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WOOD AGING IN BEER: CHEMICAL, SENSORY, AND TECHNOLOGICAL PERSPECTIVES — A CRITICAL REVIEW

ENVELHECIMENTO DA CERVEJA EM MADEIRA: PERSPECTIVAS QUÍMICAS, SENSORIAIS E TECNOLÓGICAS — UMA REVISÃO CRÍTICA

ENVEJECIMIENTO DE LA CERVEZA EN MADERA: PERSPECTIVAS QUÍMICAS, SENSORIALES Y TECNOLÓGICAS — UNA REVISIÓN CRÍTICA

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Maria Anita Mendes[1]

ABSTRACT
Wood aging has emerged as an increasingly relevant technique in craft beer production, expanding beyond its traditional applications in wine and distilled spirits. The interaction between beer and wood involves complex physical, chemical, and sensory mechanisms that significantly influence aroma, flavor, color, and overall product stability. This review examines the fundamental principles governing wood aging in beer, with emphasis on wood species and botanical origin, chemical composition, extraction kinetics, and the impact of aging parameters such as contact time, surface area, oxygen ingress, and processing format. Attention is given to the role of wood-derived volatile compounds, including lactones, aldehydes, phenols, and furanic compounds, as well as non-volatile constituents such as polyphenols and organic acids. Analytical approaches commonly applied to the study of wood-aged beers, notably gas chromatography–mass spectrometry (GC–MS) and high-performance liquid chromatography (HPLC), are discussed alongside their relevance for monitoring chemical evolution during aging. Furthermore, the integration of chemical data with sensory evaluation, supported by multivariate statistical methods, is highlighted as a key strategy for establishing chemical–sensory correlations and predicting sensory outcomes. The review also addresses the use of alternative wood formats and non-traditional wood species as tools for sensory innovation and regional differentiation, emphasizing the importance of safety assessment and process control. Overall, this work aims to provide a scientifically grounded framework for the controlled application of wood aging in craft brewing, supporting product consistency, quality optimization, and informed innovation.

Keywords: Beer. Barrel-aged beer. Wood Maturation. Wood–beer Interactions.

RESUMO
O envelhecimento em madeira tem emergido como uma técnica cada vez mais relevante na produção de cervejas artesanais, expandindo-se além de suas aplicações tradicionais em vinhos e destilados. A interação entre a cerveja e a madeira envolve mecanismos físicos, químicos e sensoriais complexos que influenciam significativamente o aroma, o sabor, a cor e a estabilidade geral do produto. Esta revisão examina os princípios fundamentais que

[1] Dr. in Science. Polytechnic School. Universidade de São Paulo (USP). São Paulo, Brazil.
E-mail: mariaanita.mendes@gmail.com Orcid: https://orcid.org/0000-0002-2078-9286
Lattes: https://lattes.cnpq.br/4809400871166644

regem o envelhecimento da cerveja em madeira, com ênfase nas espécies de madeira e sua origem botânica, na composição química, na cinética de extração e no impacto de parâmetros de envelhecimento, como tempo de contato, área de superfície, entrada de oxigênio e formato de processamento. É dada atenção ao papel dos compostos voláteis derivados da madeira, incluindo lactonas, aldeídos, fenóis e compostos furânicos, bem como aos constituintes não voláteis, como polifenóis e ácidos orgânicos. Abordagens analíticas comumente aplicadas ao estudo de cervejas envelhecidas em madeira, notadamente a cromatografia gasosa acoplada à espectrometria de massas (GC–MS) e a cromatografia líquida de alta eficiência (HPLC), são discutidas juntamente com sua relevância para o monitoramento da evolução química durante o envelhecimento. Além disso, a integração de dados químicos com a avaliação sensorial, apoiada por métodos estatísticos multivariados, é destacada como uma estratégia fundamental para estabelecer correlações químico-sensoriais e prever resultados sensoriais. A revisão também aborda o uso de formatos alternativos de madeira e de espécies de madeira não tradicionais como ferramentas para inovação sensorial e diferenciação regional, enfatizando a importância da avaliação de segurança e do controle de processos. De modo geral, este trabalho tem como objetivo fornecer uma estrutura cientificamente fundamentada para a aplicação controlada do envelhecimento em madeira na produção de cervejas artesanais, apoiando a consistência do produto, a otimização da qualidade e a inovação informada.

Palavras-chave: Cerveja. Cerveja Envelhecida em Barril. Maturação em Madeira. Interações Madeira–Cerveja.

RESUMEN

El envejecimiento en madera ha surgido como una técnica cada vez más relevante en la producción de cerveza artesanal, expandiéndose más allá de sus aplicaciones tradicionales en vino y bebidas destiladas. La interacción entre la cerveza y la madera implica mecanismos físicos, químicos y sensoriales complejos que influyen significativamente en el aroma, el sabor, el color y la estabilidad general del producto. Esta revisión examina los principios fundamentales que gobiernan el envejecimiento de la cerveza en madera, con énfasis en las especies de madera y su origen botánico, la composición química, la cinética de extracción y el impacto de los parámetros de envejecimiento, como el tiempo de contacto, el área de superficie, la entrada de oxígeno y el formato de procesamiento. Se presta especial atención al papel de los compuestos volátiles derivados de la madera, incluidos lactonas, aldehídos, fenoles y compuestos furánicos, así como a los constituyentes no volátiles, como los polifenoles y los ácidos orgánicos. Los enfoques analíticos comúnmente aplicados al estudio de las cervezas envejecidas en madera, en particular la cromatografía de gases acoplada a espectrometría de masas (GC–MS) y la cromatografía líquida de alta eficiencia (HPLC), se discuten junto con su relevancia para el monitoreo de la evolución química durante el envejecimiento. Además, la integración de datos químicos con la evaluación sensorial, respaldada por métodos estadísticos multivariados, se destaca como una estrategia clave para establecer correlaciones químico-sensoriales y predecir resultados sensoriales. La revisión también aborda el uso de formatos alternativos de madera y especies de madera no tradicionales como herramientas para la innovación sensorial y la diferenciación regional, enfatizando la importancia de la evaluación de seguridad y el control del proceso. En general, este trabajo tiene como objetivo proporcionar un marco científicamente fundamentado para la aplicación controlada del envejecimiento en madera en la elaboración de cerveza artesanal, apoyando la consistencia del producto, la optimización de la calidad y la innovación informada.

Palabras clave: Cerveza. Cerveza Envejecida en Barril. Maduración en Madera. Interacciones Madera–Cerveza.

1 INTRODUCTION

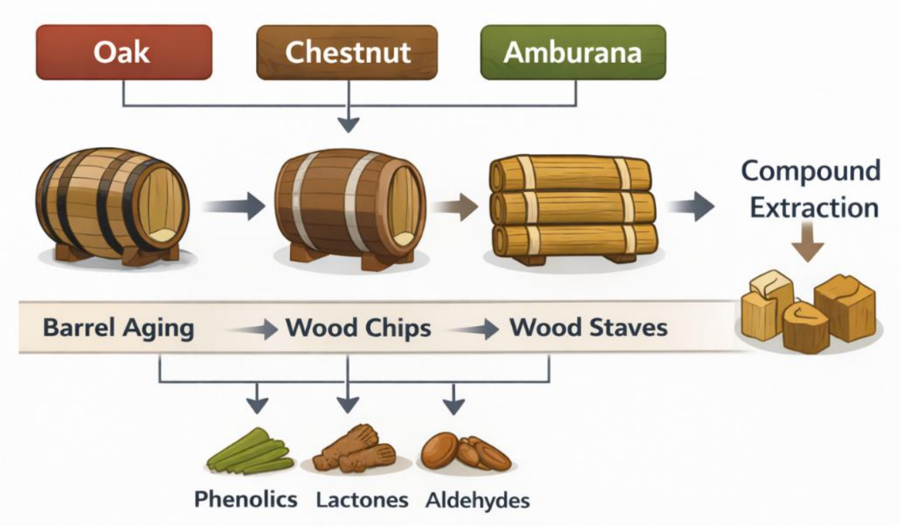
Wood aging has emerged as a significant practice in craft brewing, offering brewers a technological pathway to enhance flavor complexity, achieve sensory differentiation, and strengthen product identity. Although traditionally associated with wine and distilled spirits, the deliberate use of wood in beer has expanded considerably within the craft sector. This growth is driven both by consumer demand for novel sensory experiences and by the versatility of wood-derived compounds in shaping aroma, flavor, and mouthfeel.

The interaction between beer and wood is multifaceted. It depends on several variables, including the species of wood (Figure 1), the degree of toasting, the aging technique employed, and the composition of the beer itself. Early studies demonstrated that oak contact promotes the extraction of phenolic compounds, lactones, and aldehydes, leading to perceptible changes in aroma and flavor—most notably notes of vanilla, coconut, spice, and toast (Wyler et al., 2015) Later investigations quantified these wood-derived phenolics and examined their contribution to antioxidant capacity and beer stability (Machado et al., 2023). However, many studies have treated chemical composition and sensory perception separately, often under narrowly defined experimental conditions. More recent work has shown that factors such as wood species, toasting level, aging format (barrel versus alternatives), and beer matrix significantly influence both compound extraction and sensory expression (Bossaert et al., 2022a, 2022b). Interactions between wood aging, fermentation characteristics, and beer style have also been reported, yet these effects remain insufficiently systematized in the literature.

Against this backdrop, an integrated and brewing-oriented synthesis of current knowledge is needed. This review aims to critically examine how wood aging shapes the sensory and chemical profile of craft beers, with emphasis on wood composition, aging techniques, beer style, and fermentation characteristics. By linking chemical data with sensory perception and practical brewing considerations, the article seeks to provide a comprehensive overview of the benefits, limitations, and technological challenges associated with wood aging, while highlighting research gaps and future perspectives for its controlled and reproducible application.

Figure 1

Extraction of phenolics, lactones, and aldehydes from Oak, Chestnut, and Amburana wood via barrels, chips, or staves during aging



2 WOOD AGING IN BREWING PRACTICE

Wood aging has historically played a central role in brewing, originating from the use of wooden vessels for fermentation, storage, and transport long before stainless steel became standard (Ian Spencer Hornsey, 2003). Initially adopted for practical reasons, brewers soon realized that wood interacted chemically with beer, imparting distinctive sensory attributes and contributing to product differentiation (Charles W. Bamforth, 2023). In modern craft brewing, wood aging has been reintroduced deliberately as a flavor-modulating technique rather than a necessity, allowing brewers to explore complexity, terroir, and innovation (Pires & Brányik, 2018).

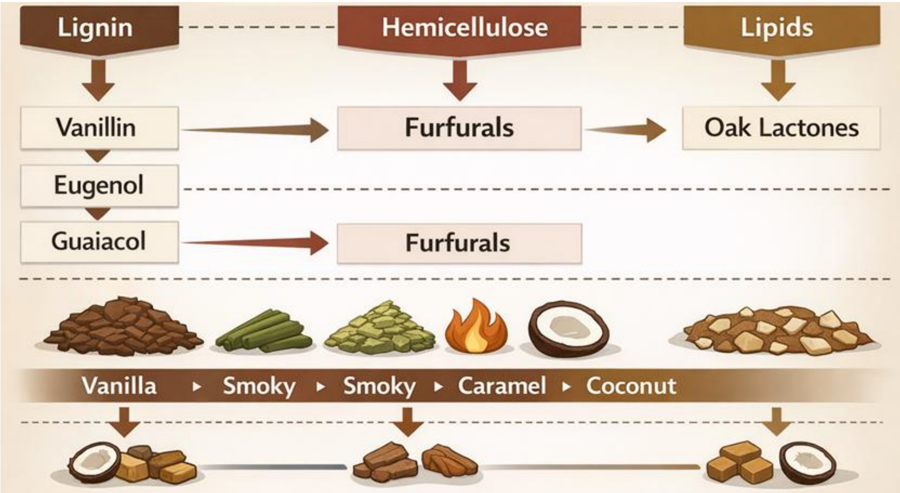
The influence of wood on beer arises from a combination of physical, chemical, and biological interactions. Wood is porous and heterogeneous, composed primarily of cellulose, hemicellulose, lignin, and a wide range of extractable compounds(Mosedale; Puech, 1998)) During aging, these extractives gradually dissolve into the beer, including phenolic compounds, lactones, aldehydes, and volatile aromatics. Compounds such as vanillin, eugenol, furfural, and oak lactones are particularly relevant because of their low sensory thresholds and pronounced impact on aroma and flavor perception(Alañón et al., 2009; Rodríguez-Bencomo et al., 2009).

Oak (*Quercus* spp.) is the most used wood in brewing, largely due to its established role in wine and spirits, its chemical stability, and its favorable sensory profile. Yet other woods—such as chestnut, cherry, maple, and amburana—have gained attention, especially in regions seeking local identity and distinctive sensory signatures. The botanical origin of the wood significantly affects its chemical composition and, consequently, the flavor compounds transferred to beer (Machado et al., 2023; Smailagić et al., 2025)

Processing and treatment of wood also play a decisive role. Toasting and charring alter the degradation pathways of lignin and hemicellulose, leading to the formation of different volatile compounds. Light toasting tends to enhance coconut and woody notes through lactone release, whereas medium to heavy toasting favors caramel, vanilla, smoky, and spicy characteristics (Figure 2). These effects allow brewers to tailor wood selection according to beer style and desired sensory expression (Arapitsas et al., 2004; Boidron; Chatonnet; Pons, 1988; Chatonnet et al., 1992; Waterhouse; Sacks; Jeffery, 2017).

Figure 2

Flavor compounds derived from lignin, hemicellulose, and lipids in wood, leading to vanillin, eugenol, guaiacol, furfurals, and oak lactones, which contribute to vanilla, smoky, caramel, and coconut notes



In practice, wood aging can be implemented using various formats, including barrels, foeders, staves, chips, cubes, and spirals. Barrels remain the most complex system, as they introduce not only wood-derived compounds but also oxygen ingress through micro-oxidation and, in some cases, microbial activity (Bossaert et al., 2022a, 2022b; Oberholster et al., 2015). Conversely, alternative formats provide greater control over extraction kinetics, reduced cost, and improved reproducibility, though with limited oxidative contribution.(González-Centeno; Chira; Teissedre, 2019)

The duration of wood contact is another critical parameter. Extraction rates are influenced by surface area, alcohol content, temperature, and beer matrix composition (Machado et al., 2023). Short contact times may yield subtle aromatic enhancements, while prolonged aging increases the risk of over-extraction, excessive astringency, or sensory imbalance. Careful monitoring of both chemical and sensory evolution is therefore essential throughout the process (Harry T. Lawless, 2010).

Overall, wood aging has evolved into a strategic tool within craft brewing, enabling the creation of beers with enhanced complexity and distinct identity. Understanding the interactions between wood characteristics, processing conditions, and beer composition is fundamental for optimizing sensory outcomes and ensuring product consistency. As wood-aged beers continue to gain commercial and academic relevance, brewers must balance tradition with scientific control to achieve reproducible and distinctive results (Sterckx; Saison; Delvaux, 2012a, 2012b).

3 CHEMICAL AND SENSORY IMPACT OF WOOD AGING ON CRAFT BEER

The impact of wood aging on craft beer is expressed primarily through changes in chemical composition and the corresponding sensory attributes (Machado et al., 2023; Sterckx; Saison; Delvaux, 2012a, 2012b). The extraction of wood-derived compounds, combined with oxidative reactions and interactions with the beer matrix, produces a complex array of volatile and non-volatile constituents that shape aroma, flavor, and mouthfeel (Mosedale; Puech, 1998). These changes can be systematically characterized using analytical techniques such as gas chromatography–mass spectrometry (GC–MS) and high-performance liquid chromatography (HPLC), alongside structured descriptive sensory analysis (Harry T. Lawless, 2010; Hildegarde Heymann, 1999; Waterhouse; Sacks; Jeffery, 2017). An integrated chemical–sensory approach is therefore essential to explain how wood aging modulates beer quality, enables style differentiation, and contributes to the perceived complexity of wood-aged craft beers.

Wood is chemically complex, and its influence on beer arises mainly from compounds derived from lignin, hemicellulose, and a diverse pool of extractives. Thermal degradation of lignin during toasting generates aromatic aldehydes and volatile phenols, while hemicellulose breakdown contributes furanic compounds associated with caramelized and toasted notes(Mosedale; Puech, 1998). In parallel, extractives such as lactones and ellagitannins are progressively solubilized into the beer matrix during aging (Waterhouse; Sacks; Jeffery, 2017). The extent and kinetics of this transfer depend not only on wood species and toasting level but also on intrinsic beer properties such as alcohol content, pH, and temperature (Machado et al., 2023; Sterckx et al., 2012b, 2012a).

3.1 VOLATILE COMPOUNDS DERIVED FROM WOOD AGING

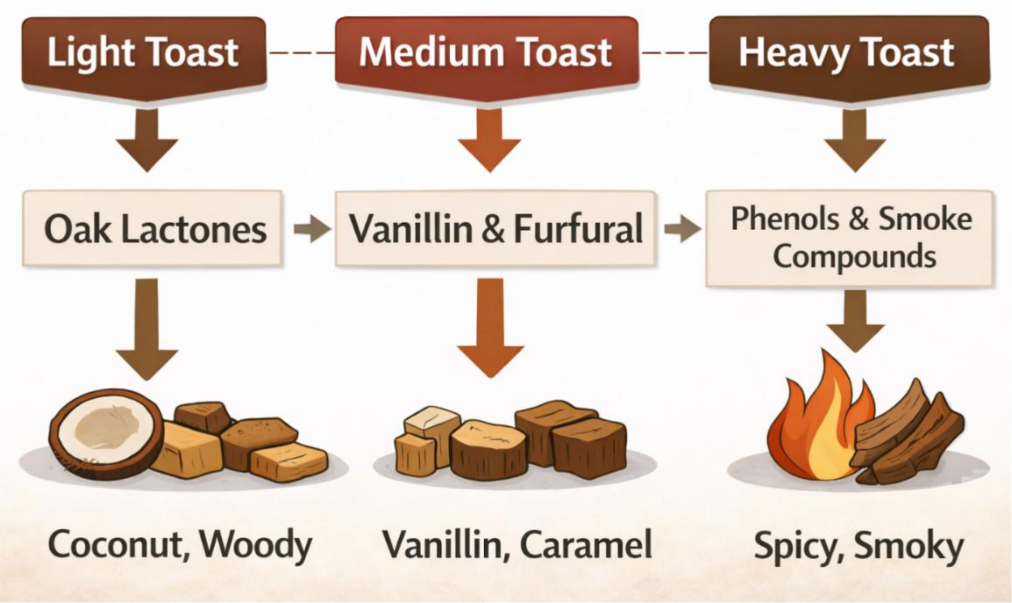
Volatile compounds are central to the aromatic profile of wood-aged beers and represent some of the most powerful drivers of sensory differentiation. They originate mainly from the thermal degradation of wood polymers during seasoning and toasting, and are later extracted into the beer matrix (Mosedale; Puech, 1998). GC–MS is the most widely used technique for identifying and quantifying these volatiles, providing detailed insight into wood-derived aroma compounds in beer (Figure 3).

- **Phenolic aldehydes** such as vanillin and syringaldehyde contribute sweet, vanilla-like notes.
- **Volatile phenols** including guaiacol and eugenol are linked to smoky, spicy, and clove-like attributes (Boidron; Chatonnet; Pons, 1988; Chatonnet et al., 1992).
- **Oak lactones** (cis- and trans-β-methyl-γ-octalactone) impart coconut, woody, and sweet aromas. Their concentration depends strongly on wood species, geographical origin, and toasting level, with American oak generally richer in lactones than European oak(Cadahía et al., 2001; Waterhouse; Sacks; Jeffery, 2017).
- **Furanic compounds** such as furfural and 5-methylfurfural, formed from hemicellulose degradation, add caramel, toasted, and almond-like notes. At moderate levels they enhance complexity, but in excess they can produce harsh or burnt flavors.

Wood aging also indirectly influences aroma through oxidative pathways and interactions with yeast-derived compounds. Slow oxygen ingress, particularly in barrel aging, promotes aldehyde and ester formation, further modifying the aromatic profile (Boulton et al., 1996). The resulting volatile composition reflects a dynamic balance between extraction, transformation, and loss, underscoring the need for integrated monitoring throughout aging.

Figure 3

Flavor compounds generated by different wood toast levels: light toast yields oak lactones (coconut, woody), medium toast produces vanillin and furfural (vanilla, caramel), and heavy toast forms phenols and smoke compounds (spicy, smoky)



3.2 NON-VOLATILE COMPONENTS AND POLYPHENOLIC PROFILE (HPLC)

Beyond volatiles, wood aging significantly alters the non-volatile composition of beer, especially through the extraction of polyphenolic compounds. These molecules shape mouthfeel, astringency, color stability, and oxidative behavior. HPLC is the preferred method for separating and quantifying these compounds (Mosedale; Puech, 1998; Waterhouse; Sacks; Jeffery, 2017).

- **Ellagitannins** interact with proteins and polysaccharides, influencing astringency and body perception (Puech, 1987). In beer, these effects are modulated by residual proteins and β-glucans from malt.
- **Phenolic acids and flavonoids** contribute to bitterness and structure (Waterhouse; Sacks; Jeffery, 2017).
- **Oxidation and polymerization reactions** during aging can increase molecular weight, affecting both color development and colloidal stability.

Moderate polyphenol extraction enhances perceived complexity, while excessive levels risk harsh bitterness or drying sensations. In addition, changes in organic acid composition subtly influence taste balance, particularly in beers aged for extended periods. Non-volatile analysis therefore complements volatile profiling, offering a fuller picture of how wood aging impacts beer quality.

3.3 SENSORY ATTRIBUTES AND CHEMICAL–SENSORY CORRELATIONS

Ultimately, chemical modifications induced by wood aging translate into sensory attributes that define the identity of wood-aged beers (Figure 4). Descriptive sensory analysis systematically characterizes aroma, flavor, and mouthfeel, enabling reproducible evaluation of wood-related effects (Harry T. Lawless, 2010; Hildegarde Heymann, 1999).

Typical descriptors include vanilla, coconut, caramel, spice, toast, smoke, and woody notes, alongside changes in bitterness, astringency, and body. Sensory outcomes depend on the concentration and balance of both volatile and non-volatile compounds (Boidron; Chatonnet; Pons, 1988; Cadahía et al., 2001; Chatonnet et al., 1992). For example:

- Phenolic aldehydes and lactones are closely tied to sweet, vanilla, and coconut aromas.
- Furanic compounds contribute toasted and caramel characteristics.
- Polyphenols influence tactile sensations such as dryness and fullness.

Establishing chemical–sensory correlations is crucial. Multivariate statistical approaches like PCA and PLS regression link analytical data from GC–MS and HPLC with sensory descriptors (Lezhnina et al., 2025). These methods identify key compounds driving specific sensory attributes and support predictive modeling of outcomes.

An integrated chemical–sensory framework not only advances scientific understanding but also provides practical guidance for brewers. By correlating analytical markers with sensory perception, brewers can tailor wood selection, processing conditions, and aging duration to achieve targeted sensory profiles while maintaining balance and consistency.

Figure 4

Wood-Aged Beer Flavor Wheel, showcasing notes of vanilla, coconut, caramel, smoke, spice, and astringency

Collectively, the evidence shows that wood aging exerts a multifaceted influence on craft beer. Controlled extraction of volatile and non-volatile compounds, combined with their interaction with the beer matrix, creates distinctive sensory profiles. Integrating GC–MS, HPLC, and sensory analysis offers a robust framework for understanding these mechanisms and optimizing brewing practice(Lezhnina et al., 2025).

4 IMPLICATIONS FOR BREWING PRACTICE AND PRODUCT DEVELOPMENT

The growing use of wood aging in craft brewing highlights the need for a scientifically informed approach that balances sensory complexity with process control and product consistency. As discussed in the previous sections, wood aging is not a passive maturation step but a dynamic process shaped by multiple interacting variables (Charles W. Bamforth, 2023; Pires; Brányik, 2018). For this reason, brewers must consider wood selection, processing conditions, and aging strategies as integral elements of recipe design and production planning (Figure 5).

Figure 5

Barrel Aging vs. Wood Chips & Staves, a flavor journey shaped by oxygen, complexity, and cost

Wood species and botanical origin are critical determinants of the chemical profile imparted to beer. Oak remains the most versatile and predictable option due to its well-characterized composition. However, alternative woods offer opportunities for regional differentiation and novel sensory expression (Bossaert et al., 2022c; Chatonnet et al., 1992). The use of non-traditional woods requires careful evaluation, since variations in polyphenolic composition and extractable compounds can significantly affect bitterness, astringency, and overall balance. Controlled pilot-scale trials, combined with analytical monitoring, are therefore recommended before commercial implementation (Mosedale; Puech, 1998).

The **format of wood contact** also plays a decisive role in extraction kinetics and reproducibility. Barrel aging provides a complex environment where wood-derived compounds, oxygen ingress, and microbial activity interact simultaneously (Bokulich; Bamforth; Mills, 2012; Boulton et al., 1996). While this approach can yield highly complex products, it introduces variability that may challenge consistency in small-scale brewing operations. In contrast, alternative formats such as chips, staves, and spirals allow greater control over surface area, contact time, and extraction rate, enabling more precise modulation of sensory attributes and improved batch-to-batch reproducibility (Kruger; Alberti; Nogueira, 2022).

Aging duration and process conditions must be optimized to prevent over-extraction and sensory imbalance. Excessive contact with wood can lead to dominant woody, bitter, or astringent characteristics that mask the intrinsic qualities of malt and hops. Regular sensory evaluation, supported by targeted chemical analysis, is essential for determining optimal aging endpoints. Factors such as alcohol content, temperature, and beer matrix composition should also be considered, as they influence extraction efficiency and compound stability (Waterhouse; Sacks; Jeffery, 2017).

From a **product development perspective**, integrating chemical and sensory data provides valuable guidance for designing wood-aged beers aligned with specific style goals and consumer expectations. Correlating analytical markers with sensory descriptors enables brewers to predict outcomes and adjust processing variables accordingly (Rodríguez-Bencomo et al., 2009). This approach supports innovation while maintaining quality and coherence, particularly in a market where wood-aged beers are often positioned as premium or limited-release products.

Overall, applying scientific principles to wood aging enhances its value as a controlled and reproducible brewing technique rather than an empirical or purely artisanal practice. By combining analytical insight with sensory evaluation, brewers can harness the full potential of wood aging to create distinctive, balanced, and consistent craft beers, reinforcing its role in contemporary brewing practice (Charles W. Bamforth, 2023; Harry T. Lawless, 2010).

5 IMPACT ON THE SENSORY PROFILE OF CRAFT BEERS

Wood aging exerts a profound influence on the sensory profile of craft beers, primarily through modifications in aroma, flavor, and mouthfeel. Aroma is often the most immediately perceptible dimension, with descriptors such as vanilla, coconut, spice, toast, and smoke frequently associated with wood contact. These attributes are largely driven by wood-derived volatile compounds, including phenolic aldehydes, lactones, and furanic compounds, whose sensory impact depends on concentration, balance, and interaction with the beer matrix (Boidron; Chatonnet; Pons, 1988; Cadahía et al., 2001; Chatonnet et al., 1992).

Beyond aroma, wood aging significantly affects flavor perception and mouthfeel. Polyphenolic compounds, particularly ellagitannins extracted from wood, contribute to bitterness, astringency, and perceived structure. Moderate levels of these compounds may enhance body and complexity, whereas excessive extraction can lead to harsh, drying sensations and sensory imbalance (Waterhouse; Sacks; Jeffery, 2017). These tactile effects are further modulated by interactions with beer proteins and polysaccharides, underscoring the importance of matrix-dependent sensory responses.

A critical aspect of successful wood aging lies in achieving balance between wood-derived characteristics and the intrinsic attributes of malt, hops, and alcohol. Excessive woody or toasted notes may obscure malt complexity or hop-derived aromas, while insufficient wood influence may result in limited sensory differentiation. Alcohol content plays a dual role: it enhances the solubility of wood-derived compounds and modulates their sensory perception, particularly for volatile and semi-volatile compounds (Mosedale; Puech, 1998).

Whenever possible, establishing chemical–sensory relationships strengthens the interpretation of sensory outcomes. Correlations between specific compounds—such as vanillin and coconut-like lactones—and their corresponding sensory descriptors provide mechanistic insight into flavor development and support predictive approaches to product design (Rodríguez-Bencomo et al., 2009). Such integration reinforces the value of combining instrumental analysis with structured sensory evaluation in studies of wood-aged beer.

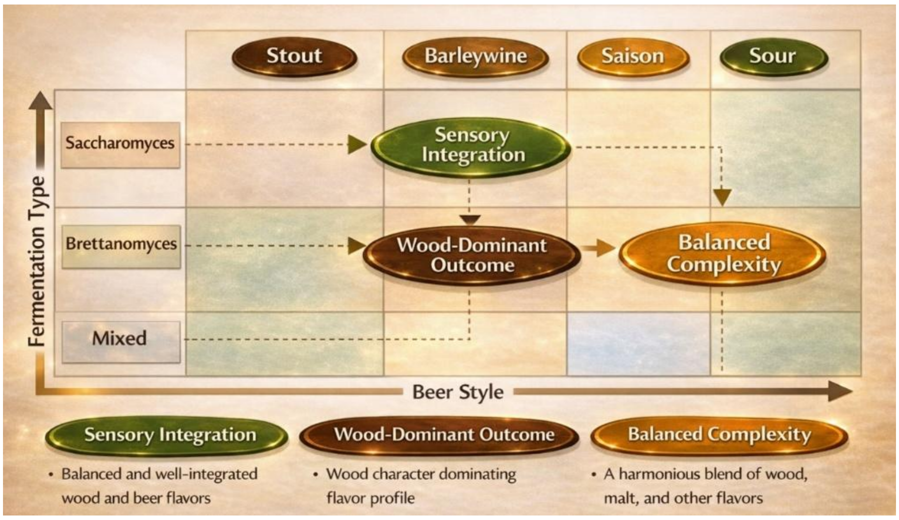
In sum, wood aging reshapes the sensory profile of craft beers in a multidimensional way. By carefully balancing volatile and non-volatile contributions, brewers can achieve products that are distinctive yet harmonious, ensuring that wood influence enhances rather than overwhelms the intrinsic character of the beer.

6 INFLUENCE OF BEER STYLE AND FERMENTATION

The suitability of wood aging is strongly influenced by beer style and fermentation characteristics (Figure 6). High-gravity and malt-forward styles, such as stouts and barleywines, are particularly well-suited to wood aging because of their robust flavor profiles and elevated alcohol content. These attributes support the integration of wood-derived compounds, allowing vanilla, caramel, and toasted notes to complement the richness of malt (Charles W. Bamforth, 2023). Sour beers and farmhouse-style saisons also demonstrate strong compatibility with wood aging, as their acidity and phenolic complexity can harmonize with woody, spicy, and smoky characteristics (Pires; Brányik, 2018).

Figure 6

Beer Flavor Outcomes Wheel, mapping fermentation type and style to sensory results



Fermentation plays a decisive role in shaping the interaction between beer and wood. The use of non-conventional yeasts, including *Brettanomyces* spp., introduces additional metabolic pathways that interact with wood-derived compounds, producing enhanced complexity and unique aromatic signatures (Bokulich; Bamforth; Mills, 2012). These interactions may amplify phenolic, fruity, or earthy notes, particularly during extended aging periods, and are often sought after in mixed fermentation beers.

Alcohol content and acidity further modulate wood extraction and sensory stability. Higher ethanol levels increase the solubility of hydrophobic compounds such as lactones, intensifying coconut and woody aromas. Conversely, lower pH values influence polyphenol extraction and perception, often accentuating astringency or dryness. Together, these parameters affect not only the immediate sensory impact but also the evolution and stability of wood-aged beers during prolonged storage (Waterhouse; Sacks; Jeffery, 2017).

In practice, aligning beer style and fermentation strategy with wood aging conditions is essential. When well matched, the synergy between beer matrix and wood compounds can elevate complexity and balance. When mismatched, however, the result may be discordant, with wood notes overwhelming or clashing with the base beer. Thus, thoughtful integration of style, fermentation, and aging parameters is key to achieving successful outcomes in wood-aged craft brewing.

7 TECHNOLOGICAL CHALLENGES AND LIMITATIONS

Despite its sensory benefits, wood aging presents several technological challenges that must be carefully managed in brewing practice (Figure 7). **Oxidation** is one of the primary risks, particularly in barrel aging, where uncontrolled oxygen ingress can lead to stale flavors, aldehyde formation, and loss of freshness (Boulton et al., 1996; Oberholster et al., 2015). While controlled micro-oxidation may enhance complexity, excessive exposure compromises product quality and stability.

Another common limitation is **over-extraction of wood-derived compounds**, which often results in dominant woody, bitter, or astringent characteristics. This risk is heightened when using alternative wood formats with high surface-area-to-volume ratios, underscoring the importance of monitoring contact time and extraction kinetics.

Variability in wood composition, even within the same species, introduces further challenges to reproducibility. Differences in botanical origin, seasoning, and toasting can lead to significant batch-to-batch variation. For craft brewers, this variability complicates consistency, especially when scaling production.

Wood aging also increases **microbiological risks**, particularly in mixed or spontaneous fermentations. Contamination can compromise both safety and sensory quality, making hygiene and monitoring essential(Bokulich; Bamforth; Mills, 2012).

Finally, achieving reproducibility at scale remains a critical challenge. Standardization of wood sourcing, processing, and analytical monitoring is necessary to translate small-scale success into consistent commercial production. Without such control, brewers risk variability that undermines both product identity and consumer trust.

Figure 7

Critical control points in wood-aging: quality assurance from wood to bottle

8 FUTURE PERSPECTIVES FOR WOOD AGING IN CRAFT BREWING

Future research and brewing practice would benefit greatly from greater experimental standardization in wood aging studies (Figure 8). Controlled comparisons of wood species, toasting levels, and aging formats would enhance reproducibility and facilitate cross-study comparisons, thereby strengthening the espitiscientific foundation of wood-aged beer research(Bokulich; Bamforth; Mills, 2012; Charles W. Bamforth, 2023).

The exploration of alternative and non-European wood species represents a promising avenue for innovation, particularly for breweries seeking regional identity and differentiation. For example, Brazilian amburana or Japanese cedar could provide distinctive sensory signatures that connect beer more closely to local culture. However, the sensory and chemical safety of these woods must be systematically evaluated to ensure their suitability for food applications (Souza et al., 2025).

Advances in analytical techniques and multivariate data analysis also offer opportunities for more robust chemical–sensory correlations. Predictive modeling of sensory outcomes based on chemical composition could allow brewers to design beers with greater precision, reducing reliance on trial-and-error approaches. Such tools would be particularly valuable for small breweries aiming to innovate while maintaining consistency.

Figure 8

Innovation meets tradition — exploring sustainability, analytics, and sensory modeling in the future of wood-aged brewing

In addition, sustainability considerations are likely to gain importance as environmental concerns increasingly shape brewing practices. Strategies such as wood reuse, by-product valorization, and circular economy approaches could help reduce waste and improve resource efficiency. For instance, reconditioning barrels for multiple uses or repurposing wood chips for other applications may align brewing innovation with ecological responsibility.

Overall, the future of wood aging in craft brewing lies in combining tradition with scientific rigor and sustainability. By exploring new wood sources, refining analytical methods, and adopting environmentally conscious practices, brewers can continue to expand the sensory possibilities of wood-aged beer while ensuring safety, reproducibility, and ecological balance.

9 CONCLUSIONS

Wood aging represents a powerful sensory tool in craft brewing, capable of enhancing complexity, structure, and product differentiation when applied under controlled conditions. Its successful implementation requires an integrated understanding of wood chemistry, beer matrix interactions, and sensory perception.

The findings discussed in this review highlight the necessity of technological control and analytical monitoring to balance innovation with consistency. Wood aging should not be seen merely as a traditional or artisanal practice, but as a scientifically grounded technique that can be optimized to achieve reproducible results.

Ultimately, the integration of chemical and sensory approaches provides a robust framework for refining wood aging strategies. By combining analytical insight with sensory evaluation, brewers can harness the full potential of wood to create distinctive, balanced, and memorable craft beers. In doing so, wood aging reinforces its relevance not only in contemporary brewing practice but also in shaping the future of beer innovation.

AI STATEMENT

The author utilized AI-assisted tools, including ChatGPT, OpenAI, Scispace, and Grammarly, to aid language editing, text revision, produce figures and improve figures captions, and enhancing clarity and organization. All scientific content, analysis, conclusions, and decisions regarding the structure and accuracy of the manuscript were solely generated, verified, and validated by the author. The AI tools were used under human oversight and did not contribute to the originality or authorship of the work.

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