief, not all aldehyde formation requires oxygen. Furfural and 5-hydroxymethylfurfural (5-HMF), both end products of Maillard reactions, show a strong correlation with beer staling and are often cited as key markers of flavour instability [14, 18, 23, 30, 51, 52]. Among them, furfural is more commonly used due to its volatility and ease of quantification by gas chromatography, whereas 5-HMF is non-volatile and requires liquid chromatography, making it less convenient for routine analysis. Both compounds arise from the degradation of sugar intermediates: furfural from pentoses and 5-HMF from hexoses. The initial reaction involves nucleophilic attack by the amino group of an amino acid or peptide on the open-chain form of a reducing sugar, forming an unstable Schiff base. This intermediate undergoes an Amadori rearrangement, yielding 1-amino-1-deoxyketoses (Amadori compounds), which are central intermediates in the Maillard pathway [53]. Cyclisation of these intermediates leads to the formation of furfural-type aldehydes, with reaction rates increasing significantly at elevated temperatures. In contrast, higher pH conditions favour alternative routes leading to 1- and 4-deoxyosones, but these are less relevant under typical brewing conditions.

While the chemical pathways leading to furfural and 5-HMF are well established, their sensory relevance in beer is less clear. These compounds have high flavour thresholds – 15,157 µg/L for furfural and 35,784 µg/L for 5-HMF – well above typical concentrations found in aged beer. As such, their direct contribution to staling aroma is likely minimal. However, spiking trials with furfural at 400 µg/L have shown perceptible changes in sensory character,

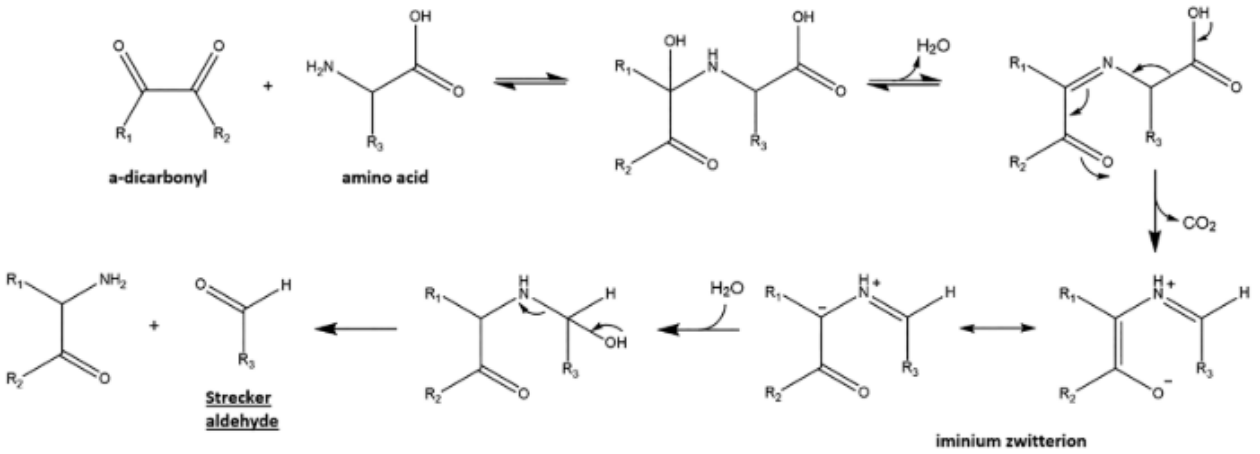


Fig. 5 An overview of Strecker degradation [29]

including increased bitterness and astringency [34], suggesting a potential role in modifying mouthfeel or interacting with other flavour compounds.

An unresolved question is whether furfural accumulation during storage results from ongoing Maillard reactions involving residual sugars and amino acids, or from the degradation of Maillard intermediates that survived earlier stages of production and continue to evolve in the finished beer. The latter hypothesis is supported by observations of linear increases in furfural concentration during ageing, even at low storage temperatures, indicating that precursor compounds remain reactive post-fermentation.

In addition to furfural formation, Maillard reactions also produce a wide array of α-dicarbonyl compounds such as glyoxal, 2-oxopropanal, and 2,3-butanedione. These intermediates can contribute directly to flavour changes or participate in Strecker degradation, further amplifying the formation of staling aldehydes. Their generation via Maillard chemistry complements the oxidation-driven pathways, making the Maillard reaction a relevant parallel contributor to flavour instability in beer. An overview of Maillard reactions leading to the formation of furfural and 5-hydroxymethylfurfural is presented in figure 4.

3.3 Strecker degradation

Strecker aldehydes constitute a major class of carbonyl compounds contributing to beer staling. Their formation involves both non-oxidative and oxidative degradation pathways of amino acids, depending on the reaction conditions and precursor availability during the brewing process and subsequent storage. Although a wide range of amino acids can participate in these reactions, only a select group of aldehydes have been consistently identified as relevant sensory markers in beer: 2-methylpropanal, 2-methylbutanal, 3-methylbutanal, methional, phenylacetaldehyde, and to a lesser extent, benzaldehyde. These compounds originate from the corresponding amino acids – valine, isoleucine, leucine, methionine, and phenylalanine – and are particularly important due to their low flavour thresholds and high volatility relative to other staling compounds.

Traditionally, Strecker degradation has been treated as a non-oxidative subset of Maillard chemistry, initiated by the reaction of amino acids with electrophilic carbonyl compounds. The primary mechanism, often termed Strecker degradation in the strict sense, involves nucleophilic attack of the amino group on an α-dicarbonyl compound, resulting in the formation of an unstable hemiaminal, which undergoes dehydration and decarboxylation to form a zwitterionic intermediate. This species ultimately rearranges to release a Strecker aldehyde, along with a corresponding α-ketoamine by-product [54]. The α-dicarbonyls involved in this reaction can originate not only from Amadori rearrangements within the Maillard pathway but also from the oxidation of polyphenols and from yeast-derived vicinal diketones such as diacetyl, which become available during fermentation. Quinones formed from phenol oxidation actively drive Strecker aldehyde formation, similar to α-dicarbonyls. Studies show that o-quinones from compounds like catechin and gallic acid efficiently react with amino acids such as phenylalanine to produce key aroma aldehydes like phenylacetaldehyde [55, 56]. The reaction mechanism involves identifiable quinone–amino acid intermediates, confirming their oxidative role. Like α-dicarbonyls, quinones can also engage in Maillard-type reactions via Michael addition with amines, influencing the formation of flavour and browning compounds [57]. This mechanism is illustrated in figure 5 and is considered chemically robust, with relevance across various thermal stages of brewing.

Alternative pathways have been proposed involving α-unsaturated carbonyls such as *trans*-2-nonenal or furfural, which can undergo similar nucleophilic additions with amino acids to yield Strecker aldehydes. However, the supporting evidence for this mechanism primarily comes from studies in non-aqueous or simplified systems, and its relevance under the aqueous and buffered conditions of beer remains uncertain. A third mechanism involves the direct reaction between Amadori compounds and amino acids, which may be further catalysed by transition metal ions. This pathway, proposed by Hofmann and Schieberle [58], has been shown to produce Strecker aldehydes in model systems, but its significance in brewing environments has yet to be fully demonstrated [29].

3.4 Direct oxidation of amino acids

For decades, Strecker mechanisms were assumed to be entirely non-oxidative, linked primarily to thermal processing and Maillard-

derived intermediates. However, more recent evidence has shifted this view, showing that oxidative degradation of amino acids via reactive oxygen species (ROS) can also lead directly to Strecker aldehyde formation. Research [59, 60, 61] provided compelling data demonstrating that hydroxyl and ethoxy radicals can abstract hydrogen atoms from amino acids, generating carbon-centred radicals that react with molecular oxygen to form hydroperoxy intermediates. These ultimately decompose into a Strecker aldehyde, along with carbon dioxide and an ammonium ion. This radical-mediated oxidative route occurs under storage conditions and does not require elevated temperatures or Maillard intermediates, highlighting the critical role of amino acid availability and residual oxygen content in the evolution of beer staling during packaging and distribution. ROS-driven Strecker pathways are gaining increasing recognition as equally important contributors to beer ageing as their non-oxidative counterparts. Proposed oxygen-induced mechanism for Strecker aldehydes formation was presented in figure 6.

3.5 Release of aldehydes from the bound-state adducts

An alternative to *de novo* aldehyde formation is the release of aldehydes from bound-state adducts [29]. Under specific conditions such as elevated pH or temperature, non-volatile aldehyde adducts can dissociate, liberating free aldehydes [62]. This mechanism was supported by Suda et al. [63], who added ^{13}C-labelled amino acids to sweet wort and inhibited Strecker degradation in the resulting beers with o-diaminobenzene. Their results showed that only 15 % of the Strecker aldehydes formed during beer ageing, while 85 % were already present due to wort production, indicating a significant reservoir of aldehydes in bound form.

Early studies identified bisulphite-bound aldehydes as potential contributors to beer ageing [64, 65]. Later investigations, involving direct quantification of bisulphite adducts via UPLC-MS, have failed to detect these adducts in malt, brewing samples, or either fresh or aged beers [66]. Imine formation between the marker aldehydes and various amino acids could also not be confirmed in the research conducted by Baert [67]. Yet, the same experiments pointed to reduced recovery of volatile aldehydes measured via HS-SPME-GC-MS in model solutions with cysteine, pointing to aldehyde adduct formation with cysteine [68]. The formation of cysteinylated aldehydes was further supported by following, involving competitive displacement using 4-vinylpyridine (4VP) and volatile aldehyde quantification by HS-SPME-GC-MS [69, 70]. Later findings showed that aldehyde release as a result of 4VP addition was due to the accompanying pH increase, as comparable release rate was observed with NaOH treatment, confirming alkaline conditions as the underlying cause [66].

Cysteinylated aldehyde adducts have been directly identified in model solutions [70] and detected in malt [41, 71, 72] and brewing samples [41, 52]. However, they have not been found in either fresh or aged beers, again questioning their significance under realistic storage conditions [20, 41]. Finally, spiking fresh beer with isotopically labelled aldehydes (2-methylbutanal-d_3 and furfural-d_3) did not result in the formation of cysteinylated nor bisulphite adducts during beer storage [66].

In contrast, when fresh commercial lager was spiked with labelled amino acids (valine-d_8 and leucine-d_3) and subjected to forced ageing (30 °C, up to three months), deuterated Strecker aldehydes (2-methylpropanal and 3-methylbutanal) were detected in the stored beers [66]. Although their concentrations remained below those of the corresponding non-labelled aldehydes, this experiment provided the first direct evidence for *de novo* aldehyde formation via Strecker degradation in the beer matrix during storage. A critical evaluation suggests that *de novo* formation pathways are more likely the source of aldehydes accumulation during beer storage, however empirical studies confirm the existence of bound-state aldehydes [52, 66, 70, 71, 72] and the presence of other types of aldehyde adducts should not be excluded in future experiments on beer flavour instability.

4 Processing factors affecting beer flavour stability

4.1 Heat

Heat plays a dual role in flavour stability, influencing both the heat load during brewing and the thermal stress encountered during storage. Among brewing operations, wort boiling applies the most significant heat input. This stage inactivates malt enzymes, sterilises

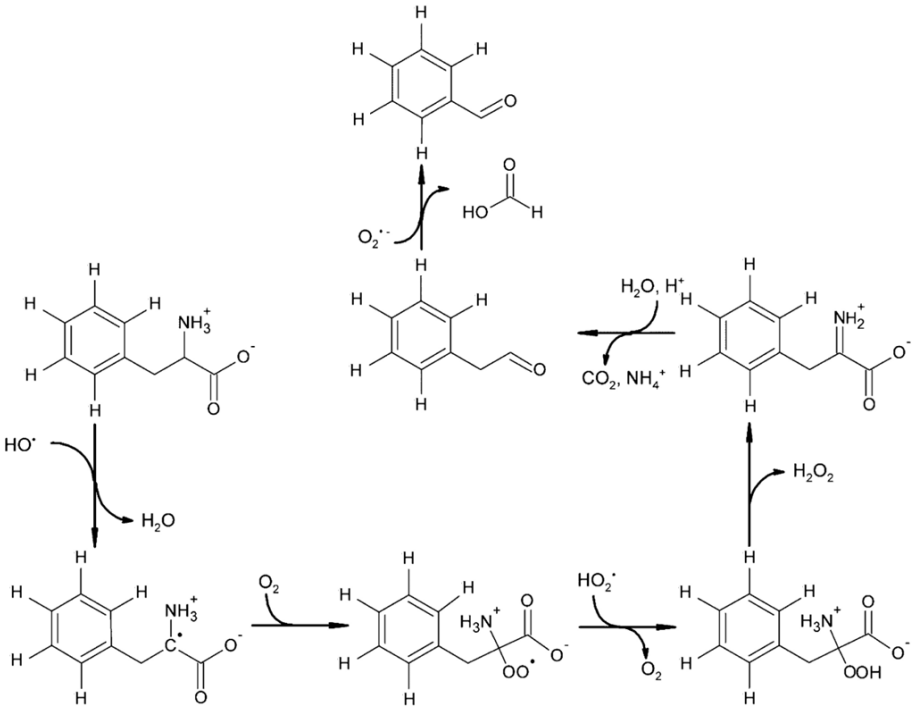


Fig. 6 Proposed oxygen-induced formation mechanism of phenylacetaldehyde and benzaldehyde from phenylalanine upon beer storage. Pathway based on Wietstock et al. [60]

the wort, extracts and isomerises hop α-acids, facilitates protein coagulation, and drives off unwanted volatiles. It also enables the conversion of S-methylmethionine (SMM) to dimethyl sulphide (DMS), which is subsequently removed by evaporation [73]. These are essential reactions for wort quality and beer flavour development. However, heat exposure during wort boiling also promotes undesirable chemical changes. Elevated temperatures accelerate Maillard reactions between amino acids and reducing sugars, leading to the formation of flavour-active carbonyls and non-volatile precursors such as dicarbonyls. These intermediates not only contribute to colour and complexity but also fuel Strecker degradation pathways that form staling aldehydes such as 2-methylpropanal and methional [74]. Moreover, thermal input enhances autoxidation of unsaturated fatty acids, initiating lipid-derived aldehydes such as *trans*-2-nonenal.

Although wort boiling can contribute to the formation of antioxidant-active compounds [75, 76, 77, 78], prolonged or excessive boiling is increasingly recognised as detrimental to long-term flavour stability. Modern brewing guidelines advocate for optimised boiling regimes, where thermal energy is applied in a way that maximises surface area exposure while minimising temperature gradients [79]. Efficient heat transfer with reduced residence time helps to preserve antioxidative potential while limiting the formation of flavour-degrading precursors.

Following production, beer remains chemically active, and its exposure to elevated heat during storage dramatically accelerates flavour deterioration. Typically, reaction rates double for approximately every 10 °C rise in temperature. This principle underlies the common practice of forced-ageing tests, where beers are subjected to high-temperature storage (e.g. 30 – 40 °C) for short durations to simulate long-term staling [14, 27, 80]. While forced-ageing is widely used to predict shelf-life performance, it does not fully replicate the chemical dynamics of natural ageing. Elevated temperatures can induce non-linear changes, including disproportionate release of bound aldehydes or activation of reaction pathways that are otherwise negligible under typical distribution conditions. For example, beers stored at 37 °C may develop sensory defects not observed at 20 °C over the same timeframe, even when adjusted for reaction rate scaling [81].

4.2 Oxygen uptake

Strict oxygen management remains a cornerstone of flavour stability strategy. Apart from the aeration step before fermentation, where yeast requires oxygen for sterol synthesis and membrane development [82, 83], all other process steps are ideally carried out under oxygen-minimised or inert conditions. This includes practices such as deaeration of brewing water, inert gas flushing during packaging, and oxygen-free mashing, lautering and filtration. Oxygen uptake is particularly critical during beer packaging, as headspace oxygen significantly influences the rate of beer staling, which was discussed in a further section of this review.

Oxygen uptake at any stage of the brewing process is broadly recognised as detrimental to flavour stability. Among all stages, oxygen ingress during packaging has been identified as particularly damaging to beer flavour stability [14, 27, 60, 84, 85, 86, 87, 88, 89]. Several studies have also pointed to a positive correlation between the oxidative stability of wort and sensory stability of the final beer [90, 91, 92, 93, 94, 95, 96, 97, 98].

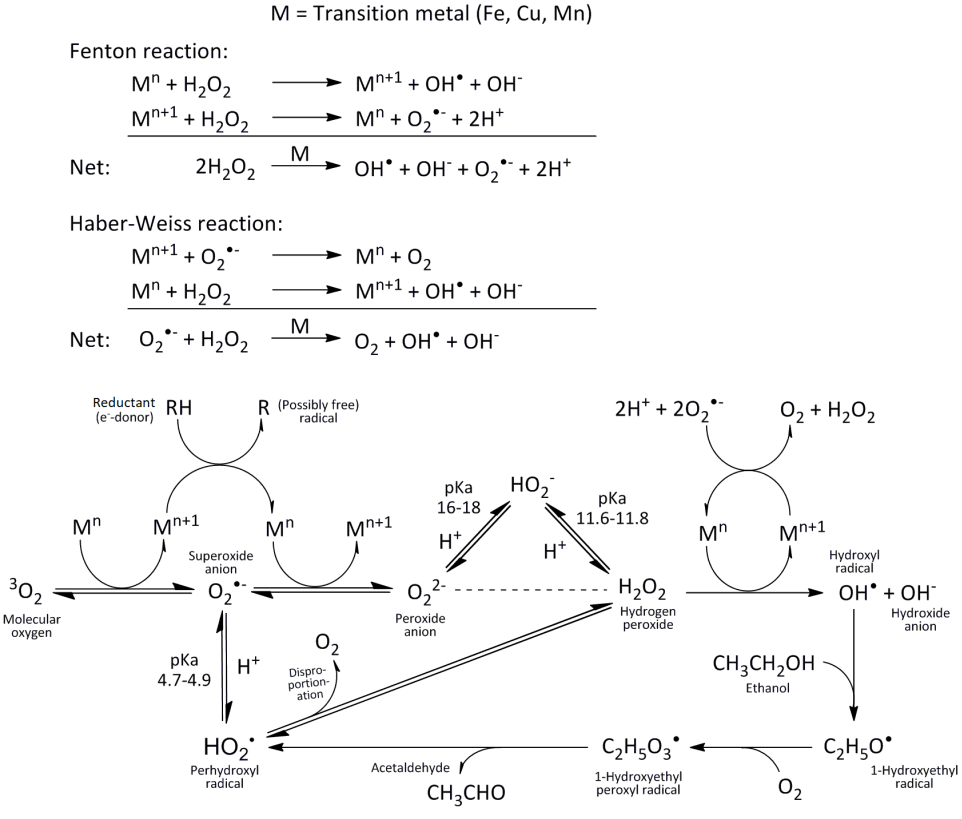


Fig. 7 Mechanism of reactive oxygen species formation in beer [14, 81, 100, 101]

While oxygen itself is relatively unreactive in its triplet ground state, it acts as a critical initiator of beer oxidation through the generation of reactive oxygen species (ROS). Upon activation – through heat, light, or interaction with transition metal catalysts – molecular oxygen can form highly reactive species such as superoxide anion, hydrogen peroxide, and ultimately the hydroxyl radical (•OH), which is considered one of the most potent initiators of flavour degradation in beer [99]. These reactions are primarily driven by Fenton and Haber–Weiss chemistry, where iron and copper ions catalyse the conversion of less reactive species into more damaging radicals [14, 81, 100]. The reaction mechanism for ROS formation was presented in figure 7.

The radical cascade initiated by ROS has multiple implications for beer stability. One particularly relevant intermediate is the 1-hydroxyethyl radical, formed when hydroxyl radicals react with ethanol – the dominant alcohol in beer [101]. This species is not only prevalent in beer

matrices but also highly reactive, contributing to the degradation of flavour-active compounds. It has been estimated that 88.4 % of reactions involving the hydroxyethyl radical occur with hop bitter acids, followed by thiol compounds (9.2 %), indicating selective reactivity patterns within the beer matrix [102].

4.3 Antioxidants and Prooxidants

The balance between antioxidants and prooxidants in the brewing matrix plays a crucial role in determining the rate of oxidative reactions responsible for the formation of staling aldehydes. These compounds either suppress or promote the generation of reactive oxygen species (ROS), which subsequently drive the oxidation of unsaturated fatty acids and amino acids, leading to flavour instability during beer storage.

Antioxidants in beer originate mainly from raw materials and yeast metabolism. A key endogenous antioxidant in beer is sulphur dioxide (SO_2), naturally produced by yeast during fermentation, particularly by bottom-fermenting strains. Sulphites act as both oxygen scavengers and carbonyl binders. They can bind reversibly with aldehydes such as methional and Strecker-derived compounds, forming adducts that reduce their volatility and sensory perception [24, 62]. While present at lower concentrations than in wine, their antioxidant contribution is relevant during early storage and maturation.

Arguably, polyphenols from malt and hops are postulated as contributors to antioxidative activity, including phenolic acids, flavonoids, and proanthocyanidins [103, 104, 105]. However, their interaction with beer components, such as proteins and transition metals, can paradoxically catalyse oxidative reactions under certain conditions [106, 107], which stems from their strong reducing activity. Beyond polyphenols, Maillard reaction products, such as reductones and melanoidins formed during malt kilning and roasting, contribute significantly to the radical-scavenging capacity of wort and beer, yet also display strong reducing properties [108, 109, 110].

The dual role of certain compounds as either antioxidants or prooxidants remains a subject of debate, largely due to the analytical methods used to evaluate their effects. Traditional assays such as DPPH and ABTS measure the capacity of compounds to quench stable, artificial radicals, primarily reflecting antioxidant potential. In contrast, oxygen probes offer a robust and straight forward measurement of the rate of oxygen consumption in a given system. Furthermore, electron spin resonance (ESR) based methods provide a more complete view by directly detecting real-time radical formation (via spin adducts) under conditions representing beer storage. Unlike selective assays, ESR catches the net balance of both antioxidant and pro-oxidant activities, offering a more accurate assessment of oxidative behaviour in complex matrices.

Prooxidants, in contrast, accelerate oxidative processes. Transition metal ions, especially iron (Fe^{2+}) and copper (Cu^{2+}) which are present in trace levels, catalyse ROS formation through the Fenton and Haber–Weiss reactions. These metals are introduced primarily via malt and brewing water [81, 111, 112], and their removal or chelation is critical for managing oxidative stability.

In addition, a number of compounds exhibit dual roles, acting as antioxidants or prooxidants depending on their concentration, redox environment, and interactions with other matrix components. Certain polyphenols, particularly flavonoids, can exhibit prooxidant activity under specific conditions – especially in the presence of metal ions and molecular oxygen – via autoxidation pathways that generate hydrogen peroxide and superoxide radicals [113, 114]. Similarly, Maillard reaction intermediates, such as enediol-containing reductones, can act as prooxidants by reducing iron and copper ions and keeping them in their active lower oxidation states, Fe(II) and Cu(I), and thereby enhancing redox cycling, particularly in acidic environments like beer [77, 115, 116]. These compounds are especially relevant in dark speciality malts, which may negatively affect flavour stability due to their high redox activity despite their antioxidant potential.

Brewing practice can influence the antioxidant–prooxidant balance in several ways. Water treatment methods such as reverse osmosis and deionisation help to eliminate transition metals. Chelating agents like gallotannins, ellagic acid, or hop polyphenol extracts may be added during mashing to bind prooxidant ions. Additionally, malt selection and kilning conditions can be tailored to favour antioxidant potential while limiting the generation of prooxidant intermediates.

4.4 pH

While the influence of pH on beer staling is less pronounced than that of heat or oxygen exposure, recent studies confirm that pH modulates key chemical and enzymatic reactions involved in aldehyde formation and radical generation. Its effect spans both beer ageing behaviour and precursor formation during brewing, particularly in the mash.

With regard to packaged beer, earlier work by Kaneda et al. [117] identified a direct relationship between low pH and accelerated staling reactions. When hydrochloric acid was added to fresh beer, reducing the pH from 4.3 to 4.1 or 3.8, a marked increase in staling was observed. However, this effect was absent in already aged beers, suggesting that pH influences aldehyde formation pathways, rather than triggering the release of carbonyls from bound states. Additional studies have shown that beers with reduced pH values during storage exhibit higher intensities of known staling markers such as *trans*-2-nonenal, methional, and β-damascenone [118, 119].

In wort production, pH plays a more complex role, particularly during mashing. First of all, Bamforth [120] pointed out a relevant challenge, when referring to literature sources taking under investigation pH conditions. A significant challenge frequently encountered stems from the common practice of measuring wort or mash pH at room temperature and assuming a constant value at elevated temperatures. Contrary to this assumption, studies have demonstrated that at 65 °C, the pH of a wort can be approximately 0.35 pH units lower than its measurement at room temperature [121, 122].

Previous investigations have repeatedly suggested mashing-in at higher temperature (approx. 63 °C) together with pH reduction to 5.2, aiming at immediate LOX inactivation and inhibition of formation of lipid oxidation aldehydes e.g. *trans*-2-nonenal [14, 27, 29, 37,

86, 87, 93, 123, 124, 125, 126, 127, 128]. However, recent research has raised questions about this strategy. Mashing at elevated pH conditions results in worts of reduced iron content [122, 129, 130], which potentially may result in reduced formation of reactive oxygen species catalysed by Fenton and Haber-Weiss reactions. Additionally, higher pH conditions during brewing favour chelation and complex formation of transition metal ions, which can be removed during wort filtration or clarification [122, 131, 132, 133, 134].

The dual effect – LOX inhibition at low pH versus metal removal at higher pH – highlights a fundamental trade-off in mash optimisation. It also underscores the need for more integrated studies that evaluate both enzymatic and non-enzymatic oxidation under controlled pH conditions. To date, few investigations have simultaneously considered both mechanisms within the same experimental framework.

4.5 Shear forces

Shear forces from stirring, pumping, and transfer operations during brewing may contribute to flavour instability by increasing oxygen ingress and disrupting protective matrix structures. These mechanical stresses, particularly prior to wort boiling, enhance air–liquid contact and oxygen dissolution, promoting oxidative reactions that form staling aldehydes [87, 134, 135]. Agitation may also destabilise protein–polyphenol complexes, releasing transition metal ions. Modern high-efficiency brewhouses often involve greater mechanical input – such as vibration-assisted mash tuns, centrifugal clarification, or rapid recirculation – which could raise oxidative potential if not properly managed. Technologies like laminar-flow stirring have been introduced to mitigate such risks [29, 136, 137]. However, the implications remain largely theoretical, as the specific role of shear forces in beer flavour stability has not been directly investigated in empirical brewing studies.

4.6 Light

Light exposure is a well-established contributor to flavour instability in beer, primarily through riboflavin-sensitised reactions that generate undesirable aroma-active compounds. A prime example is the 3-methyl-2-ene-1-thiol (MBT/lightstruck, flavour descriptor: skunky) [138] caused by the photodecomposition of iso-α-acids [139, 140, 141, 142, 143, 144]. The synthesis of 3-methylbut-2-ene-1-thiol occurs through the recombination of a sulfhydryl radical (formed from the photooxidation of cysteine or other thiol-containing derivatives) and 3-methylbut-2-enyl radical, originating from the photodegradation of isohumulones [142]. The use of reduced iso-α-acids (rho-, tetra- and hexahydro-isohumulones) instead of non-reduced hop extracts in beer production prevents from lightstruck formation upon beer exposure to light [145]. The use of brown bottles, cans or secondary cardboard packaging blocks eliminate light-induced degrading mechanism upon beer storage.

Moreover, a variety of aldehydes have been also observed upon photo-oxidation of oleic and linoleic acids in beer [37, 146, 147]. Light irradiation activates photosensitisers such as riboflavin, which excite triplet oxygen to singlet oxygen, subsequently reacting with fatty acids forming hydroperoxides and aldehydes, independent of temperature [29]. However, the total oxygen level in packaged beer (unless packaged under aerobic conditions) is typically too low to support singlet oxygen formation, making light-induced aldehyde formation during storage less probable.

5 Influence of raw materials on beer flavour stability

5.1 Water

The composition and treatment of brewing water exert a significant influence on both flavour perception and flavour stability in beer. While minerals such as calcium, magnesium, sulphate, and chloride contribute to mouthfeel and balance, water chemistry also plays a key role in modulating oxidative reactions during wort production. From a flavour perspective, sulphate is known to enhance perceived dryness and accentuate hop bitterness, whereas chloride contributes to a fuller, rounder palate and softens bitterness [83, 84, 148]. The ratio of sulphate to chloride, often targeted between 5:1 and 1:2 depending on beer style, can shift the flavour profile from crisp and hoppy to smooth and malty [149].

Beyond taste modulation, water treatment strategies are critical to flavour stability, particularly through their influence on oxidation pathways. Deaeration of brewing water is widely recommended to prevent oxygen ingress during mashing and sparging, where unsaturated fatty acids are especially vulnerable to enzymatic and non-enzymatic oxidation [27, 86, 93, 134, 150]. Additionally, acidifying sparging water has been proposed to enhance the release of aldehydes from reversible adducts, such as bisulphite- or thiol-bound forms, enabling their evaporation during wort boiling [29, 62, 151].

A critical consideration in water chemistry is the content of transition metal ions, especially iron and copper, which catalyse the formation of reactive oxygen species via Fenton and Haber–Weiss mechanisms [81, 152]. For this reason, most modern breweries implement deionisation, reverse osmosis, or nanofiltration to eliminate trace metals from local water supplies. Treated water is then reconstituted with brewing salts to meet stylistic and process requirements, and in some cases, supplemented with compounds such as hop polyphenols to enhance antioxidative capacity [83, 84].

5.2 Malt

Malt is a key contributor to both the flavour profile and the flavour stability of beer. Its composition significantly affects the presence and development of staling compounds through a combination of precursor supply, enzymatic activity, and redox-active components. Numerous studies have explored the relationship between malt characteristics and beer staling, highlighting malt's complex role in either promoting or mitigating flavour deterioration [18, 41, 43, 72, 153, 154, 155, 156, 157].

Malt supplies a wide range of precursors for carbonyl formation, including free amino acids, reducing sugars, and α-dicarbonyls, which are directly involved in Strecker degradation and Maillard-type pathways. Malts with lower proteolytic modification, indicated by reduced Kolbach index or free amino nitrogen (FAN), have been

associated with improved flavour stability [18, 157, 158]. Conversely, highly modified malts result in increased formation of Strecker aldehydes in both wort [159] and aged beer [160, 161]. The use of high-colour malts or malts with elevated thiobarbituric acid index (TBI) has also been associated with enhanced staleness intensity in forced-ageing trials [153, 154].

Beyond precursors, malt is the primary source of lipoxygenase (LOX) enzymes, especially LOX-1 and LOX-2, which catalyse the oxygenation of linoleic and linolenic acids to hydroperoxides. These intermediates subsequently degrade into aldehydes such as *trans*-2-nonenal and hexanal [29, 38, 39, 162]. Malt is also the main contributor of transition metal ions, such as iron and copper, which catalyse the formation of reactive oxygen species via Fenton and Haber–Weiss reactions, further accelerating aldehyde formation [81, 111, 112].

Importantly, malt does not merely supply precursors – it also contains staling aldehydes themselves, detectable in both green and kilned malts. Volatile compounds such as 3-methylbutanal, 2-methylpropanal, and 2-methylbutanal are typically found at the highest levels, alongside trace amounts of *trans*-2-nonenal [71, 162, 163, 164, 165, 166, 167]. Additionally, bound aldehydes – particularly cysteine adducts – have been identified in malt [41, 66, 72], though their contribution to staling during beer storage remains unclear.

On the other hand, malt also contains components with antioxidant potential, especially polyphenols, which can scavenge free radicals and inhibit oxidative reactions. It is estimated that 80 % of beer's total phenolic content originates from malt [168]. Polyphenolic compounds such as phenolic acids act by donating hydrogen atoms or electrons and forming stable radical intermediates, which interrupt oxidative chain reactions [105, 169]. Flavonoids and proanthocyanidins, in particular, show strong radical-scavenging properties, largely governed by their hydroxylation pattern [170, 171, 172]. Beers brewed with malts of higher antioxidant capacity have been reported to display greater flavour retention during ageing [103, 173, 174].

However, this antioxidative potential is not unambiguous. Phenolic compounds can also act as pro-oxidants, particularly under the influence of oxygen and transition metals, generating reactive oxygen species via autoxidation [113, 114]. Reductones and Maillard reaction products formed during kilning and roasting may contribute to antioxidant activity, but also promote ROS formation by enhancing redox cycling of metal ions [78, 108, 109, 110, 115, 175, 176].

The type and degree of malt roasting is particularly relevant. Dark speciality malts have been shown to give more extensive oxidative reactions in wort and beer [154, 177, 178], likely due to the redox activity of Maillard intermediates such as reductones. However, the caramelised, roasted flavours present in dark beers may mask some of the ageing off-flavours, resulting in prolongation of consumer-perceived beer flavour stability. As an alternative approach, partial or complete substitution of malt with unmalted adjuncts – such as rice, corn, or unmalted barley – has shown potential for improving flavour stability. These adjuncts tend to reduce wort colour, metal ion content, and staling aldehyde levels [179, 180, 181]. Brewing trials incorporating unmalted barley have resulted in beers with enhanced oxidative resistance, as measured by electron spin resonance [182].

5.3 Hops

Hops contribute not only to the bitterness and aroma of beer but also to its oxidative stability during storage. One of the most notable transformations associated with hops during ageing involves the degradation of iso-α-acids, the primary bittering compounds formed from the thermal isomerisation of α-acids during wort boiling. These compounds are inherently unstable and undergo gradual degradation over time, influenced by oxidative, photochemical, and thermal conditions [18, 23, 143, 183, 184, 185, 186, 187, 188, 189, 190]. Among their isomers, *trans*-iso-α-acids degrade more rapidly than their cis-counterparts, contributing to bitterness loss during shelf life [23, 183, 189].

The degradation of iso-α-acids involves multiple chemical pathways, including photo-oxidation, autoxidation, proton-catalysed reactions, and reactions with radical species, such as the 1-hydroxyethyl radical [187, 191]. Although some early studies proposed that these pathways might contribute to the formation of volatile aldehydes [192, 193], more recent investigations have cast doubt on this hypothesis. In a controlled comparison, De Clippeleer et al. [194] observed similar increases in aldehydes such as 2-methylpropanal, 2-methylbutanal, and 3-methylbutanal across beers regardless of the type or presence of iso-α-acids. This suggests that the degradation of hop-derived bittering compounds is not a significant source of staling aldehydes, and other mechanisms – such as amino acid degradation – are likely more relevant.

Nevertheless, hops do play a protective role against oxidation, largely due to their polyphenolic content and α-acids, both of which possess antioxidant properties. Hop polyphenols have been shown to enhance radical scavenging activity in beer, potentially delaying flavour deterioration [103, 195, 196, 197]. Additionally, α-acids themselves exhibit antioxidative behaviour by reacting with radical species and chelating metal ions [61, 89, 198, 199].

Beyond kettle additions, hops are often introduced during fermentation or maturation in a process known as dry hopping, aimed at enhancing aroma without additional bitterness. However, dry hopping introduces certain risks to flavour stability. Oxygen ingress during hop additions can promote oxidative reactions, while transition metal ions (leached from hop material) can catalyse the formation of reactive oxygen species. Despite these risks, recent studies suggest that dry hopping may still provide net oxidative benefits. Hrabia et al. [200] reported a reduction in radical formation rates in dry-hopped beers, likely due to the presence of hop-derived antioxidants, including residual α-acids. Furthermore, the post-fermentation addition of hops in a beer-like system, such as kombucha (a non-alcoholic fermented beverage produced by a symbiotic culture of bacteria and yeast) was found to decrease the rate of radical formation [201].

5.4 Yeast

Yeast contributes significantly to flavour stability in beer, since they have the potential to reduce aldehydes [41, 202]. During fer-

mentation aldehydes are reduced to their corresponding higher alcohols, which are less flavour-active or may positively influence aroma. This reduction occurs via two metabolic routes: (1) *de novo* synthesis of 2-oxo (α-keto) acids from carbohydrates through pyruvate metabolism, and (2) the catabolism of amino acids through the Ehrlich pathway [203, 204, 205, 206]. Both pathways generate reactive intermediates that are decarboxylated and subsequently reduced to alcohols, which was presented in figure 8.

The enzymatic system responsible for this reduction includes alcohol dehydrogenases [207, 208], NAD(P)H-dependent reductases, and aldo-keto reductases, which differ in substrate specificity [209, 210, 211]. Yeast also reduce α-dicarbonyl intermediates of Maillard reactions, limiting the formation of Strecker aldehydes. In model beer systems, introducing isolated yeast reductases reduced dicarbonyl concentrations during forced ageing [212], while overexpression of these enzymes led to beers containing up to 40 % lower levels of Strecker aldehydes [213].

Fermentation trials have shown that when aldehydes are added to pitching wort, they are efficiently removed during primary fermentation. This process coincides with increases in esters and higher alcohols, and a decrease in aldehyde-associated malty notes [63, 211, 2014]. Aldehyde reduction starts early in fermentation and occurs most rapidly for linear saturated aldehydes, such as 2-methylpropanal and methional [202, 208]. Warmer fermentation conditions have been associated with faster reduction, likely due to increased enzyme activity.

Although fermentation conditions such as yeast strain, temperature, pitching rate, and re-pitching strategies can influence the reduction rate, studies consistently show that final aldehyde concentrations after fermentation tend to stabilise across different brewing scales and conditions [211, 215, 216]. This points to other limiting factors, possibly related to matrix interactions.

One earlier hypothesis proposed that some aldehydes become unavailable to yeast due to binding with wort components, such as imine formation, bisulphite addition, or interactions with polyphenols [29]. However, more recent work has not supported this view. In fermentation samples, no cysteine- or bisulphite-bound aldehydes were detected, suggesting these adducts are unlikely to explain the residual aldehyde levels observed in finished beer [41, 66].

6 Impact of Brewing Steps on Aldehyde Management

Beyond raw materials and environmental conditions, the specific operations applied during beer production have a significant impact on flavour stability, which is described step by step in the following subsections.

6.1 Mashing and lautering

Mash production is a critical stage in beer processing with significant implications for flavour stability, particularly due to its influence on oxidation pathways and precursor formation. Effective control of oxygen exposure upstream begins with the design of the malt and milling system. It has been recommended that malt storage, milling equipment, and water contact points be maintained under inert atmosphere to minimise oxygen ingress [87, 93, 134]. Milling strategies should aim to reduce embryo damage and limit lipoxygenase (LOX) activity, both of which are associated with the release of fatty acid oxidation products [29]. Although wet milling can enhance the extraction of sugars and proteins, it may also increase oxidation risk through rapid transfer of unsaturated fatty acids and oxygen exposure. Additionally, husk damage from aggressive milling slows lautering, prolonging wort contact with heat and potentially oxygen, especially in systems lacking oxygen-limited conditions.

Mashing efficiency has been directly linked to the chemical composition of the resulting wort and its oxidative stability. Faster mashing regimes are generally favourable, as they reduce time under thermal load and limit the accumulation of flavour-negative compounds such

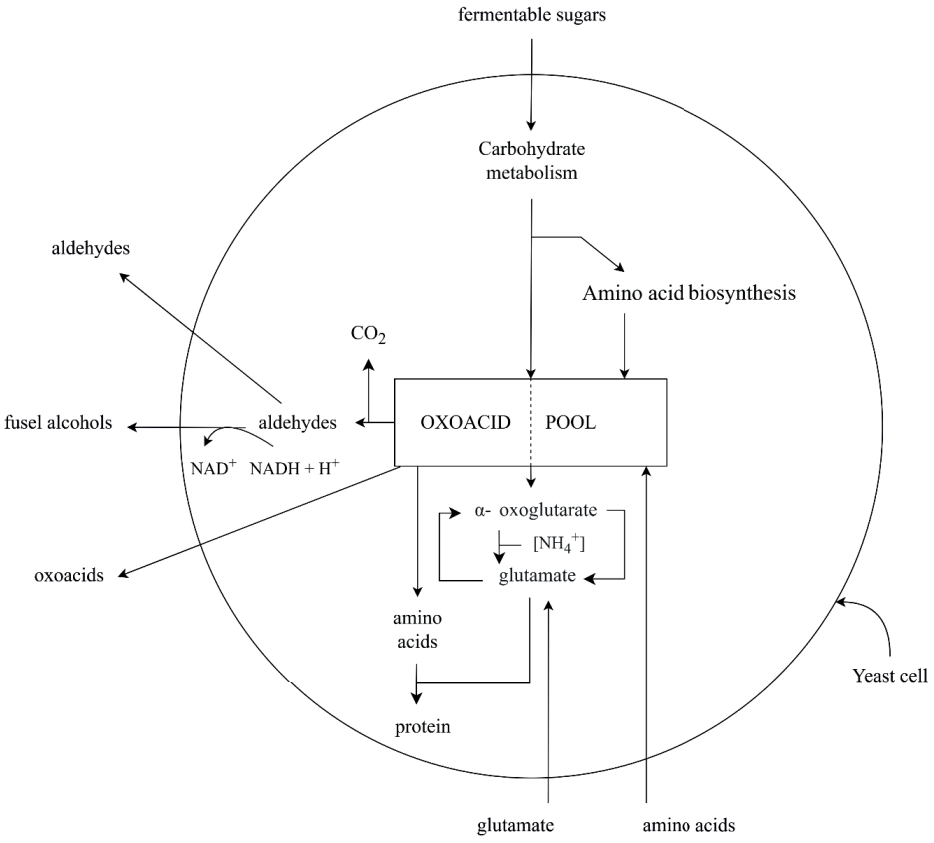


Fig. 8 Amino acid metabolism and the production of beer α-keto (oxo) acids, aldehydes and higher alcohols

as thiobarbituric acid reactive substances (TBIs). System designs incorporating oversized chimneys with condensate traps help to remove volatile aldehydes and prevent their reintroduction into the mash vessel [136, 137]. Mechanical improvements such as laminar stirring or vibration-assisted systems can further accelerate enzymatic reactions and reduce shear stress, ultimately shortening mash times and minimising oxidation.

LOX activity is highest during early mashing, coinciding with the release and formation of fatty acid-derived staling aldehydes such as *trans*-2-nonenal [41, 42]. Consequently, mashing under inert atmosphere has been widely recommended to limit both enzymatic and non-enzymatic oxidative reactions [93, 217]. Supplementation with antioxidants like ascorbic acid has also been explored, particularly in systems expressing ascorbic acid oxidase activity [218]. However, the most consistently effective strategy for LOX inactivation has been mashing-in at elevated temperatures (~ 63 °C) in combination with pH adjustment to approximately 5.2. This approach reduces hydroperoxide formation and limits lipid oxidation, while maintaining adequate enzymatic function [14, 27, 86, 126, 127, 134].

While low pH conditions promote LOX inactivation, they may also increase the extraction of transition metal ions, particularly iron and copper, from malt [122, 129, 130, 219]. These metals catalyse Fenton and Haber–Weiss reactions, exacerbating radical formation and aldehyde production. Recent strategies have focused on removing or inactivating these metals during mashing, where pH and matrix conditions are more favourable for chelation than in finished beer. Organic acids, proteins, polyphenols, and gallotannins have all been explored for their metal-binding properties, with positive outcomes for flavour stability [122, 217, 220]. Additionally, mash additions of hops or hop polyphenols have been found to significantly reduce metal ion concentrations in sweet wort [89], and recent studies highlight ellagic acid as a particularly effective chelator under mash conditions [122, 131, 132, 133].

Optimization of the lautering and wort separation process is equally important for flavour stability. Shorter filtration times reduce thermal stress and the formation of oxidation products [135, 236]. The addition of gallotannins and hop-derived polyphenol extracts to the sparging liquor has shown to improve flavour retention while enhancing filtration rates [197, 217]. Lautering should be conducted under oxygen-free conditions to avoid reintroduction of oxidative potential. Acidified sparging offers additional benefits by lowering proanthocyanidin extraction from husk material and promoting the release of aldehydes from reversible imine adducts, which can be effectively removed during wort boiling [29].

Clear wort is a consistent predictor of improved flavour stability, largely due to its lower content of oxidation precursors. Studies have shown that many organic radicals are bound to the husk material and do not transfer into the copper wort or final beer [177]. Effective wort separation also removes a substantial proportion of transition metals – up to 90 % by mass has been found in spent grains [112, 221]. This suggests that systems optimized for clear wort production, such as thin bed mash filtration, may offer a technical advantage. Although pilot trials found no major sensory differences between thin bed and lauter tun filtration [222], the consistently lower metal and staling compound content in clear worts supports continued adoption of filtration technologies that maximize separation efficiency.

6.2 Wort boiling and clarification

In the context of beer flavour stability, wort boiling plays a pivotal role in shaping the chemical profile of the final product. One of the most significant outcomes of this stage is the evaporation of volatile compounds, particularly staling aldehydes and dimethyl sulphide (DMS), which is thermally formed from its non-volatile precursor S-methylmethionine [82]. Effective removal of aldehydes during wort boiling reduces the aldehyde load passed into later processing stages and, consequently, into the final beer. This not only limits the direct presence of staling compounds but may also reduce the pool of compounds capable of forming bound aldehyde derivatives post-boiling. In one study using labelled amino acids, as much as 85 % of Strecker aldehydes in aged beer were shown to originate from precursors introduced during wort production [63], highlighting the importance of this phase in managing long-term flavour stability.

Despite the loss of aldehydes via evaporation, boiling also promotes their formation. Thus, the net concentration of aldehydes during boiling is governed by a dynamic balance between their thermal generation and their concurrent volatilisation. The rate at which these compounds evaporate is influenced by several factors, including their intrinsic volatility, the wort matrix, and boiling conditions. Although boiling points are often used as proxies for volatility, they are determined for pure compounds and do not reflect the behaviour of aldehydes in highly dilute aqueous or hydroalcoholic environments like wort and beer. In these matrices, more accurate indicators of volatility include Henry's law constants (K_H) or experimentally determined vapour pressures (p^0) and limiting separation factors (K^∞), which describe vapour–liquid equilibrium in dilute systems [223, 224, 225, 226]. These parameters, determined via recirculating stills, allow brewers to model evaporation behaviour more accurately using residue curve analysis, potentially optimising the removal of specific aldehydes.

Boiling is not associated with oxidative reactions in the classical sense, as oxygen solubility in boiling wort is negligible, and oxygen exclusion during boiling is straightforward [91]. Instead, aldehyde formation occurs primarily through non-oxidative mechanisms such as Maillard and Strecker reactions. The rate and profile of these pathways depend on pH, thermal input, and wort composition. During boiling, Strecker aldehydes typically increase in a pseudo-zero-order manner, while furans follow a first-order trend and lipid oxidation products do not proceed [227]. Lower wort pH slows Maillard reactivity initially but favours the formation of desirable volatiles over unwanted precursors. Wort thickness and extract level also influence thermal load, as seen in the thiobarbituric index (TBI), with reduced precursor accumulation observed at pH 5.5 in low-extract worts [228].

Pilot-scale studies have explored optimisations of wort boiling that balance flavour stability with process efficiency. For example, Yano et al. [229] found that treating the second wort fraction at 78 °C before recombining it with the first wort and reboiling for 10 min-

utes resulted in beers with acceptable flavour stability. However, when this second wort was pre-treated with fining agents such as PVPP, silica gel, bentonite, or activated carbon, a significant loss of flavour stability was observed. These findings may suggest that such treatments may inadvertently promote aldehyde formation via lipid oxidation or interfere with aldehyde-scavenging mechanisms. Nonetheless, the mechanism behind this effect remains unclear and given the diversity of fining agents and their modes of action, it is unlikely that a single pathway explains the observed impact. Additional variables such as oxygen introduction from solid additions may have contributed.

To reduce heat load while maintaining volatile removal, technological alternatives such as stripping columns have been proposed. These systems use counter-current gas flow to evaporate volatiles from clarified wort while it flows downward through packed columns. When integrated with isomerised hop products, stripping columns could offer a promising route to reduce thermal stress without compromising flavour quality. In parallel, hopping techniques also influence flavour stability. Fresh hops contain higher levels of polyphenols and antioxidants compared to aged hops, which may contain oxidised bitter acids and aldehyde precursors. Hop-derived α- and β-acids have demonstrated antioxidant properties capable of suppressing Strecker aldehyde formation [61], and supplementation of sweet wort with hop polyphenol extracts has been shown to improve flavour stability [197, 217]. Moreover, incremental hop dosing during wort boiling has been associated with improved stability in lager-style beers [89].

Post-boiling, the separation of hot trub is another critical factor. This step must be carefully managed to avoid oxygen ingress, ensure rapid and complete clarification, and achieve effective separation of trub from the bitter wort [123]. Similar to boiling, aldehydes may continue to form during whirlpooling due to residual heat, while some evaporation may still occur. The net change in aldehyde content during this step is again governed by a balance between thermal formation and removal [42]. Importantly, hop constituents with metal-chelating properties often accumulate in the trub, along with metal ions such as iron and copper, both of which catalyse oxidative pathways [61, 81]. Effective removal of hot trub can therefore reduce metal load and suppress subsequent flavour degradation.

Various clarification techniques are employed, including gravitational settling and whirlpooling, with the latter being the most widely used due to its simplicity and effectiveness. Wort is pumped tangentially into a vessel, generating rotational flow that causes trub to settle in a cone-shaped pile at the centre. More recently, centrifugal separators have been introduced, offering the advantage of faster clarification and reduced thermal exposure – both beneficial for preserving flavour integrity [83, 84].

Following clarification, rapid cooling of wort to fermentation temperature is essential to minimise further heat-induced degradation. Quick cooling reduces the duration of thermal exposure, thereby preserving volatile aroma compounds and limiting the formation of new aldehydes [123]. Although wort aeration is necessary to support yeast health and growth, dissolved oxygen levels up to 8 mg/L appear to have minimal direct effect on flavour stability due to the low temperature and short exposure time prior to fermentation onset [230].

6.3 Fermentation and maturation

Fermentation is one of the most influential stages in determining beer flavour stability, as during fermentation aldehydes formed during the brewing process are reduced to marginal levels (fig. 9). A swift initiation of fermentation is recommended to limit oxidative reactions in the wort before dissolved oxygen is consumed by actively metabolising yeast [84]. This rapid onset is facilitated by the use of yeast with high vitality and viability, which ensures not only effective attenuation but also protection against early-stage aldehyde accumulation. Yeast exhibits a strong reducing capacity toward aldehydes, making them essential in controlling the carbonyl profile of beer. This reduction occurs largely independent of the initial aldehyde concentration, although the efficiency of this activity varies between strains [231, 232]. The reduction is so robust that yeasts are able to convert most carbonyls to their corresponding

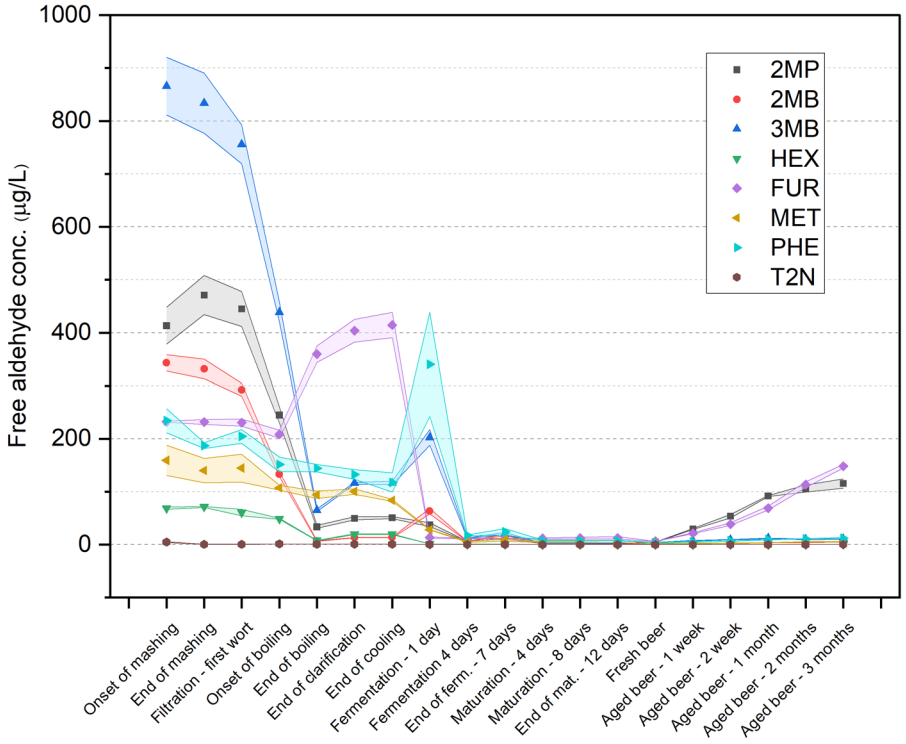


Fig. 9 **Evolution of free aldehydes during wort production, fermentation and beer ageing processes. Data points represent determined mean values (n=3) for 2-methylpropanal (2MP), 2-methylbutanal (2MB), 3-methylbutanal (3MB), hexanal (HEX), furfural (FUR), methional (MET), phenylacetaldehyde (PHE) and *trans*-2-nonenal (T2N) at a given sample point and colour fillings indicate the confidence bands [52]**

alcohols, even in refermented beers, suggesting consistent activity across different fermentation conditions [233].

During fermentation, the presence of yeast also influences the concentration of metal ions, particularly iron, which is believed to be reduced or immobilised through binding with proteins or other cellular components [112, 148]. Managing yeast health is therefore crucial not only for aldehyde reduction but also for mitigating oxidative catalysis driven by transition metals. A vigorous fermentation additionally supports the reduction of vicinal diketones and other off-flavour compounds [87]. Given these effects, the use of strains selected for aldehyde-reducing efficiency has become a recognised strategy to enhance beer flavour stability [63].

Yeast also contributes to flavour stability through the production of sulphite, which serves both as antioxidant and as an agent capable of reversibly forming adducts with aldehydes. Sulphite secretion varies by strain but is generally enhanced by bottom-fermenting yeast and low fermentation temperatures [232, 234, 235, 236]. Pitching rate and aeration also influence sulphite production. Optimal sulphite levels for flavour protection are typically reported between 7 – 10 mg/L [84, 236, 237], though actual concentrations can fluctuate depending on yeast management and fermentation conditions.

The behaviour of sulphite in beer remains an area of active research. Analytical challenges related to sensitivity, repeatability, and reproducibility have complicated the interpretation of sulphite dynamics [237]. Functionally, sulphite serve a dual role: it act as antioxidant that slow oxidative reactions, and it can form non-volatile bisulphite-aldehyde adducts. While these adducts temporarily stabilise aldehydes in non-volatile form, they may dissociate over time, releasing free aldehydes back into the beer during storage [27, 29, 68, 69]. However, more recent studies suggest that these adducts may be less relevant than previously thought, as they were not detected in fresh or aged beers under standard conditions [66].

Beyond aldehyde reduction and antioxidant effects, yeast also influence the sensory profile of beer through the secretion of flavour-masking metabolites such as esters. For instance, isoamyl acetate and other fruity compounds can modulate perception of ageing-related off-flavours. Top-fermenting strains generally produce higher levels of esters and their formation can be further enhanced by fermentation geometry, with horizontal vessels favouring ester production [231, 232]. These masking effects contribute an additional layer to yeast's protective influence on beer flavour.

6.4 Downstream processing

After fermentation, beer undergoes several downstream processes, including filtration, stabilisation, carbonation, and packaging. At this stage, oxygen should already be consumed by yeast metabolism, yet the risk of reintroduction remains high. Filtration, particularly using kieselguhr, poses a well-known oxygen ingress hazard due to unavoidable air contact [84]. In addition, kieselguhr is a source of transition metal ions such as iron and copper, which catalyse oxidative reactions and may compromise flavour stability if not effectively removed [81, 238]. Alternative clarification methods that reduce oxygen exposure and metal contamination are therefore preferable, though many brewers continue to rely on traditional practices due to cost and scalability.

Beer stabilisation methods, such as treatment with polyvinylpolypyrrolidone (PVPP), target haze-active polyphenols but can inadvertently reduce the antioxidant capacity of the beer. Nonetheless, studies have shown that PVPP treatment does not significantly impair flavour stability, even after forced ageing [103, 239]. The use of post-production antioxidants such as ascorbic acid is more controversial. While permitted in some brewing contexts, these additives are banned under the German Purity Law, and their actual efficacy in slowing flavour deterioration remains uncertain [240]. In contrast, sulphites have demonstrated significant potential in extending beer freshness due to their dual role as antioxidants and carbonyl-binding agents. Although not permitted in all brewing traditions, sulphites are widely used outside Germany and are considered one of the more effective additives for preserving flavour stability [237]. Carbonation itself is not considered a major factor in flavour stability, assuming proper CO_2 purity and handling.

The impact of pasteurisation on flavour retention continues to generate debate. While the application of heat inevitably causes degradation of volatile aroma compounds, particularly esters, it may also contribute to improved oxidative stability under certain conditions. Cao et al. [241] reported increased levels of heat-derived volatiles and reduced ester concentrations with higher pasteurisation intensity, confirming its sensory impact. However, studies using electron spin resonance (ESR) have shown that pasteurised beers exhibit slower radical formation and sulphite depletion compared to unpasteurised counterparts, suggesting a stabilising effect on redox balance [242]. The authors proposed that protein precipitation during pasteurisation may reduce metal-binding capacity, thereby limiting catalytic oxidation. Additional findings have suggested that pasteurisation could reduce ester hydrolysis during storage by degrading esterase enzymes [242]. Wackerbauer and Zufall [244] suggested that short-time, high-temperature pasteurisation is less damaging than current techniques.

Among all downstream steps, packaging represents the most critical control point for flavour preservation. Even trace oxygen ingress during filling can negate upstream efforts to protect beer quality [29, 81, 87]. Technological advances in filling have enabled brewers to achieve oxygen levels below 0.15 mg/L in bottled beers, around 0.25 mg/L in cans and below 0.1 mg/L in kegs [84]. PET bottles, however, remain more permeable to oxygen, with typical levels around 3 mg/L, making them less suitable for long-term storage. Innovations such as oxygen-scavenging crown caps and can linings have demonstrated enhanced protection against oxygen ingress [245, 246], and further development in packaging materials (such as carbonyl-binding can coatings) continues.

Light exposure also poses a threat to flavour stability, particularly through the well-documented "lightstruck" reaction involving 3-methyl-2-butene-1-thiol (MBT), which gives beer a skunky aroma [141]. Beyond MBT formation, light can also trigger iso-α-acid degradation and aldehyde formation via photochemical mechanisms [29, 247]. Light-induced mechanisms leading to the formation of aldehydes are less probable in packaged beer, as it typically lacks sufficient dissolved oxygen (unless filled under aerobic conditions) to sup-

Table 2 Critical Control Points in the Brewing Process Influencing Beer Flavour Stability

Raw Materials	General	Mashing and Mash Filtration		Wort Bioling, Clarification, and Cooling	Fermentation and Maturation	Upstream processing	Packaging	Storage and Distribution
Use of deaerated and demineralised (removal of oxygen and transition metals)	Maintain oxygen-free conditions throughout entire processing, except for pre-feremntation wort aeration	Keep malt storage, milling, and water contact points under inert atmosphere to limit oxygen ingress.	Use faster mashing to reduce thermal load and limit TBI formation.	Avoid excessive boiling and extended wort heat exposure	Select yeast strains efficient in aldehyde reduction	Minimise oxygen uptake during filtration through inert atmosphere or closed systems.	Implement limited-oxygen packaging technologies (e.g. inert gas purging, counter-pressure filling) and monitor TPO to stay below 100 ppb; packaging is the most critical step for preserving beer flavour stability	Avoid vibrations and high-temperature conditions during beer transportation and storage
Use of low-modified malts (low Kolbach-Index and FAN)and limit overmodified, high-colour malts (high in TBI, Maillard intermediates, Strecker aldehydes precursors, transistion metals)	Minimise heat load throughout malting and brewing; keep hot transfers short to limit oxidative and Maillard-related flavour degradation	Use deaerated water and oxygen-free conditions during mashing and lautering.	Apply laminar stirring or vibration-assisted systems to speed up mashing and reduce oxidation from shear stress	Use boiling kettles that maximise surface exposure and minimise temperature gradients; use oversized chimneys with condensate traps to remove volatile aldehydes and prevent re-entry	Ensure rapid fermentation onset using high-vitality yeast to limit early oxidative reactions	Consider alternatives to kieselguhr filtration to minimise oxygen ingress and introduction of transition metal ions	Use cans or kegs for full light protection; brown or dark-green bottles offer sufficient UV shielding	Preferably use cold chain storage (≤8 °C) across warehousing, transport, and retail
Use malts rich in polyphenols (e.g. flavonoids, proanthocyanidins) to enhance antioxidant capacity	Minimise iron and copper levels; promote chelation by amino acids, melanoidins, gallotannins or ellagic acid to suppress radical formation	Use milling strategies that minimise embryo damage and LOX activity.	Add hops, hop polyphenols, gallotannins or ellagic acid during mashing to chelate metal ions and reduce oxidation	Consider stripping columns—particularly with modified hop products—to reduce thermal load while ensuring volatile removal.	Optimise strain, temperature, pitching rate, and aeration to enhance yeast sulphite production	Optimise pasteurisation to balance microbial stability with minimal thermal stress	Avoid PET bottles for long-term storage due to high oxygen permeability	Use cardboard boxes (ideally wrapped in plastic film) for improved protection against heat, light, and vibration during storage and transport
The use of brewing adjuncts (rice, corn, unmalted barley) may improve oxidative stability	Promote and protect endogenous antioxidants (polyphenols, reductones, melanoidins, vitamins, sulphites)	Mash in at ~63 °C (and pH 5.2) to inactivate LOX and limit lipid oxidation aldehydes (e.g. trans-2-nonenal).	Minimise wort filtration time to reduce thermal stress and oxidation	Use fresh hops or hop polyphenol extracts; consider incremental dosing during boiling to improve flavour stability	Dry hopping poses oxidation risks (O_2 ingress, metal ions) but may offer net antioxidant benefits via hop-derived compounds		Consider bottle conditioning ensuring ongoing aldehyde reduction and oxygen scavenging	Ensure regular stock rotation and minimise storage duration
Use malts with low LOX activity		Higher mash pH may lower wort iron content and enhance metal chelation, reducing autoxidation via Fenton chemistry.	Use acidified sparging to reduce husk polyphenol extraction and release bound aldehydes for removal during boiling	Ensure swift and efficient hot trub separation post-boil to minimise oxygen ingress, remove metal ions, and limit aldehyde formation				
Application of hops rich in polyphenols and α-acids can improve antioxidative activity via radical scavenging and/or metal chlation		Minimise shear forces (e.g. stirring, pumping) before boiling to reduce oxygen ingress and matrix disruption; consider laminar-flow technologies	Clear wort production is recommended to minimise staling precursors	Rapidly cool wort after clarification to minimise thermal load				

port the formation of singlet oxygen. Brown and dark-green bottles provide partial protection against UV exposure, but aluminium cans and kegs offer complete light exclusion, making them the most effective option for preventing light-induced flavour defects [84, 141].

Conditioned beers (those refermented in the bottle or krausened with fresh yeast) have shown improved flavour stability, even when yeast cell counts are relatively low [214, 233, 248]. The presence of viable yeast may continue to reduce residual aldehydes and scavenge oxygen, offering a protective effect. However, these benefits must be weighed against potential drawbacks, such as autolysis in bottom-fermented beers, which can lead to proteolytic off-flavours and haze or sediment formation in packaged beer. These sensory and visual issues may limit the acceptability of bottle-conditioned beers for certain markets, despite their improved chemical stability.

6.5 Storage and distribution

Storage and distribution remain critical and often underestimated stages in the maintenance of beer flavour stability. Despite precision in brewing and packaging, flavour deterioration can still occur once beer enters the supply chain - largely due to environmental conditions that are beyond the direct control of the brewer. Elevated heat, light exposure, and physical agitation during transportation are among the most significant contributors to sensory changes during distribution, especially for beers exported over long distances [123, 249].

Heat is the most influential factor affecting chemical degradation during storage, with numerous studies advocating for the implementation of a cold supply chain to preserve flavour quality [14, 29, 87]. Beer stored at 8 °C can be expected to retain freshness for roughly twice as long as beer stored at 18 °C. The temperature dependence underlines the importance of refrigerated storage throughout warehousing, transport, and retail.

Beyond thermal conditions, mechanical stress from vibrations during transport also plays a role in flavour stability. Janssen et al. [250] demonstrated that sustained vibration negatively affects colloidal stability, potentially accelerating haze formation and protein-polyphenol interactions. More critically, vibrations may promote oxygen ingress into packaged beer, especially in non-hermetic containers, thus fuelling oxidation reactions [251]. The nature and impact of these vibrations vary depending on the transport method, with sea and land freight producing different intensities and frequencies of mechanical shock [250, 252].

Packaging configuration can mitigate some of these risks. Studies have shown that beers distributed in corrugated cardboard boxes experience fewer quality losses than those transported in plastic crates, likely due to better insulation from heat, light, and mechanical stress. The combination of cardboard boxes wrapped in plastic film appears to offer optimal protection by combining thermal insulation, light shielding, and vibration dampening [19, 253].

Finally, warehousing practices have a direct impact on product freshness. Maintaining continuous stock rotation and minimising storage duration are fundamental to preserving beer quality on the shelf. Extended storage times, especially at elevated ambient temperatures, increase the likelihood of oxidative changes and stale flavour development, even if beer is properly packaged. Regular turnover and proper warehouse climate control remain simple yet essential tools for managing flavour stability during distribution [29].

6.6 Summary of Process Impact on Flavour Stability

Each step in the brewing process plays a distinct role in determining the flavour stability of the final beer. From malt selection and mashing conditions to wort boiling, fermentation, and packaging, multiple control points influence the formation or mitigation of staling compounds. Critical factors include oxygen ingress, heat load, metal ion content, and yeast metabolic activity. Table 2 summarises the key control points throughout the brewing process that directly impact beer flavour stability.

7 Conclusions

It is extremely challenging to obtain a clear picture elucidating the phenomenon of beer flavour instability, mostly due to the complexity of the malting and brewing processes as well as numerous compounds involved and the sheer diversity of mechanisms behind their formation. The key contributors to beer staling are aldehyde compounds and two general pathways for their production have been proposed: *de novo* formation and the release from the bound-state. In fact, little is known about the relative importance of the mechanisms and the occurrence of staling aldehydes in stored beer, still posing a relevant research gap. Recent research on bound state aldehydes cannot confirm their relative contribution to beer staling. Volatile aldehydes present in malt or formed during the brewing process are unlikely to end up in the final beer and thus cannot be a direct cause for beer staling. In this connection, research attention should be drawn to the generation of precursors and intermediate products for aldehyde formation during malting and brewing. This involves i.a. α-dicarbonyls for Strecker degradation, 3-deoxysones from pentosans as intermediates for Maillard reactions and/or trihydroxy fatty acids as precursors for lipid oxidation aldehydes.

In recent decades, significant advancements have been made in both raw materials and brewing operations, yet continuous progress remains essential. The development of innovative malt types with reduced staling potential has enabled brewers to minimise the initial pool of flavour-degrading precursors. These malts also allow for higher initial mashing temperatures, effectively shortening the mash duration and reducing thermal stress. From a process engineering perspective, ongoing research into lowering the heat load during wort production is particularly relevant, as reduced thermal input limits the formation of Strecker aldehydes and Maillard-derived compounds, both fundamental to flavour instability. Additionally, targeted strategies to remove transition metal ions – especially iron and copper – from early stages such as mashing and lautering have shown promise in limiting oxidative reactions catalysed by Fenton-type mechanisms. Parallel to these developments, investigations into yeast strain selection and fermentation conditions continue to reveal the crucial role of yeast metabolism not only in aldehyde reduction but also in sulphite production and the secretion of flavour-masking esters.

Lastly, innovations in packaging technologies remain an active field of research, with improvements in oxygen-scavenging materials, light-blocking containers, and advanced sealing systems.

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