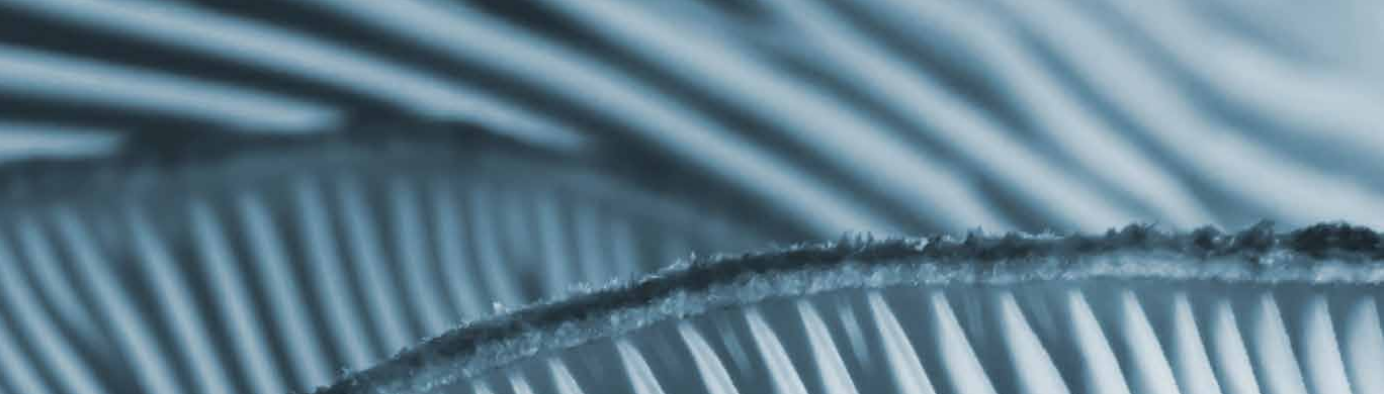


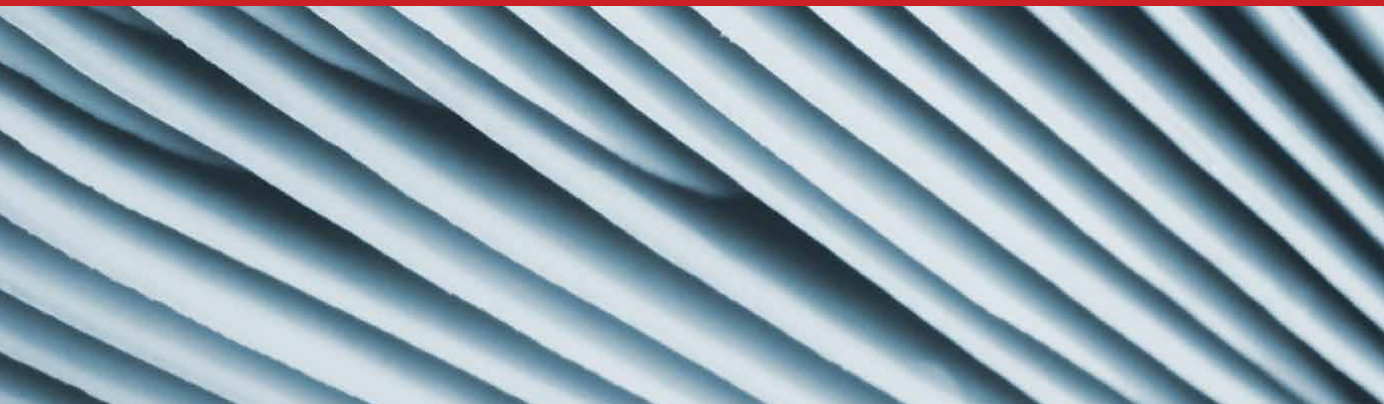


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Food Science and Nutrition, Volume 20

Emerging Trends in Beverage Industry

*Edited by Antonio Morata,
Alice Vilela and Paola Domizio*



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Food Science and Nutrition

Volume 20

Aims and Scope of the Series

The significance of food is undeniable, especially in light of the impending challenge facing humanity: ensuring there will be enough food to meet the basic needs of a population expected to reach approximately 10 billion by 2050. These food-related challenges align with some of the United Nations' sustainable development goals, with a target to achieve them by 2030. One thing is certain: food should be not only nourishing and safe but also tailored to the diverse needs of individuals throughout their lifetimes, all while meeting consumers' sensory expectations. Understanding the diverse chemical composition of food, often referred to as biodiversity, and how these components can contribute to human health by considering factors like bioaccessibility, bioavailability, and bioactivity at the organ level, is crucial for grasping and promoting a healthy diet. Thanks to the continuous evolution of analytical methods and interdisciplinary research, significant strides have been made in the field of food science and nutrition.

Meet the Series Editor



Maria Rosário Bronze has been working in Analytical Chemistry since 1986. Her Ph.D. in 1999 contributed to the study of food products using capillary electrophoresis. The main goal of her research since 1999 has been focused on Analytical Chemistry applied mainly to the analysis of foods and by-products of food industry. She conducted research in collaboration with national and international research groups, at iBET and ITQB Technology Division. From 2017 until 2021 she was head of Food & Health Division at iBET and head of the Food Functionality and Bioactives Laboratory. MR Bronze has been an Associate Professor at the Pharmacy Faculty of Lisbon University and head of the Structural Analysis Laboratory since 2012. As a researcher, MR Bronze is a Senior Scientific Advisor at Food & Health Division at iBET and Head of Food Functionality and Bioactives Laboratory at the same Institute, Collaborator at iMED and Researcher at ITQB NOVA. Her current research is focused on quality and beneficial health effects of food components. Gas and liquid chromatography associated with mass spectrometry are used by MR Bronze in the characterization of samples. Sensory evaluation is also an important area of her research. The main food products studied by her are olive tree products (olive, olive oil, leaves), cereals such as maize, legumes (faba bean, pea, chickpea, lentils) fruits (apple, grapes, opuntia ficus), fruit juices and wine, among others. More recently her interests have also involved biodiversity, bioaccessibility, and bioavailability studies on food products and their components, mainly phytochemicals as phenolic compounds, using different analytical tools such as mass spectrometry. As a senior scientific advisor at Food & Health Division at iBET she is involved in different areas: (i) isolation, characterization and formulation of bioactive and functional compounds or extracts from natural sources and wastes from food and other related industries; (ii) pre-clinical assays to provide support to understand health claims related with the beneficial effects of food nutrients/bioactive components; (iii) establishment of analytical methodologies including mass spectrometry state-of-the-art to fully characterize different matrices, from food products, natural extracts or biological fluids (Food Functionality and Bioactives Laboratory).

Meet the Volume Editor



Antonio Morata is a Professor of Food Science and Technology at the Universidad Politécnica de Madrid (UPM), Spain, specializing in wine technology. He is a director of the master's program in viticulture and enology and a coordinator of the master's program in food engineering at UPM. Dr. Morata is also a Professor of Enology and Wine Technology at the European Master of Viticulture and Enology (Euromaster Vinifera). He is a Spanish delegate to the group of experts in wine technology and the president of the wine microbiology section of the International Organization of Vine and Wine (OIV). He has authored more than 100 research articles, 10 books, 8 journal special issues, and 26 book chapters. Professor Morata was listed among the top 2% of scientists worldwide by Stanford University, USA, in 2021–2025. A recent review in AJGWR lists him among the 10 most productive researchers in “wine science” for the period 2016–21 (<https://doi.org/10.1111/ajgw.12546>, table 7).



Alice Vilela holds a degree in Enology, an MSc in Genetics and Species Improvement, and a Ph.D. in Microbiology from UTAD. She has taught at UTAD since 1999 and is currently an Assistant Professor in the Department of Agronomy (ECAV), teaching across undergraduate, master's, and doctoral levels. She holds leadership roles as Director of the MSc in Oenology and Viticulture, Vice-Director of the BSc in Oenology, and Director of the UTAD Tasters Panel. She has participated in over 20 funded national and international projects. Her research focuses on wine biotechnology, particularly bioreduction of volatile acidity, biodealcoholization of wines, sensory evaluation of food and wines, and development of sensory tests. She has over 100 SCI publications (h-index 30) and was listed among Stanford's top 2% most cited scientists (2021–2024).



Paola Domizio is a Professor of Food Technology at the University of Florence, where she coordinates the Master's Degree in Sustainable Innovation in Viticulture and Oenology. She teaches “Planning and Management of the Winemaking Process” in the same Master's program and “Stabilization and Conditioning of Wines” in the undergraduate Viticulture and Oenology program. She has conducted research at the Biotechnology Research Institute (CNR, Montreal) and the University of California, Davis. Her research focuses on yeast glycoproteins, non-*Saccharomyces* yeasts, yeast derivatives, enzymatic activities, aroma formation, and wine colloidal stability. Her scientific output includes about 80 research contributions published in international peer-reviewed journals with an impact factor, as well as in national and international journals in the oenological field, and presented at national and international scientific conferences.

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Preface

The beverage industry is as old as human history, with traditional products such as wine, beer, tea, and coffee, each steeped in thousands of years of tradition. However, it remains a modern and dynamic sector, rich in innovation and challenging opportunities. This book compiles recent advances in the beverage industry, focusing on innovations in traditional products, sustainability, emerging technologies for processing and preservation, regulatory frameworks, and health and safety.

The introductory chapter focuses on innovative developments in the beverage industry, detailing opportunities in traditional beverages, evolving consumer preferences, and the integration of sustainable practices. It also explores emerging technologies for processing and preservation. Additionally, health considerations are a major focus in the production of functional beverages containing bioactive compounds.

The second chapter examines the regulatory framework and the legal challenges in the food regulations, addressing the production of novel foods, the potential use of GMOs, health and sustainability considerations, and the management of byproducts and upcycled foods.

Another chapter focuses on innovations in the beverages industry, including the development of new functional beverages, the use of smart packaging to ensure safety and stability, and the production of plant-based drinks.

The next chapter addresses sustainable packaging solutions, covering edible packaging, packaging minimization, and the use of biodegradable materials as an alternative to conventional plastics, all from a sustainable development perspective.

Wines, one of the oldest fermented beverages, rich in culture, tradition, glamour, and innovation, are covered across two chapters. The first chapter explores emerging wines, including NoLo products, and the technologies and biotechnologies involved in their production, such as the use of non-*Saccharomyces* yeasts, the application of emerging non-thermal technologies for production and preservation, sustainable techniques to reduce chemical additives, and the potential use of yeast derivatives to improve wine quality and stability. The second chapter focuses on the antioxidant capacity and phenol stability of wines produced through extended maceration, including the currently fashionable ancient-style orange wines.

Coffee, another of the oldest and most widely consumed plant-based beverages, is examined in detail in a dedicated chapter. This chapter explores its cultural significance and traditions, consumption trends, and the health effects of its phenolic and other bioactive components. The impact of globalization on coffee seed production, processing, and consumption is also evaluated.

The final chapter addresses the presence of natural mycotoxins in beverages and their health implication. Strategies for control and monitoring, including instrumental analytical techniques and modern specific biosensors, are discussed to ensure safer beverages with positive health effects.

In summary, the book provides a comprehensive analysis of the main factors influencing the production of traditional and innovative beverages, with a strong emphasis on health and sustainable production practices.

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Introductory Chapter: Emerging Trends in the Beverage Industry

Paola Domizio, Alice Vilela and Antonio Morata

1. Emerging trends in the beverage industry: Key innovations and market shifts

The beverage industry is undergoing a profound transformation, driven by increasing consumer demand for health-oriented products, sustainable practices, and the integration of advanced technologies. This evolution is multifaceted, encompassing the growing popularity of functional beverages, the adoption of environmentally responsible strategies, the implementation of novel processing technologies, the expansion of digitalization, and the rising demand for craft and low- or no-alcohol alternatives.

A particularly dynamic area of growth lies in the functional beverage segment, which incorporates the bioactive ingredients such as probiotics, vitamins, and plant-derived extracts. These products are specifically designed to provide the health benefits, including strengthened immune function, enhanced cognitive performance, and improvements in physical appearance [1–3]. Current innovations in this sector focus on overcoming challenges related to ingredient stability, bioavailability, and sensory quality, utilizing the advanced techniques such as encapsulation, emulsification, and high-pressure homogenization [1, 2].

Traditional beverages, whether fermented or not, such as coffee, tea, wine, beer, cider, kombucha, and others, continue to be popular. They incorporate innovations in processing, varieties, fermentation, biotechnology, and natural methods to stabilize and preserve them. Many of them have social implications, protecting the quality of life in the developed countries and rural areas for producers, while also creating innovative processes and industries with high added value and a positive impact on consumers.

Sustainability has emerged as a central priority within the industry, with companies increasingly adopting eco-friendly approaches across production and supply chains. Efforts include sourcing organic and locally produced raw materials, as well as developing sustainable packaging solutions, such as biopolymers, nanocomposites, and active or intelligent packaging technologies [4].

Technological advancements are further reshaping the beverage processing industry. The application of non-thermal techniques—including high-pressure processing, pulsed electric fields, cold plasma, and ultrasound—has demonstrated the considerable potential in enhancing product safety, quality, and shelf life, while maintaining nutritional value and sensory integrity [5, 6].

Emerging non-thermal technologies are creating new opportunities for developing healthier beverages with the reduced chemical additives. These innovative processes enhance the extraction of natural antioxidants, pigments, and flavor compounds,

Trend/innovation	Description/impact	Citations
Functional beverages	Health-focused, bioactive ingredients	[1–3]
Sustainability & local sourcing	Eco-friendly, local ingredients, sustainable packaging	[4]
Advanced processing techniques	Nonthermal, AI, robotics for quality & efficiency	[5–7]
Low/no-alcohol & craft drinks	Health, variety, premiumization	[8, 9, 11, 12]

Table 1.
Summary of major emerging trends and innovations in beverages.

improving both the nutritional value and sensory quality of beverages. For consumers, the appeal of clean-label products—those free from artificial stabilizers and preservatives—is the robust. This is achieved through the application of gentle physical methods for processing, stabilizing, and preserving beverages, rather than relying on synthetic chemical interventions.

Moreover, this approach supports Goal 12 of the United Nations 2030 Agenda for Sustainable Development: “Ensure sustainable consumption and production patterns.” It promotes the efficient use of natural resources and the sustainable management of chemicals, aiming to establish environmentally responsible and resource-efficient food production systems by 2030.

At the same time, the integration of digital technologies, artificial intelligence, and robotics is transforming beverage production and consumer engagement. These tools optimize quality control, enable personalized product recommendations, and enhance customer experiences [7].

Consumer preferences are also evolving toward low- and no-alcohol beverages, particularly in affluent markets where health awareness and product premiumization drive demand [8–11]. In parallel, the craft beverage movement continues to thrive, fueled by consumer interest in distinctive flavor profiles, artisanal quality, and experiential consumption [10, 12].

Table 1 presents a summary of key trends and innovations in the beverage industry.

2. Emerging technologies to control the stability of beverages

Main issues concerning the stability of beverages are: (i) refermentations or development of spoilage or pathogenic microorganisms, (ii) degradation of nutritional value, and (iii) deterioration of sensory quality. The conventional way to preserve beverages involves thermal techniques, such as heating processes (pasteurization or sterilization) and chilling systems (refrigeration), as well as physical techniques like microbial filtration. Some of these technologies are useful for preserving beverages during short periods (pasteurization and refrigeration), while others are used for long-term preservation (microfiltration or thermal sterilization). Thermal treatments have a clear impact on nutritional and sensory quality, whereas microfiltration is gentler and does not affect oxidative enzymes.

Emerging non-thermal technologies are currently extensively used in beverage processing because they do not incorporate chemical inputs like other physical techniques. They also help control microbial stability and are incredibly gentle with molecules responsible for sensory and nutritional quality. They can produce typically pasteurized and controlled non-sporulated bacteria, which require refrigerated storage. However, they can usually achieve shelf-life periods of 1 month or longer, maintaining optimal

sensory and nutritional quality, similar to freshly prepared beverages from fruits, vegetables, or milk. The more efficient industrial-scale methods currently include High Hydrostatic Pressure (HHP), Pulsed Electric Fields (PEF), Pulsed Light (PL), and irradiation (ebeam or UV). All of them have an intense effect on microorganisms producing pasteurization while protecting molecules with sensory impact (pigments, aroma compounds, and flavors) or nutritional value (vitamins) [13–16].

UHPH, Ultra High-Pressure Homogenization, is another key physical technology capable of producing continuous pasteurization or sterilization of fruit juices, vegetal or animal milks, fermented beverages, and many others. Additionally, colloidal particles are nanofragmented, producing very stable turbid beverages. The high impact of the valve also denatures enzymes controlling enzymatic oxidations and other enzyme degradative processes [17, 18].

All these technologies can be used to extend the shelf life and preserve the sensory and nutritional quality of juices, smoothies, kombuchas, and energetic or nutraceutical beverages, allowing the production of new beverages with high sensory expression and innovative composition.

3. Emerging edible packaging

A central issue in beverages is the packaging of individual doses in plastic bottles, which produces the vast amounts of plastic residues. Even with new polymers such as PET, these residues are difficult to recycle and pose significant environmental and health problems due to the release of micro- and nanoplastics. These micro- and nano-sized particles can be incorporated into the diet and also inhaled, passing the plasmatic barriers and being absorbed into the human organism with undetermined long-term effects. Some studies describe ingestions of several grams per year. So, it will be a key health issue in the near future [19].

Edible packaging materials formed by biodegradable natural biopolymers (polysaccharides, vegetal fibers, proteins, and others) can be a way to overcome this threat [20]. Some prototypes of beverages packaged in natural polymer films are already available on the market, with the packaging being consumed along with the drink. However, these materials currently do not ensure adequate stability, permeability, and barrier properties, though continuous improvement is being made each year.

New materials with suitable biodegradability, such as paper-waxed materials, can be used for beverage packaging. Nanotechnology offers a key strategy for producing these materials [20] through processes such as nanoprinting, nanospraying, or electrocovering. Moreover, nanocoverings used in edible packaging can incorporate antimicrobials, nutraceuticals, shelf life indicators, and other functional components.

4. Conclusions

The beverage industry is undergoing a significant transformation driven by innovations that cater to the growing consumer demand for health-focused, sustainable, and technologically advanced products. Entities that adapt effectively to these evolving trends—by delivering functional, sustainable, and sophisticated offerings—are uniquely positioned to satisfy not only the dynamic preferences of consumers but also the stringent requirements set by regulatory authorities.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 2

Legal Challenges of Innovative Technologies in the Beverage Sector

Tilman Reinhardt and Lynn Noufaily

Abstract

The chapter provides an overview of legal challenges for innovative beverage technologies in the European Union (EU). We examine food safety and pre-market authorization requirements, focusing on the novel food framework in Regulation (EU) 2015/2283. This framework is relevant for new ingredients, such as cannabidiol (CBD), algal- and plant-based compounds, as well as for upcycled food from side-streams, such as brewer's spent grain, spent yeast, or carbon dioxide (CO₂). It can also apply to innovative production processes, such as ultraviolet-C (UV-C) radiation or alternative fermentations with new microorganisms. In this context, we also explore legal questions on the use of genetically modified microorganisms (GMMs), especially whether trace amounts of recombinant DNA can trigger an application of the framework for genetically modified organisms (GMO) under Regulations (EC) No 1829/2003 and 1830/2003. A second focus of the chapter lies on food information law. We analyze the framework for nutrition and health claims under Regulation (EC) No 1924/2006 and potential pathways, such as plain ingredient labelling for micronutrients. We also examine the emerging regulation of environmental and sustainability claims, such as climate neutrality and upcycled food.

Keywords: food law, novel foods, health claims, green claims, upcycled foods

1. Introduction

Innovation in the beverage sector is shaped by various market developments. Key trends include a rising demand for healthy and functional products, alongside increasing interest in circular economy and upcycling approaches that utilize side-streams, such as brewer's spent grain and fruit pomace. This chapter describes how the legal frameworks on food safety and food information in the European Union (EU) determine how innovative products can be placed on the market. We first analyze pre-market authorization requirements under the frameworks for novel foods (2.1) and genetically modified organisms (GMOs) (2.2). We then look at labelling issues, in particular the regulation on health and nutrition claims (3.1), as well as the emerging framework for sustainability or "green" claims (3.2). We finish by drawing some tentative conclusions (4).

2. Food safety and pre-market authorization

According to the EU's General Food Law (Regulation (EC) No 178/2002), food can generally be put on the market if it is not unsafe. For certain food products, such as additives, novel foods, or GMOs, however, an ex ante authorization is necessary. This can apply to certain new ingredients, such as CBD, algal- or plant-based compounds, or “upcycled” products derived from side-streams (brewer's spent grain, spent yeast, CO₂, etc.), as well as innovative production processes, such as the use of UV-C radiation or “alternative” fermentations with new microorganisms.

2.1 Novel foods

Novel foods in the EU are subject to Regulation (EU) No 2283/2015 (Novel Food Regulation) (hereinafter: NFR). This regulation aims to ensure that new food products and processes do not constitute a risk to human health and safety. It defines novel foods as “foods not used for human consumption to a significant degree within the Union before 15th May 1997” in 10 novel food categories.

Novel foods require pre-market authorization before being placed on the market. Only when a novel food is included in the Union List of Novel Foods can it be legally sold across the Union. An authorized novel food reaching the market is as safe as a non-novel food and—unlike GMOs—does not require specific labelling (**Figure 1**).

2.1.1 Authorization procedure

The novel foods authorization process aims to verify that novel foods do not pose safety risks to human health based on available scientific evidence. It ensures that the intended use of novel food does not mislead consumers, especially in cases where a novel food is meant to replace another food and undergoes a significant change in nutritional value. Also, novel foods should not differ in a way that would cause their consumption to be nutritionally disadvantageous for consumers.

The authorization procedure consists of a scientific risk assessment by the European Food Safety Authority (EFSA) and a political risk management decision

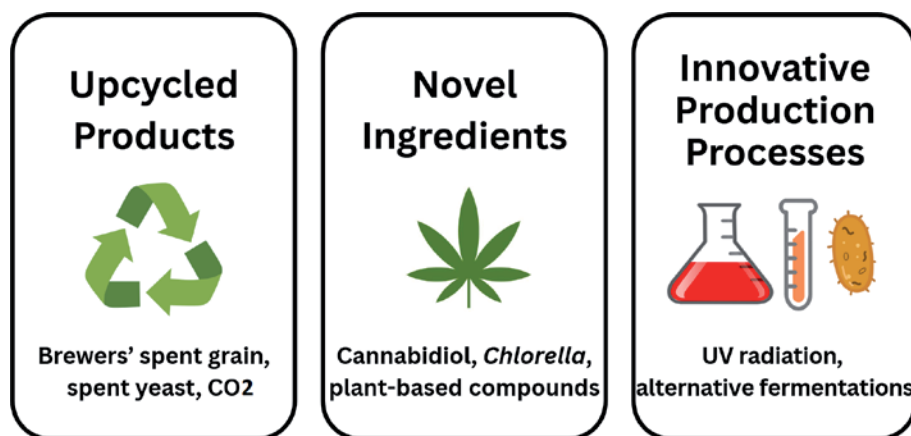


Figure 1.
Examples of novel foods in the beverage industry (own elaboration).

involving the European Commission and Member States' representatives in the Standing Committee on Plants, Animals, Food and Feed (PAFF Committee).

The procedure begins with the production of a dossier, submitted by the applicant through a centralized portal managed by the European Commission. Once the application is received, the dossier is forwarded to the EFSA. The dossier must contain some general information on the applicant, the nature and production processes of the novel food, and a proposal for conditions of use and labelling requirements for the novel food. The dossier must also contain scientific evidence that proves the novel food's safety. The technical parts of the dossier must be prepared according to the most update guidelines available from the EFSA. On 30 September 2024, the EFSA published the last "Guidance on the Scientific Requirements for an Application for Authorisation of a Novel Food," which applies from 1 February 2025.

When receiving the dossier, the EFSA has 9 months to review it (Article 11 NFR). The Scientific Opinion of the EFSA is based on the data submitted by the applicant and on available scientific evidence. The EFSA does not conduct independent, original studies on the content of the application. The EFSA assessment shall consider whether the product is as safe as a comparable non-novel food, that the composition of the novel food and the conditions of use do not pose a safety risk, and that the consumption of the novel food would not be nutritionally disadvantageous for the consumer.

The EFSA has the power to halt the procedure if more data are needed from the applicant. These delays might be due to the study design, scope, or results. Studies conducted for the purpose of being included in the dossier must be notified to the EFSA before they take place. Failure to do so might result in delays of over 6 months and require a resubmission of the application.

Applicants can receive pre-submission advice from the EFSA, prior to the submission of the application. However, this advice can only concern the generic aspects of the application and not the specific design of studies. It is without prejudice and non-committal as to any subsequent assessment and should not involve EFSA personnel dealing with the assessment of the application.

Once the EFSA publishes its Scientific Opinion, the European Commission has 7 months to prepare a draft implementing regulation authorizing the novel foods taking into consideration the Scientific Opinion, the precautionary principle, and other legitimate factors (Article 12 NFR). The implementing regulation is then voted upon in the PAFF Committee, where Member States' representatives vote on the regulation in a qualified majority voting procedure according to Regulation (EU) No 182/2011.

If the novel food is authorized, the authorization is generic, meaning that every food business operator can place the product on the market, providing that conditions of use and labelling requirements are respected. However, applicants can ask for the application of the "data protection clause," which stipulates that original scientific studies presented by the applicant and deemed necessary for the good outcome of the application cannot be used for the benefit of subsequent applicants for a non-renewable period of 5 years (Article 26 NFR). In practice, this grants a limited market exclusivity, as other applicants would need to submit their own dossier, when willing to place novel food on the market in those 5 years.

The scope of each individual novel food authorization is accurately defined in the implementing regulation authorizing its placement on the market and adding it to the Union List of Novel Foods. The authorizations only cover individual products manufactured under specific condition for specific uses. For example, the novel food "Frozen, dried and powder forms of *Acheta domestica* (house cricket)" is authorized for use in several food categories, including "beer-like beverages, alcoholic drink

mixes,” or “meat analogues” (Commission Implementing Regulation (EU) 2023/5). For “meat analogues,” the use of frozen cricket is allowed for a maximum level of 5 g per 100 g but only 0.1 g per 100 g for beer-like beverages.

According to the regulation, the authorization procedure should last no more 17 months. In practice however, due to the EFSA’s ability to halt the procedure, the procedure lasts around 31 months on average [1]. The length and the data requirements of the novel food authorization procedure are considered significant challenges for innovators in the EU [2].

2.1.2 National consultation procedures, novel production processes, and qualified presumption of safety

To provide certainty to operators, Article 4 NFR provides for a national consultation procedure to clarify the novel food status and determine whether an authorization is necessary. The consultation involves submitting a detailed dossier to a Member State’s competent authority that includes information on the composition, production process, history of use, and intended use of the food. The competent authority evaluates whether the food was consumed to a significant degree within the EU before 15 May 1997. If necessary, the authority may consult other Member States or the European Commission. The results of the national consultation procedure are published by the European Commission on its official Novel Food status Catalog and consultation database.

Regarding beverage innovation, the novel food category in Article 3(2)(a)(vii) NFR can present a particular challenge. It defines as novel any “*food resulting from a production process not used for food production within the Union before 15 May 1997, which gives rise to significant changes in the composition or structure of a food, affecting its nutritional value, metabolism or the level of undesirable substances.*” This provision operates as a broad “catch-all” category [3], meaning that even familiar ingredients and processes may be subject to a novel food authorization.

Case law on this category remains limited. In his opinion in the Court of Justice of the European Union (CJEU) Case C-141/22 (TLL The Longevity Labs GmbH v Optimize Health Solutions mi GmbH and BM), the Advocate General Campos Sánchez-Bordona concluded that that novelty of a processing technology must be assessed specific to the food in question, reinforcing the inherently case-by-case nature of such evaluations.

National Article 4 consultations further illustrate the strict interpretation of production process category. For example, in a 2024 French consultation, UV-C-treated wine was classified as novel—even though the use of UV-C treatment is common in other food sectors—because its application to wine was judged to potentially alter composition or safety. In fact, not a single national consultation procedure related to production process under Article 3(2)(a)(vii) NFR so far concluded that the product in question was not novel.

The category of “novel production process” in Art. 3(2)(a)(vii) NFR could potentially also apply to new fermentation processes. The use of alternative yeasts and other microorganisms has become an important area of innovation, e.g. in the production of alcohol-free beer [4]. New yeast strains are also used to lower the alcohol content of wine in times of climate change and increase aromatic substances such as glycerol [5].

With regard to microorganisms intentionally added to food or feed, the EFSA’s Qualified Presumption of Safety (QPS) framework supports the safety assessment [6]. When a microorganism used in a novel food application has been granted QPS status, EFSA generally limits its safety assessment to verifying that the specific

strain complies with the qualifications listed for the species, such as the absence of antimicrobial resistance or toxigenic potential. This can significantly reduce the data requirements and timeline for applicants. However, the QPS list does not replace the novel food authorization process! If a microorganism or the product derived from it has not been used to a significant degree in the EU before 15 May 1997, a full novel food application may still be required.

2.1.3 Examples of novel foods in the beverage industry

Cannabidiol (CBD) has gained prominence in the European food and beverage market following the 2020 CJEU judgment in the Kanavape case (C-663/18), which clarified that CBD extracted from hemp is classified as a narcotic if it has no psychoactive effects. Member States initially took divergent approaches to the regulation of CBD products. In 2022 however, EFSA concluded that CBD is a novel food requiring pre-market authorization. At the same time, it highlighted data gaps concerning hepatotoxicity, gastrointestinal effects, endocrine disruption, and neurological development, and suspended the assessment pending the submission of additional evidence (so called “clock-stop”) [7].

Algal ingredients have entered the Union list of authorized novel foods or were classified as non-novel in national Art. 4 consultation procedures. For example, *Chlorella vulgaris*, *Parachlorella kessleri*, and *Auxenochlorella protothecoides* were deemed not novel in Article 4 consultations because they have long-standing use as food supplements in the EU. By contrast, less common species, such as *Scenedesmus acutus* and *Tetraselmis chuii*, have required full novel food authorization before market placement due to insufficient consumption history.

Plant-based compounds like coffee cherry pulp (cascara) and its infusion were authorized as a novel food by Implementing Regulation (EU) 2022/47, permitting its use in non-alcoholic beverages and herbal infusions with mandatory caffeine labeling. Similarly, coffee leaves were approved as a traditional food from a third country via Implementing Regulation (EU) 2020/917, after the Commission verified their safe history of use in non-EU countries.

“Upcycled” products derived from side-streams of the beverage industry can also require a novel food authorization, depending on the concrete production process: partially hydrolyzed protein derived from spent barley (*Hordeum vulgare*) and rice (*Oryza sativa*) was authorized by Implementing Regulation (EU) 2023/2851 based on an application of AB InBev’s spin-off EverGrain. Yeast-derived β -glucans from *Saccharomyces cerevisiae* has been authorized by Implementing Decision 2011/762/EU under the then-applicable Regulation (EC) No 258/97.

However, as described above, the novelty can depend on the specific production process. Mechanically separated fractions of brewers’ spent grain, for example, were assessed to be not novel in a Dutch Article 4 consultation in 2023. Similarly, conventionally extracted yeast proteins have been classified as non-novel, facilitating the emerging market for spent yeast in both traditional products like Marmite and new solutions like Prew:tein from German start-up ProteinDistillery.

An ongoing authorization procedure concerns Solein, a novel protein produced by cultivating a specific strain of hydrogenotrophic bacteria from the genus *Xanthobacter* through fermentation using CO₂, hydrogen, and minerals as substrates. This product, developed by the Finnish company Solar Foods, has already received novel food authorization in Singapore as well as a self-determined GRAS (“Generally Recognized As Safe”) status in the United States.

2.2 Genetically modified organisms

If genetically modified microorganisms (GMMs) are used in the production of beverages, the framework for GMOs—comprising Regulation (EC) No 1829/2003 on GM food/feed and Regulation (EC) No 1830/2003 on traceability and labelling – may also play a role. GMOs, like novel foods, require pre-market authorization. However, they are also subject to stringent criteria concerning supply chain traceability and consumer labelling.

GMMs are already used in commercial beverage production both in- and outside the EU. Californian company Berkeley Yeast, for example, commercializes genetically modified beer yeast strains that reduce diacetyl formation, leading to shorter fermentation times while improving consistency. Other yeast strains improve aromatic characteristics, for example, by enhancing thiols without adding hops. In wine production, engineered yeasts may be used to reduce ethanol content (a common need in times of climate change) and increase glycerol (although this can to a certain extent already be accomplished with non-engineered yeast, such as Lallemend's Lalvin ICV Okay).

Whether or not the use of GMMs in beverage production triggers an application of the EU GMO framework depends on whether the GMM or its derivatives are present in the final food product or not. Products that are merely produced “with” but not “from” GMOs are outside the scope (cf. Recital 16 of Reg. (EC) No 1829/2003).

In fact, the use of GMMs in food production is already well established, primarily in the form of processing aids [8]. Common examples include enzymes, such as chymosin for cheese production, amylases for baking and brewing, and invertases or pectinases for juice processing. These enzymes are only used as processing aids and are not present in the final food final product, which therefore does not itself qualify as a GMO. GMMs are also used in the production of amino acids and flavor compounds, such as glutamate (E620) for savory seasonings or riboflavin (vitamin B2) for fortification. In these cases, again, only the microbial cell factories are considered to be genetically modified, not the purified ingredient.

In the case of fermented beverages, GMO classification therefore depends on whether filtering or downstream processing completely removes viable yeast cells.

An ongoing debate concerns the question whether trace amounts of recombinant DNA in the final product can trigger a GMO classification. Industry and academic authors argue that trace amounts of recombinant DNA (rDNA) in final products are of no regulatory relevance as long as all GMMs are removed and the DNA is non-functional [9].

The relevance of this discussion goes far beyond the beverage sector and essentially extends to all precision fermentation products. A notable case concerns soy leghemoglobin (LegH Prep), a color additive derived from genetically modified yeast *Komagataella phaffii* Panel. Favorable risk evaluations have been issued by EFSA's Additives and GMO Panels in 2024, explicitly looking at the functionality and evolutionary advantages of recombinant DNA sequences. Still, political stakeholders, for example in the European Parliament, question whether the risk assessment has been sufficiently precautionary and the additive has not been authorized yet.

3. Food information

The legal framework for food information is crucial for marketing innovative beverages to end-consumers. In line with consumer trends, the rules for nutrition

and health claims as well as claims related to the sustainability (“green claims”) are of particular relevance.

3.1 Health and nutrition claims

In the EU, health claims are tightly regulated in Regulation (EC) No 1924/2006 nutrition and health claim regulation (NHCR) to prevent misleading messaging and ensure that only scientifically substantiated statements appear on foods and beverages. In Article 2(2)(5) NHCR, a health claim is defined as “*any claim that states, suggests or implies that a relationship exists between a food category, a food or one of its constituents and health.*” To be used legally, such claims must be authorized by the European Commission based on a scientific evaluation by EFSA (Articles 13 and 14 NHCR). Applicants must submit a comprehensive dossier with human data to substantiate a cause-effect relationship. All authorized or rejected claims as well as references to scientific opinions and relevant conditions of use are published in the EU Register of Nutrition and Health Claims.

The rules on health claims are interpreted strictly by both national and European courts. For example, generic statements like “relaxing” or “digestible” are usually categorized as health claims. Scientifically sound claims may still be rejected as misleading, as illustrated by the CJEU’s Dextro Energy glucose case (C-296/16 P).

Even for authorized claims, the NHCR sets strict standards regarding their presentation on the label. For example, health claims must appear in proximity to the product name and must be worded without altering the scientific or regulatory intent in the EU Register. Article 10 NHCR requires that the label provide mandatory accompanying information, including a statement on the importance of a varied and balanced diet, the quantity of the nutrient or substance required to achieve the claimed effect, and, if relevant, a warning for target populations and on excessive consumption. Any implied health message through graphics or symbols must comply with the same standards (cf. CJEU Case C-524/18).

A transitional exemption from the NHCR applies to certain health claims related to certain botanical substances until the Commission completes their evaluation (Article 28(6) NHCR). In a judgment from 30 April 2025 (C-386/23, Novel Nutriology), the CJEU confirmed not only this exception but also made it clear, that it only applies to botanicals for which claims had been submitted before 2008.

The restrictive legal framework and the fact that beverages often contain only small amounts of certain micronutrients make it challenging to communicate potential functional benefits of innovative beverages. As a result, producers must explore alternative, legally compliant strategies to convey product benefits.

For certain aspects, nutrition claims provide a comparatively easier pathway than health claims. A nutrition claim is defined in Article 2(2)(4) NHCR as “*any claim that states, suggests, or implies that a food has particular beneficial nutritional properties due to the energy (calorific value) it provides, provides at a reduced or increased rate, or does not provide, and/or due to the nutrients or other substances it contains, contains in reduced or increased proportions, or does not contain.*”

Unlike health claims, nutrition claims do not require individual pre-market authorization, but may be used if they comply with the conditions specified in Annex I and Annex II of the NHCR—for example, a 30% reduction in a nutrient for the claim “light,” or the presence of a minimum quantity of a nutrient to claim “source of” or “high in.” However, all nutrition claims require either an established Nutrient



Figure 2.
Options for the labelling of functional beverages (own elaboration).

Reference Value (NRV) or a specific quantitative threshold explicitly defined in the Regulation's annexes.

Bioactives common in functional beverages—such as flavonoids, polyphenols, xanthohumol, or β -glucan—generally lack NRVs and therefore cannot carry content claims like “source of...”. However, such ingredients could still appear as factual but neutral ingredient declarations (e.g., “contains beta-glucan”) (Figure 2).

For developers of innovative functional beverages, this regulatory landscape presents both challenges and opportunities. While health claims are heavily restricted, creatively highlighting ingredients, providing clear dosage information, and engaging in educational outreach can build credibility and align with consumer expectations without violating regulations. A pragmatic, consumer-informed strategy—focusing on transparency rather than formal claims—can foster trust and innovation within the tight legal framework. In fact, empirical consumer studies suggest that consumers do not necessarily value health claims more than precise information on ingredients [10]. Health-conscious consumers and supplement users may already feel confident in their knowledge of which substances they need. In this sense, ingredient transparency and contextual consumer education may play a stronger role than specific claims in stimulating consumer confidence and willingness to buy.

3.2 Sustainability labelling

Consumers are getting more conscious not only about health aspects, but also about the sustainability of food and beverages. In this sense, the relevance of sustainability labelling and climate claims has grown in recent years. Also, the legal framework for “green claims” is undergoing substantial legal evolution.

According to Article 7 of the Food Information Regulation (EU) No 1169/2011, all food information, including voluntary statements, must not mislead consumers about a product's characteristics, effects, or properties, and must be accurate, clear, and not confusing. Article 36 further specifies that voluntary food information must be truthful, unambiguous, and, where relevant, supported by scientific evidence. These rules have been interpreted increasingly strictly by national courts regarding sustainability claims.

Especially climate claims have become a target of nongovernmental organization (NGO) lawsuits in several Member States. In Germany, in a landmark decision on 27 June 2024, the Federal Court of Justice (BGH, Case I ZR 98/23) ruled that advertising a product as “climate-neutral” was unlawful when such a claim is based on a mere “compensation” of emissions, instead of actual in-product emission reductions.

This decision anticipates legislative changes at the EU level. Under the Empowering Consumers for the Green Transition Directive (EmpoCo Directive), Member States must ban unsubstantiated environmental claims, including vague slogans like “green,” “climate-friendly,” or “carbon neutral,” unless supported by clear, objective, publicly available evidence, preferably from independent third-party verification. Starting from 2026, companies will be liable if their sustainability messaging lacks the required transparency or is misleading about future environmental performance or durability.

In its proposal for a Green Claims Directive (COM/2023/166 final), the EU legislator intended to go even further and set uniform EU-wide standards for substantiating environmental claims via independent verification and life-cycle analysis and a mandatory ex ante authorization process. However, negotiations on the proposal stalled in mid-2025 due to concerns about bureaucratic burdens on enterprises.

For products derived from side-streams, the term “upcycling” has become increasingly common in both marketing and scientific literature. So far, no case law or administrative guidance specifically addresses the use of “upcycling” in food or beverage labelling. Potential confusion arises because the term appears to overlap conceptually with the waste hierarchy under EU waste law, which distinguishes waste recovery, recycling, and reuse. However, in the context of food, upcycling does not refer to products legally classified as waste, which would trigger waste-handling obligations and require compliance with “end-of-waste” criteria before entering the food chain. Instead, it is used to describe the valorization of safe, edible side-streams such as brewers' spent grain or yeast into higher-value ingredients for food, beverages, or supplements. It remains to be seen under which conditions such claims may potentially be considered misleading by the courts. In the United States, the term has already gained greater regulatory and market clarity through a voluntary Upcycled Certified™ standard by the Upcycled Food Association.

The most privileged sustainability standard—within current and proposed EU consumer protection frameworks—is the EU organic certification under Regulation (EU) 2018/848: only products certified under this regulation may carry the EU organic logo and use of the term “organic” as well as related terms. Annex I of the EmpoCo Directive exempts environmental claims tied to recognized sustainability labels, notably the EU organic logo from being considered generic and potentially misleading. Similarly, the Commission's draft for a Green Claims Directive positions the organic logo as a benchmark for traceable and verified sustainability communication. This regulatory privilege coincides with strong consumer associations between organic certification and sustainability as well as health. In fact, consumer research indicates that many assume that organic products are not only environmentally friendly, but also healthier [11], although health claims are not legally implied by the

designation. As a result, organic certification may offer a powerful, implicit consumer appeal without violating legal restrictions on health and environmental claims.

4. Conclusions

Innovation in the beverage industry is essential to respond to both market demand and policy expectations. A study, conducted by Deloitte in 2025 (“Prost auf die Gesundheit!”), found that 69% of consumers support replacing unhealthy beverages with healthier alternatives, and 61% perceive the selection of healthy beverages on supermarket shelves as insufficient. This highlights the need for portfolio expansion, either through new product development or through reformulation. Indeed, no other product category shows such a pronounced gap between actual consumption and dietary recommendations as beverages [12]. In its 2025 Vision for Agriculture and Food (COM/2025/75 final), the European Commission also acknowledged the key role of the food and beverage industry for achieving the EU’s 2040 environmental sustainability targets.

The stringent rules and lengthy authorization procedures for novel foods, however, remain a challenge for food and beverage innovators (2). It remains to be seen whether the EU will adopt a more innovation-friendly approach, as seen in Singapore, Australia, the UK, or the United States, where shorter procedures, pre-authorization tastings, and flexible regulator interactions as well as so-called regulatory sandboxes facilitate faster market access for novel products.

European food law is also strict with respect to health and sustainability labeling. While it is debatable whether these restrictions significantly advance public health objectives, the general trajectory indicates that requirements will continue to tighten. For innovators, however, this must not necessarily be negative. Although simple health or sustainability claims are difficult to make, the framework encourages clean labelling and transparent communication. Successful and compliant strategies could involve highlighting individual metabolites and leveraging consumer education beyond the label. In addition, the EU organic certification—whether justified or not—can function as a powerful combined health and sustainability signifier for the growing health-conscious consumer segment.

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Innovations Driving the Future of Beverage Industry

Domas Galih Patria, Cindytia Selvina Bernas and Jenshinn Lin

Abstract

The beverage industry is experiencing significant changes due to advancements in ingredients, processing technologies, packaging, and sustainability practices. Consumer demand is increasingly shifting from traditional soft drinks and juices to functional beverages that contain bioactive compounds, including probiotics, antioxidants, and adaptogens. These beverages provide specific health benefits, such as immune support and stress relief. The sector has experienced notable expansion in plant-based and alternative beverages, catering to the preferences of vegan, vegetarian, and flexitarian consumers, while also aligning with ethical and environmental principles. Advanced processing technologies such as high-pressure processing, pulsed electric fields, ultrasonication, fermentation, and extrusion facilitate the production of beverages that exhibit enhanced safety, prolonged shelf life, and maintained nutritional and sensory qualities, all while avoiding the use of synthetic additives. Smart packaging solutions utilizing sensors, indicators, and RFID systems convert packaging into active elements that monitor freshness, temperature, and contamination, thereby improving food safety and consumer trust. Sustainability has evolved into a strategic priority, with companies adopting circular economy principles, biodegradable materials, and resource-efficient designs to mitigate environmental impact. Digital technologies, including Internet of Things (IoT), artificial intelligence (AI), and blockchain, enhance supply chain transparency and traceability, facilitating the development of personalized nutrition solutions based on individual health data. The industry is transforming its role from merely providing hydration to offering functional, health-oriented, and environmentally responsible products by incorporating consumer expectations, technological advancements, and sustainable practices. This approach positions the beverage sector as a leader in innovation, addressing changing global challenges and consumer lifestyles.

Keywords: beverage innovation, functional beverages, smart packaging, sustainable processing, plant-based drinks

1. Introduction

The global beverage industry is experiencing significant transformation driven by rapid innovations in ingredients, processing technologies, and consumer engagement strategies. The beverage market, previously dominated by traditional soft drinks and juices, is currently undergoing transformation due to an increasing demand for

innovative, healthier, technologically advanced products, and more sustainable [1]. Key innovations encompass the incorporation of plant-based and alternative ingredients, which address the needs of vegan and vegetarian diets while promoting ethical and sustainable sourcing practices. The inclusion of bioactive compounds, including antioxidants, adaptogens, probiotics, and prebiotics, has transformed beverages into functional foods, providing specific health benefits such as immune support, stress relief, and improved digestive health. The development of low- or no-sugar formulations that preserve flavor integrity simultaneously addresses concerns regarding sugar intake and associated health issues [2–4].

The current market features several popular functional beverages, including yogurt drinks fortified with prebiotics and probiotics, functional milk enhanced with calcium, omega-3 fatty acids, and essential vitamins, and fruit juices enriched with vitamins and omega-3. Furthermore, functional waters, which include vitamin- and mineral-fortified drinks, sports and energy beverages, herbal infusions, and wellness-oriented water formulations, have attracted significant consumer interest due to their perceived health advantages [5]. It served purposes beyond basic hydration or nourishment; they are specifically designed to produce targeted physiological effects that enhance overall health and well-being. These beverages have been linked to various health-promoting effects. It may lower the risk of chronic diseases, including cancer and cardiovascular conditions, enhance immune function, improve physical stamina and cognitive performance. Additionally, these products are frequently formulated to function as anti-stress, anti-aging, antioxidant, and anti-inflammatory agents, thereby attracting health-conscious consumers from diverse age demographics [6]. The ongoing validation of bioactive compounds and nutraceuticals through scientific research is anticipated to increase the demand for functional beverages, thereby fostering innovation in formulation, flavor, and delivery systems. This trend indicates a significant change in consumer behavior toward preventive health and wellness, with beverages assuming a more prominent role in daily dietary practices.

The beverage industry is leading in technological innovation, propelled by increasing consumer demand for products that are safe, nutritious, sustainably produced, and compatible with contemporary lifestyles. The increasing focus on health and environmental issues is influencing consumer purchasing behavior, prompting the industry to adopt advanced processing techniques and digital technologies to address these changing demands. Significant developments include thermal and non-thermal physical technologies, specifically high-pressure processing (HPP), pulsed electric fields (PEF), ultrasonication (US), extrusion, and fermentation [7–9]. These techniques provide various advantages, such as enhanced microbial safety, prolonged shelf life, and the maintenance of nutritional and sensory attributes, all without the use of synthetic preservatives. Furthermore, these methods are employed to create novel beverage types and improve the functional and sensory attributes of traditional drinks. Moreover, advancements in fermentation biotechnologies and new methodologies for flavor and texture enhancement are broadening the scope for innovative beverage formulation. These advanced technologies are transforming the beverage industry by emphasizing safety, quality, sustainability, and consumer satisfaction.

Modern packaging integrates active and intelligent technologies that engage with the product or its surroundings to improve quality, safety, and sustainability. Active systems, including oxygen scavengers and moisture absorbers, mitigate spoilage by regulating internal conditions. Concurrently, intelligent features such as biosensors and time-temperature indicators facilitate real-time monitoring, enhancing food safety and consumer confidence [10]. These technologies play a crucial role in

beverages such as wine, juice, and beer, where oxidative degradation and alterations in aroma affect sensory and nutritional quality. Comprehending these processes enables the development of specialized packaging solutions that preserve flavor, color, and volatile compounds throughout the product's shelf life [11]. Sustainability is a significant emphasis, with biodegradable and nanocomposite materials providing environmentally friendly alternatives to conventional plastics. The beverage industry is implementing circular economy principles, including energy efficiency, resource optimization, and waste valorization, to achieve environmental objectives and align with consumer demands for sustainable and ethical products. Advancements in digital technologies, including IoT, AI, and blockchain, enhance smart packaging by improving traceability, transparency, and supply chain efficiency. These tools facilitate the emergence of personalized nutrition by utilizing health data to provide customized dietary solutions and promoting innovation centered on consumer needs [12].

Sustainability has emerged as a central theme in this evolution. It is no longer regarded merely as a corporate responsibility; it has evolved into a strategic differentiator for companies aiming to align with contemporary consumer expectations [13]. Companies are progressively integrating environmental and social responsibility into their product development, branding, and communication strategies. Contemporary consumers evaluate beverages based on functional and sensory attributes, as well as their congruence with personal values, including environmental sustainability, ethical sourcing, and corporate transparency. Consequently, businesses that implement and effectively convey sustainable practices achieve a competitive advantage via significant product differentiation and enhanced brand loyalty. Research on sustainable consumption has predominantly concentrated on environmental dimensions, whereas environmental psychology has examined pro-environmental behaviors such as energy and water conservation. Concurrently, marketing studies have underscored the significance of green purchase behavior. Analyzing the factors influencing eco-conscious consumer choices allows social marketers, policymakers, and businesses to foster sustainable behaviors over the long term [14]. The beverage industry has implemented cost-effective sustainability strategies in response to climate-related risks and the demand for circular economy models. Four key managerial practices at the product level facilitate the adoption of Circular Economy (CE) in this sector: (i) improving energy efficiency and utilizing renewable energy; (ii) enhancing resource efficiency through optimized products and processes; (iii) designing products for circularity; and (iv) converting waste into valuable resources [15].

2. Functional ingredients

The beverage industry is evolving due to a rise in innovations focused on functional ingredients, as consumers increasingly demand drinks that provide health benefits beyond mere hydration. Functional beverages frequently incorporate bioactive compounds, including phenolics, vitamins, minerals, amino acids, probiotics, prebiotics, and unsaturated fatty acids, derived from plants, animals, and agro-food waste, to promote well-being and target specific health issues [16]. Functional beverages, including probiotic drinks, immune boosters, energy drinks, and plant-based options, are formulated to enhance specific health aspects such as digestion, immunity, and cognitive function [17]. The incorporation of medicinal and aromatic plants, along with natural additives such as polyphenols and essential oils, enhances the nutritional profile and improves sensory attributes, including flavor and aroma.

2.1 Probiotic drinks

Probiotic drinks are beverages containing live beneficial microorganisms, including specific strains of bacteria and yeast, designed to promote gut health and enhance overall well-being. Probiotic strains commonly present in these beverages are *Lactobacillus acidophilus*, *Lactobacillus casei*, and *Bifidobacterium bifidum*. Dairy products such as yogurt and fermented milk have historically served as primary sources of probiotics. However, there is an increasing trend toward non-dairy alternatives, including fruit juices, cereal-based beverages, and plant-based milks, aimed at accommodating lactose-intolerant, vegan, and health-conscious consumers. In the fermentation process, probiotic bacteria decompose sugars and generate lactic acid, which serves to preserve the beverage while also imparting a tangy flavor and a smooth texture. These beverages offer various health benefits, including improved digestion, enhanced immune function, reduced serum cholesterol, and a potential decrease in the risk of gastrointestinal infections and inflammatory bowel diseases [18]. The formulation of probiotic beverages necessitates the meticulous selection of resilient probiotic strains capable of withstanding processing, storage, and transit through the gastrointestinal tract, while also preserving favorable taste and texture. Probiotic drinks derived from fruit and cereal sources are noteworthy due to their integration of the nutritional advantages of the base ingredients with the functional properties of probiotics, making them attractive to individuals pursuing non-dairy alternatives [19]. Ensuring the safety and efficacy of these products is essential, as not all probiotic strains provide identical benefits, and their interactions with the beverage matrix can influence both their viability and the sensory characteristics of the drink.

2.2 Immune boosters

Immune booster drinks are formulated beverages aimed at enhancing the body's natural defenses through a concentrated blend of nutrients and bioactive compounds that support immune function. These beverages typically contain ingredients high in antioxidants, including vitamin C, flavonoids, and polyphenols, which assist in neutralizing detrimental free radicals and mitigating inflammation. Common components consist of fruits such as dragon fruit, which offers vitamin C and betacyanin [20], alongside herbal extracts from plants including ginger, lemongrass, holy basil, and various other medicinal herbs, all acknowledged for their immunomodulatory properties [21, 22]. Certain formulations include spices and botanicals traditionally recognized for their immune-strengthening properties, including turmeric, garlic, and tulsi [23]. Research indicates that these natural ingredients can activate immune cells, improve antioxidant activity, and offer antimicrobial advantages, thereby effectively supporting the body's defense against infections [24]. The formulation of immune booster beverages incorporates sensory attributes such as taste and aroma to enhance consumer acceptance, with effective products achieving a balance between nutritional benefits and palatability. Regular consumption of these beverages, particularly during periods of stress, seasonal transitions, or heightened exposure to pathogens, may enhance the body's capacity to prevent infections and facilitate quicker recovery from illnesses. These beverages enhance immunity while also offering energy and hydration, thus serving as a practical and advantageous component of a daily health regimen. Immune booster drinks can enhance overall wellness, but their efficacy is maximized when integrated with a balanced diet, regular physical activity, sufficient sleep, and other healthy lifestyle practices. The rising interest in preventive

health, particularly following global health challenges, has led to an increased popularity of immune booster drinks as convenient and natural options for daily wellness.

2.3 Energy drinks

Energy drinks are widely consumed beverages designed to enhance energy, alertness, and both physical and mental performance, primarily through elevated concentrations of caffeine, sugars, and additional components such as taurine, B vitamins, ginseng, and guarana. Moderate consumption can improve exercise performance, mental focus, and endurance, primarily due to caffeine's recognized ergogenic effects. However, these benefits may be accompanied by health risks, particularly when intake is excessive or among sensitive populations, including adolescents, children, or individuals with pre-existing health conditions [25]. The consumption of energy drinks has increased markedly among adolescents and adults, positioning these beverages as a primary source of dietary caffeine. Excessive intake is associated with negative outcomes such as elevated blood pressure, heart arrhythmia, sleep disturbances, nervousness, and potentially severe cardiovascular events [26]. The interaction of caffeine with additional stimulants or alcohol can exacerbate health risks and encourage hazardous behaviors [27]. Although energy drinks are popular among athletes, students, and those with rigorous schedules, they should not be considered a replacement for adequate rest and a balanced diet. Consuming these beverages responsibly is essential, especially for adolescents and those with pre-existing health conditions, to reduce potential adverse effects linked to excessive stimulation and overconsumption.

2.4 Plant-based beverages

Plant-based beverages have become significant alternatives to conventional dairy products, influenced by rising consumer demand for non-dairy options stemming from lactose intolerance, milk allergies, ethical considerations, and environmental issues. Beverages derived from various plant sources, including soy, almonds, oats, coconut, rice, and nuts, present diverse sensory profiles and nutritional compositions. These compositions frequently encompass dietary fiber, unsaturated fatty acids, and bioactive compounds such as polyphenols and phytosterols. Plant-based beverage production generally exhibits a reduced environmental impact regarding greenhouse gas emissions, water consumption, and land use when contrasted with traditional dairy production [28]. Challenges remain in attaining sensory and nutritional equivalency with cow's milk, highlighting the need for continued research in formulation, fortification, and processing technologies. Consumer demand for ethical, allergen-friendly, and lactose-free options is increasing, positioning plant-based beverages as a critical area for innovation in the functional food and beverage sector.

3. Processing technologies

3.1 High-pressure processing (HPP)

High-pressure processing (HPP) represents a significant advancement in the beverage industry, providing a non-thermal method for achieving product safety and prolonging shelf life compared to conventional heat treatments. High-Pressure Processing

(HPP) applies pressures ranging from 300 to 600 MPa to inactivate spoilage microorganisms and pathogenic bacteria, including *Escherichia coli*, *Salmonella enterica*, and *Listeria monocytogenes* [29]. This method maintains the nutritional and sensory qualities of the product more effectively than traditional thermal methods. High-pressure processing (HPP) aids in preserving bioactive compounds, antioxidants, and vitamins, rendering it especially beneficial for fruit juices and functional beverages that prioritize freshness and nutritional value [30]. Furthermore, high-pressure processing (HPP) demonstrates a greater efficacy in reducing specific food contaminants, including mycotoxins, compared to heat treatments [31]. Although high-pressure processing (HPP) does not eliminate bacterial spores, its efficacy can be improved when used in conjunction with refrigeration, natural additives, and low pH, thereby enhancing microbial safety and extending shelf life [32]. With the rising consumer demand for minimally processed, clean-label beverages, high-pressure processing (HPP) is set to assume a significant role in providing safe, high-quality, and nutritious drinks.

3.2 Ultrasonication (US)

Ultrasonication processing has garnered considerable interest in the beverage industry as a novel, non-thermal technology that improves product quality, safety, and functionality. Ultrasonication utilizes high-frequency sound waves to induce cavitation, resulting in improved homogenization, reduced particle size, and enhanced emulsification in various liquid foods and beverages, such as dairy and fruit juices [33]. Research conducted by Gavahian et al. [34] indicates that US technology enhances wine maturation, optimizes fermentation, accelerates aging, and deactivates microbes, leading to improved quality as demonstrated by enhanced critical aging markers, such as phenolic compounds and color intensity. Ultrasound enhances the phytochemical, physicochemical, biological, and organoleptic characteristics of alcoholic beverages. This technology led to a 50% enhancement in anthocyanin concentrations in red wine. The production rate improved significantly due to a reduction in aging time exceeding 90%. Ultrasound is a cost-effective technology that facilitates waste valorization, enhances resource efficiency, and improves profitability in the winery sector. Although this chapter presents extensive literature and successful industrial applications, additional efforts are necessary to upscale ultrasound and its applications to other types of liquors. Ultrasonication has been demonstrated to enhance the retention of bioactive compounds, antioxidants, and vitamins, as well as to improve the stability and organoleptic properties of beverages [35]. Furthermore, it enhances extraction processes, minimizes processing durations, and facilitates seamless integration into current production lines, presenting a cost-efficient and eco-friendly alternative to conventional thermal treatments. Recent studies indicate their potential for the production of functional and prebiotic beverages that offer enhanced health benefits and improved shelf stability [36]. With the increasing consumer demand for minimally processed, high-quality beverages, ultrasonication is set to significantly influence the future of beverage processing.

3.3 Pulsed electric field (PEF)

Pulsed electric field (PEF) processing represents a sophisticated non-thermal technology that is gaining traction in the beverage industry. It aims to enhance microbial safety and prolong shelf life while maintaining the nutritional and sensory attributes of products. Applying short bursts of high voltage to liquid foods, such as

fruit and vegetable juices, induces electroporation in cell membranes through PEF, effectively inactivating spoilage and pathogenic microorganisms as well as certain enzymes, while avoiding the heat-induced degradation of vitamins, phenolic compounds, and other bioactive substances [37]. PEF-treated beverages exhibit superior retention of ascorbic acid, flavor, color, and overall sensory acceptability when contrasted with conventional thermal pasteurization, thereby enhancing their appeal to health-conscious consumers [38]. PEF enhances extraction yields of valuable compounds and serves as a pretreatment to improve the efficiency of subsequent processing steps. The effectiveness of technology is contingent upon parameters including electric field strength, pulse duration, and treatment time, all of which require careful optimization for each product. PEF has demonstrated potential in laboratory and pilot studies; however, the advancement of dependable and economical electrical systems is essential for broader industrial implementation.

3.4 Microencapsulation and nanoencapsulation

Microencapsulation and nanoencapsulation are sophisticated processing methods employed in the beverage industry to improve the stability, bioavailability, and controlled release of functional ingredients, including vitamins, antioxidants, probiotics, and essential oils. These technologies encapsulate sensitive bioactive compounds within protective coatings at the micro or nanoscale, thereby safeguarding them from unfavorable environmental conditions, interactions with other food components, and degradation during processing and storage [39]. Microencapsulation enhances the retention and targeted release of nutrients, whereas nanoencapsulation provides further advantages, including increased solubility, taste masking, and improved absorption in the gastrointestinal tract. Encapsulation methods commonly employed are spray-drying, freeze-drying, emulsification, coacervation, and extrusion. The selection of wall material and technique is customized according to the specific application and intended release profile. Encapsulation strategies in beverage applications enhance the viability of probiotics, stabilize flavors and colorants, and improve the delivery of health-promoting compounds, thereby facilitating the creation of innovative functional beverages. The utilization of encapsulated bioactives derived from plant sources and agro-industrial by-products promotes sustainability and circular economy efforts within the food and beverage industry.

3.5 Fermentation

Fermentation processing is fundamental to the beverage industry, employing microorganisms like yeasts, bacteria, and molds to transform sugars and other substrates into alcohol, organic acids, and various flavor and aroma compounds. This ancient technique, with origins spanning thousands of years, is crucial for the production of beverages such as beer, wine, yogurt drinks, and various traditional and plant-based fermented drinks. It also improves preservation, nutritional value, and sensory attributes [40]. Recent advancements in fermentation have transitioned production from spontaneous, artisanal techniques to regulated processes utilizing selected starter cultures, thereby enhancing consistency, safety, and efficiency. Fermentation extends shelf life, inhibits spoilage, and produces health-promoting metabolites, probiotics, and bioactive compounds, rendering fermented beverages appealing as functional foods [41]. Contemporary advancements encompass the application of novel microbial strains, biotechnological instruments, and emerging processing technologies to enhance product quality and broaden the variety of

available beverages. Fermentation is increasingly utilized to enhance the value of by-products and promote sustainability in beverage production, particularly within the coffee industry, where it improves product quality and waste management.

4. Smart modern packaging

The packaging industry is influenced by various stakeholders, including producers, retailers, and consumers, each with distinct priorities, and there is often a lack of consensus on the value that packaging adds to products. Packaging traditionally functions to safeguard food from degradation due to environmental factors including oxygen, light, and moisture; to contain and facilitate the safe transportation of products; and to furnish consumers with critical ingredient and nutritional information. Historically, packaging has been viewed as a passive barrier that prevents external contamination and the migration of harmful substances into food [42–44].

Food and beverage packaging commonly utilizes materials such as glass, metals (including aluminum and tinplate), paper and paperboards, and various plastics. The selection of suitable materials is essential for maintaining product quality and freshness throughout distribution and storage processes [11]. Beverage packaging frequently integrates multiple materials to optimize their functional and esthetic advantages. Recent advancements in the field emphasize multilayer systems, active and intelligent packaging technologies, and sustainable alternatives such as bio-based polymers, all designed to minimize environmental impact while improving product protection and consumer attractiveness [45, 46]. **Table 1** presents a summary of the advantages and disadvantages associated with various materials utilized in beverage packaging.

Plastic bottles constitute the predominant type of beverage packaging globally, primarily attributable to their low production costs and functional benefits, including thermostability, microwavability, optical clarity, and versatility in dimensions and forms. Polyethylene terephthalate (PET) and high-density polyethylene (HDPE) are the predominant plastics utilized in beverage bottles, both recognized as major

No	Materials	Advantages	Disadvantages
1.	Glass	• Capable of being reused and recycled • Enhanced break resistance enables manufacturers to utilize thinner glass. • Devoid of odor and chemically stable • Resistant to gases and vapors • Preservation of product freshness over an extended duration without compromising taste or flavor. • Effective for heat sterilization. • Stiff • Effective insulation • Production in various forms • Variations in glass color can safeguard light-sensitive contents. • Clear	• Constraints in thin glass • Significant mass • Costs associated with transportation • Brittleness refers to the tendency of a material to fracture or break without significant deformation when subjected to stress. • Vulnerability to fractures due to internal pressure, impact, or thermal shock.

No	Materials	Advantages	Disadvantages
2.	Metal	• Adaptability • Physical security measures • Properties of barriers • Formability and esthetic potential • Capable of being recycled • Acceptance by consumers	• Aluminum exhibits a higher cost relative to alternative metals and materials, such as steel. • The inability to be welded limits its application to the production of seamless containers
3.	Paper and Paperboard	• Minimal weight • Cost-effective relative to alternative packaging systems • Capable of being recycled • Cost-effective and efficient protection • Available in various forms tailored to distinct food conditions. • Facilitated usability for consumers • Excellent strength-to-weight ratio.	• Inadequate barrier properties to light and moisture • Not intended for long-term food protection. When utilized as primary packaging, it is coated or laminated to enhance its functional and protective characteristics. • The integration of other materials impedes the subsequent recycling process. • Prone to tearfulness
4.	Plastic	• Flexible and adaptable • Transformed into sheets, shapes, and structures • Adaptable • Resistant to chemical agents • Cost-effective • Lightweight • A broad spectrum of physical and optical characteristics • Heat sealable materials are designed to bond through the application of heat, facilitating effective sealing processes in various applications • Simple to print • Incorporated into production processes in which the package is formed, filled, and sealed within a single production line	• Variable permeability to light, gases, vapors, and low molecular weight molecules • Limited reuse and recycling properties

Source: Marina Ramos et al. [11].

Table 1.
 Summary of the advantages and disadvantages associated with various materials utilized in beverage packaging.

environmental pollutants [47]. Plastic packaging can be produced as single films or as laminated and co-extruded structures, integrating various materials to improve barrier properties while often minimizing the overall material usage. While plastics offer advantages such as maintaining beverage safety, convenience, and temperature stability, they also present significant disadvantages, particularly their inconsistent permeability to light, gases, and vapors, which can compromise product quality [11, 48]. Calls to ban plastic beverage bottles arise from environmental and public

health concern. In areas with inadequate infrastructure or during emergencies when tap water may be contaminated, plastic bottles serve as a practical and often necessary solution for obtaining safe drinking water. Plastic packaging is essential for global beverage distribution; however, it introduces intricate sustainability challenges that require careful consideration alongside functionality and public health requirements.

Currently, three primary technologies facilitate intelligent beverage packaging: (a) sensors, (b) indicators, and (c) RFID (Radio Frequency Identification) systems [49]. **Table 2** presents recent trends in intelligent beverage packaging. Sensors are particularly notable for their transformative role in detecting and measuring physical or chemical changes, thereby facilitating the monitoring of product quality. Recent developments in printed electronics, nanotechnology, and biotechnology have broadened their applications in beverages and various food products [49, 50].

Recent advancements feature nano sensors engineered to identify contaminants, pathogens, allergens, and adulterants within intricate beverage matrices. Nano sensors are generally categorized into three types: nanoparticle-based, optical, and electro-chemical. Visible color changes, such as the transition of gold nanoparticles from red to blue, are commonly utilized for the detection of melamine in milk. Additional instances comprise fluorescence-based assays for the detection of cyanide in drinking water, liposome-based detectors for pesticides, and the application of magnetic nanoparticles for the isolation and quantification of bacteria in contaminated milk [51–55].

Sensors and indicators offer straightforward visual signals regarding spoilage or temperature violations, whereas RFID systems improve traceability and enable real-time monitoring throughout supply chains. These technologies convert packaging from a passive barrier to an active, intelligent system that enhances safety, quality, and consumer confidence.

The application of nanomaterials in sensing has increased significantly in recent years, motivated by the demand for compact, selective, and reversible chemical sensors that exhibit low detection limits and wide applicability. Carbon nanomaterials (CNs), which encompass nanoparticles such as carbon black and fullerenes, along with graphene, graphite nanofibers, and nanotubes, have garnered considerable interest owing to their high specific surface area, remarkable sensitivity, electrical conductivity, and mechanical strength [49]. These properties render them highly suitable for incorporation into advanced chemical sensors.

Indicators provide immediate visual cues regarding product status, often manifested through irreversible color changes, intensified hues, or dye migration, thereby aiding in the prevention of misinterpretation. Indicators differ from sensors in that they do not quantify analytes or retain measurement data longitudinally. Recent innovations encompass gas sensors, time-temperature indicators, thermochromic inks, and freshness labels. Gas sensors identify specific gases through alterations in physical parameters, which are subsequently measured externally [50]. The OxyDot® system incorporates an oxygen-sensitive fluorescent dye within packaging, while a fiber-optic pen non-invasively measures oxygen levels by detecting fluorescence quenching. The UPM Shelf-Life Guard label transitions from transparent to blue, indicating that air has supplanted the modified atmosphere within the package [11].

Moreover, radio frequency identification (RFID) constitutes an additional dimension of intelligent packaging. RFID systems comprise a chip, antenna, and reader, facilitating wireless data exchange through electromagnetic waves. RFID tags are utilized for product tracking, theft prevention, and anti-counterfeiting. They can store various information, including product codes, expiration dates, and location data, thereby improving traceability and automation in the supply chain [11].

Intelligent packaging	Product	Principle	Material
Sensors	Milk	Determination of melamine concentration using colorimetric analysis	—
	Water	Determination of cyanide concentration using fluorimetric analysis	—
	Water	Detection of pesticides using fluorimetric methods	—
	Commercial Beverages	Glucose concentration	—
	Milk	Aflatoxin B17 concentration	—
	Milk	<i>Mycobacterium avium</i> species. <i>Paratuberculosis</i> concentration	—
Indicators	Water, Oil, and Beverages	Oxygen indicator	Plastic
	Liquid Products	Gas release from packaging	Plastic
	Milk	Colorimetric polymerization reaction and enzymatic hydrolysis of a lipid substrate accompanied by pH reduction	Plastic and Carton
	Wine	Thermosensitive compounds and color change reactions	Glass
	Beer	Temperature sensor	Metal and Glass
	Orange Juice	Temperature sensor	Plastic and Glass
	Coffee	Temperature sensor	Plastic
	Coffee	Temperature sensor and time detector associated with freshness settings	Plastic
	Beverages	A self-adhesive pad, which incorporates a blue-dyed fatty acid ester within a carrier material, serves to monitor temperature exposure instead of assessing direct product quality. The dye remains fixed until the temperature surpasses a predetermined response threshold, initiating a phase transition in the carrier. This modification facilitates the diffusion of dye along a wick, with the distance traveled by the dye serving as a visual representation of the duration and extent of temperature exposure.	—
	Beverages	The active zone transitions from silver to white, with an increased fading rate observed at elevated storage temperatures.	—
RFID	Fat-free and Whole Milk	Assess the freshness of milk	Carton
	Wine	Observe temperature	Glass
	Water	Observe temperature	Plastic
	Liquors	Anti-counterfeiting measures, logistics, and proof of duty payment	Glass

Source: Marina Ramos et al. [11]; Rajan and Wani [12].

Table 2.
Recent trends in intelligent beverage packaging.

5. Sustainability

The beverage industry is at a pivotal point, encountering increasing pressure to adapt to global sustainability issues and changing consumer demands. Historically, sustainability initiatives in this sector have predominantly been supply-side oriented, emphasizing the reduction of environmental impact *via* resource-efficient production, eco-friendly packaging, and circular economy practices [15, 56]. These strategies have produced quantifiable environmental benefits; however, they constitute only a segment of a larger shift toward sustainability. Scholars and practitioners increasingly acknowledge that demand-side factors, especially consumer attitudes, perceptions, and behaviors, are essential for transformative change [13].

In recent years, an increasing number of consumers have identified as flexitarian, vegetarian, or vegan, coinciding with heightened awareness of ethical sourcing, animal welfare, and carbon footprints [57, 58]. The observed trends have stimulated market expansion for plant-based alternatives, organic-certified beverages, and products that emphasize fair trade and local origin claims [59, 60]. Research indicates that numerous consumers demonstrate a willingness to pay premium prices for products regarded as sustainable or ethically produced. Empirical research consistently demonstrates an attitude-behavior gap; consumers express strong pro-sustainability attitudes, yet these intentions do not consistently manifest in purchasing behavior [61–63].

This disconnect highlights the complexity of sustainable consumption, shaped by psychological factors (e.g., personal norms, trust, and perceived consumer effectiveness), socio-cultural influences, and contextual barriers including price, sensory preferences, convenience, and product availability [13]. In addition to personal motivations, packaging and labeling are crucial in conveying sustainability characteristics and influencing consumer perceptions [62]. Effective and visually appealing packaging enhances perceived authenticity and aids in closing the attitude-behavior gap [56].

Sustainability in the beverage industry encompasses not only environmental issues but also economic and social dimensions. Local sourcing, fair trade certifications, and transparent supply chains enhance value for consumers who prioritize community support and equitable practices [57]. The circular economy enhances these initiatives by emphasizing resource efficiency, designing products for recyclability, and valorizing waste—strategies that are increasingly sought after by environmentally aware consumers [15].

Rodriguez-Sanchez and Sellers-Rubio, 2021 [13] assert that the incorporation of demand-side perspectives is essential for attaining comprehensive sustainability. The research agenda emphasizes the exploration of emotional and affective factors in purchasing decisions, the analysis of cross-category differences in consumer expectations, and the effective communication of social and economic sustainability dimensions. These insights are essential for aligning marketing, innovation, and policy strategies with consumer values, thereby bridging the gap between stated consumer values and actual purchasing behavior.

Analyzing the impact of consumer demand on sustainability within the beverages industry is crucial for facilitating significant change. Research underscores the significance of consumer perceptions, willingness to pay, and the essential function of packaging in conveying sustainability attributes. The interplay among social, economic, and environmental dimensions of sustainability influences purchasing

behavior and brand trust. By identifying key gaps in the literature and synthesizing current findings, these insights help guide the development of products, packaging, and marketing strategies that not only meet but also actively shape consumer expectations for more sustainable beverage choices.

6. Conclusions

The beverage industry is experiencing a dynamic transformation shaped by technological innovation, evolving consumer expectations, and a growing commitment to sustainability. Recent advancements in processing technologies, including high-pressure processing, pulsed electric fields, and fermentation, allow manufacturers to create beverages that are safer, healthier, and more nutritionally balanced, while reducing reliance on synthetic additives. The integration of smart packaging solutions, which include sensors, indicators, and RFID systems, enhances traceability, extends shelf life, and fosters consumer trust by providing real-time product information.

The industry is responding to rising demand for functional and health-oriented products by innovating with plant-based and alternative ingredients, bioactive compounds, and reduced-sugar formulations. This approach addresses diverse dietary preferences and promotes overall wellness. Sustainability has become a key strategic focus, as companies implement circular economy principles, utilize biodegradable materials, and adopt resource-efficient production methods to mitigate environmental impact and conform to global climate objectives.

Digital technologies, including the Internet of Things (IoT), artificial intelligence (AI), and blockchain, are enhancing supply chain transparency and facilitating advanced personalization in beverage offerings. These developments indicate an industry that is both adapting to change and actively influencing the future of food and drink. The beverage industry is redefining its role in contemporary society by aligning product innovation with consumer values and sustainability objectives, transitioning from mere refreshment to contributions in health, environmental stewardship, and social responsibility. The ongoing trends will direct the sector, maintaining its resilience, competitiveness, and responsiveness to the demands of a swiftly changing global market.

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Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

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Appendixes and nomenclature

HPP	high-pressure processing
PEF	pulsed electric fields
IoT	internet of things
AI	artificial intelligence
RFID	radio frequency identification
PET	polyethylene terephthalate
HDPE	high-density polyethylene
CNs	carbon nanomaterials
CE	circular economy
Term	Description
Functional Beverages	Drinks containing added bioactive ingredients designed to deliver health benefits beyond basic hydration.
Smart Packaging	Packaging systems incorporating active (e.g., scavengers) and intelligent (e.g., sensors, indicators, and RFID) functions.
Circular Economy	Economic model aimed at maximizing resource efficiency, reducing waste, and promoting reuse and recycling.
Bioactive Compounds	Components such as probiotics, antioxidants, and polyphenols that provide health benefits.

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Chapter 4

Edible Packaging of Food Items and Beverages

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Abstract

Microbes, enzymes, oxidation, and other environmental variables during handling and storage make food ingredients extremely vulnerable to spoiling. Food must be protected from a variety of elements by being properly packaged. Paper, plastic, etc., are only a few of the packaging materials employed for food packaging; however, these constituents are neither environmentally friendly nor sustainable. Disposing of food waste and packaging has become an issue at recent times. Edible packaging uses sustainable materials that are completely biodegradable and safe to eat together with the product. Because of its better qualities, edible packaging may be a viable substitute for traditional packaging. Food-grade films, coatings, or containers are constructed by lipids, carbohydrates, proteins, composites, and other materials. In addition to preserving food safety and cleanliness and protecting food and food items from deterioration, edible packaging actively lowers food waste. A novel tactic to raise the quality of food is edible packaging. To increase the package's beneficial function for packaged food, additives are applied during its manufacturing. Edible coatings and films are recent sustainable types of techniques for covering food-related items. This chapter covers edible packaging materials, edible film and coating fabrication techniques, beverage-related packaging and benefits, and drawbacks of edible packaging.

Keywords: edible films, biopolymer, edible packaging materials, edible coatings, food packaging, beverage

1. Introduction

Enclosing and safeguarding goods for use, storage, and distribution is known as packaging. The market offers a variety of packaging materials, including paper, plastic, cardboard, and others [1]. According to market and research reports (2020–2025), the annual use of materials derived from plastic has grown by around 230 million tons so far. Furthermore, synthetic and plastic-based materials are not biodegradable and have numerous negative effects on the environment [2]. Because of easy to shape, less weight, and less cost, plastics are widely used in food packaging, but they are non-degradable and have a negative impact on environment [3]. Some materials, such as paper and paperboard, have relatively high recycling rates (over 20% in conventional packaging), whereas other materials, like various plastics, typically have less than 20%; that is, low recycling rates pose an environmental burden. Packaging materials that do not biodegrade are unsustainable and pollute the environment [4].

Films, coatings, or containers made of food ingredients that are safe to consume with the product [5]. By forming a barrier against water and oxidation and regulating enzymatic activation, edible packaging helps shield food items from chemical, microbiological, mechanical, and physical harm. Qualities of edible constituents and food products are enhanced by the use of active ingredients such as plant extracts, nanomaterials, cross-linkers, in edible packaging [2]. A variety of additives, including flavorings, colorings, and sweeteners, are present in packaging material. Edible packaging is structured by lipid, carbohydrate, protein, composite, etc. [1, 5]. To improve the food preservation, increase lifespan, and guarantee microbiological safety, bioactive substances are added in active packaging. Film strength, stability, and controlled release are enhanced *via* nanocomposite reinforcement [6]. But in intelligent packaging, some sensors are embedded in the packages such as anthocyanin and curcumin. Some are used as pH indicators in edible packaging of meat products and seafood [7].

Food packaging by edible packages actively reduces food waste while maintaining safety and cleanliness and shielding food and food items from deterioration. According to estimates, about 30% of food produced ends up in landfills as a result of spoiling during harvesting and transportation [8]. Food in edible packaging retains its moisture content, gas, and fragrance [9]. Food packaging materials should be environmentally friendly, naturally organic, better in quality and positive for health. The food business faces a difficulty in creating environmentally friendly packaging while reducing pollutants [5]. Biopolymers-based edible packaging is more famous at present [10]. Films, coatings, sheets, and pouches are all examples of edible packaging. Thickness is a crucial physical characteristic in edible film formation and less than 0.3 mm is thought to be the ideal thickness [11].

Vegetable and fruit postharvesting preservation is essential to minimize the respiration rates, regulate moisture loss, decrease physiological changes, and stop microbial infections [12]. The controlled interchange of gases such as O₂, CO₂, and ethylene required in the respiration of food products is made possible by edible packaging [13]. The organoleptic qualities of packed meals can also be improved by edible packaging, which can customize the surface qualities such as hydrophobicity, hydrophilicity, flavors, and colors [4]. Although it may appear to be a recent development, edible packaging is actually a very old technique that has been used for generations to preserve food. In order to preserve them and prevent water loss during storage and transportation, wax was originally applied to lemons and oranges in China during the twelfth century [14]. Commercial waxing and lipid coatings were used on fruits and vegetables in the 1930s to promote natural respiration and avoid dehydration while in transit [3]. Using edible packaging has certain drawbacks, such as the new edible wrappers being more expensive than synthetic packaging. After the packing, an additional container is required. Sometimes, edible packaging is not suited for flavor [1]. In this chapter, edible packaging materials, edible packaging preparation processes and advantage and limitations related to edible packaging are discussed.

2. Edible packaging materials

Natural polymers are the packaging materials that are edible and pose no health risks to humans when consumed directly. Proteins, lipids, polysaccharides, and composites are used in packaging (**Table 1**). Edible materials can be combined with other ingredients or may be used alone in a variety of food technology applications (**Table 2**) [29]. By employing nanotechnological methods and incorporating bioactive

Polysaccharides • <i>Marine</i>: agar, alginate, carrageenan • <i>Microbial</i>: xanthan gum, pullulan • <i>Plant</i>: cellulose, hemicellulose, starch, pectin • <i>Animal</i>: chitin, chitosan	Lipids • <i>Plant</i>: oils, waxes, fatty acids, cutin, resin • <i>Animal</i>: animal fats, bee wax, resin	Additives • <i>Plasticizer</i>: polyols, mono & oligosaccharides, lipid and its derivatives • <i>Emulsifier</i>: natural lecithins, sodium lauryl sulfate, glycerol monopalmitate etc. • <i>Antimicrobial</i>: chemical agents, natural extracts and probiotics • <i>Plant extract</i>: extracts of plant's seeds, roots, bark, buds, flowers, and leaves
Protein • <i>Plant</i>: wheat gluten, corn zein, soya protein, pea protein • <i>Animal</i>: collagen, gelatin, fish protein • <i>Milk</i>: casein, whey protein	Composite • Multicomponent • Lipid and protein mixture • Carbohydrates and protein mixture • Carbohydrates and lipid mixture • Synthetic and natural polymers mixture	

Table 1.
Edible packaging materials.

Food items	Edible materials	Effect	Reference
Blueberries and raspberries	Carrageenan and green tea extract	Antiviral action against hepatitis A virus and murine norovirus	[15]
Banana	Aloe gel, lemon peel extract, and glycerol	Decrease in the prevalence of ascorbic acid, fruit deterioration, reduction in weight, and anthracnose illness	[16]
Apple	Sodium alginate, calcium chloride, and glycerol	Improved antioxidant activity during storage, decreased chill injury, respiration rate, and physiological loss of weight.	[17]
Lemon	Coconut oil and beeswax	Color retention and increased shelf life	[18]
Strawberries	Banana starch, chitosan, and <i>Aloe vera</i> gel and glycerol	Decrease in PLW, stiffness, and enhancement of general qualitative characteristics	[19]
Lime fruit	Pectin-based coating	During storage, there was a progressive rise in shriveling or wilting and a loss of green color; these changes were increased by higher temperatures.	[20]
Strawberries	Chitosan/MFC-based composite films/coating	An important improvement in the mechanical, barrier, and colloidal stability qualities necessary for environmentally friendly food packing applications was obtained.	[21]
Dry goods and grains	Carboxymethyl cellulose (CMC), starch-cellulose nanocomposites	Forming a barrier of fat and gas in beans, breakfast cereals, and nuts.	[22]

Food items	Edible materials	Effect	Reference
Apple slices	Locust bean gum, cladode polyphenols, and <i>Opuntia</i> mucilage to create an active edible film	Apple slices' freshness is well preserved, and their shelf life is increased while they are being stored.	[23]
Fruits and vegetables	Incorporating starch, carrageenan, nanocellulose (NC), <i>Aloe vera</i> , and hibiscus flower extract	Enhanced water vapor permeability, solubility, wettability, and moisture absorption; biodegradability and efficient UV radiation barriers	[24]
Dairy product	Carrageenan, cellulose derivatives (methylcellulose)	Keeping cheese and yogurt wet and stopping the oxidation of fat	[22]
Instant coffee powder	Edible films comprising κ-carrageenan/carboxymethyl starch/gum ghatti	Water-soluble edible films enhanced the stability of solid beverages.	[25]
Pork	Chitosan-gelatin edible coatings incorporating grape seed extract	Effectively prevented microbiological spoiling and pork oxidation; grape seed extract increased antioxidant activity against meat oxidation	[26]
Chicken thighs	EFs based on pectin from watermelon rind (<i>Citrullus lanatus</i>) with kiwifruit peel extract (<i>Actinidia chinensis</i>)	Reduced concentrations of peroxide and acid-reactive compounds were noted	[27]
Chicken meat	Composite EFs based on fish gelatin-pectin containing lemongrass essential oils (EOs)	Showed elevated TS, EB, antibacterial activity, and antioxidant activity	[28]

Table 2.

A list of edible packaging materials used for food item packaging and their effect.

substances, plant-based material's functional properties, durability, and quality of food have all been improved [30]. These materials produce no waste, are nontoxic, biodegradable, and include transport-active chemicals [31].

2.1 Polysaccharides

Polysaccharides are natural biopolymers that have different types of sources such as marine, microbial, plant, and animal (**Table 1**). The most prevalent natural macromolecule in nature is polysaccharide, which is employed extensively in the creation of food packaging [31]. Polysaccharides are made up of lengthy chains of polymeric carbohydrates joined by glycosidic linkages. They are harmless, colorless, tasteless, and selectively gas permeable. Alginate, cellulose, and pectin are examples of polysaccharides that provide a strong structure and effective gas barrier qualities [32]. Polysaccharides are also effective oxygen barriers. The sole drawback of polysaccharide-based edible packaging is its weak water vapor barrier capability, which is caused by polar groups that make the biopolymers hydrophilic [33]. The edible packaging cracks and flakes are due to the hydrophilic character of the biopolymers based on polysaccharides [34]. In response to growing environmental concerns brought on by the widespread use of plastic packaging, edible films based on polysaccharides have been researched extensively as food packaging materials. A chitosan (CS) and carboxymethyl cellulose (CMC) combination creates a binary edible film that has drawn a lot of attention recently [35]. Pectin-based packaging has found extensive use in

both fresh and processed foods because of its barrier quality against physical factors such as moisture and gases; moreover, it also works as active ingredient carrier that helps in food preservation and extends the life of it [36].

2.2 Proteins

A polymer of amino acids, proteins have different sources such as plant, animal, and milk are being used in packaging (**Table 1**). Edible films are created by multilevel protein complexes. However, because the proteins have a higher atomization energy per unit volume, protein films are fragile and brittle. Reinforcing materials and active compound additions can be added to boost the film's functional and physical qualities [29]. Although protein coatings have limited water barrier qualities, they have comparatively excellent mechanical qualities and are good at blocking gases (CO₂, O₂) lipids, and fragrances [3]. Food quality has largely decreased because of lipid oxidation, which can be prevented by employing edible protein film that can stop oxygen from penetrating [37]. Because of their relatively high mechanical power, proteins can be used to guard fruits and vegetables against deterioration. Compared to lipids, polysaccharides and proteins have a hydrophilic nature and have inferior moisture resistance. However, the primary disadvantage of edible packaging related to proteins is their weak gas barrier properties that are caused by hydrophilic substances. As a result, a number of researchers have sought to create edible packaging made of polysaccharides and proteins that has strong gas and water barrier qualities by adding crosslinking agents [38].

2.3 Lipids

Lipids are being used in edible packaging of food goods [2]. Lipids have the ability of nonpolar solvents and also contain hydrophilic and hydrophobic character [8]. Wax and other lipids were initially used to cover citrus fruits [39]. Plants, animals, and insects are the natural source of lipids [29]. Lipids have comparatively strong moisture barrier qualities and minimal water vapor penetration. The moisture barrier effectiveness of plant and animal waxes is better than that of other types [40]. Lipids are fairly thick, easily broken, and demonstrate poor adhesion to hydrophilic food-stuffs. They also have weak structural and visual features [8]. Usually, lipids combine to proteins or polysaccharides to create a multilayer coating that enhances the film's ability to withstand with water absorption [1].

2.4 Composite

Researchers are now concentrating on composite-related edible packaging that is also referred to as multicomponent systems to boost the lifespan of food goods [41]. Utilizing the synergistic modifications in the film to overcome its particular shortcomings in certain qualities is the primary credo of composite film manufacture [39]. Composite films are generated from merging distinct polymers such as lipids, proteins, carbohydrates, and synthetic polymers. Protein-polysaccharide interaction produces a mono-phase film that possesses the improved mechanical character [42]. Combining protein and lipid results in a film with improved organoleptic qualities and stronger, better barrier qualities, which raises its commercial worth [1]. The quantity of biopolymers used determines whether composite edible films are binary or ternary. The combination of pectin with zeolite Y created a binary edible film

[43]. Chitosan, cassava starch, and whey protein were utilized in composite edible packaging for fruits with the enhanced physical characteristics [44]. Bio-composite films were made for active edible food packaging that are made of carrageenan/starch reinforced with nanocellulose [24].

2.5 Additives

2.5.1 Plasticizers

Low-molecular-weight substances known as plasticizers give a material more strength and flexibility. Because plasticizers have the ability to lower intermolecular tensions in polymers, they can be included in coatings or films to boost permeability to gases and water [8]. Monosaccharides, oligosaccharides, polyols and lipids, and their byproducts (fatty acids, surfactants) are often used as plasticizers in packaging [45]. Glycerol is frequently used to improve the mechanical properties of polysaccharide-based film and to keep starch-based goods wet [46]. Glycerol-sage seed gum film is one example of how adding various lipidic plasticizers to a film or coating can have a good impact. It has been shown that these plasticizers increase the film's thickness, moisture content, and moisture uptake [47]. The 3-D molecular arrangement of biopolymers is altered by plasticizers [48].

2.5.2 Emulsifiers

Because emulsifiers are both polar and non-polar, they function as surface-active agents that can mix immiscible liquids, such as water and oil. Because they aid in achieving the adequate wettability to the product, a prerequisite for appropriate area of the surface and the covering substance's adherence, emulsifiers are crucial. Because they are amphiphilic, many proteins exhibit emulsifying qualities [8, 49]. Significant emulsifiers include natural lecithins and other common emulsifiers include glycerol monopalmitate, sodium lauryl sulfate, acetylated monoglyceride, glycerol monostearate, polysorbate 80, sorbitan monostearate, etc. [50].

2.5.3 Antimicrobials

Additives called antimicrobial chemicals are used to prevent the growth of microorganisms, including harmful ones, and to regulate biological deterioration. Antimicrobial agents are frequently administered directly to the food for packaging. Edible films may contain a variety of antimicrobial ingredient types [51]. The best way to prevent additional food contamination and deterioration would be to use the antibacterial treatments. Every antimicrobial drug has a distinct function and responds differently to most bacteria [52]. Bacteriocins are the peptides that inhibit bacteria's growth [53]. The limited research on bacteriophage-treated edible films and coatings was covered. Food items can be preserved by phage-added edible packaging, which also contains strong antibacterial qualities [54]. Investigating insects as a source of antimicrobial peptides may help to find substances that can stop the growth of a variety of pathogens in various dietary applications and can be used in edible packaging [55].

2.5.4 Plant extracts

The extracts are made from a variety of plants and their parts. Their antibacterial qualities are mostly because of phenolic compounds, which are present in different

parts of plants and spices [56]. Phenolic substances are bioactive and show antibacterial and antioxidant properties and are found in oil extracted from plants such as radish, clove [57]. Foods can include natural antimicrobials without the use of preservatives or other antimicrobials. Plant-derived extracts in a polymer substrate provide packaging materials their different qualities, such as physical, antioxidant, antibiotic [2].

2.6 Others

Biopolymers include organic acids, plant extracts, antibacterial compounds, essential oils, probiotics, and prebiotics, as well as other active agents. They are non-toxic, environmentally benign, biocompatible, and biodegradable [2]. To be environmentally friendly, biodegradable polymers are frequently chosen. Marine seafood, plants, and algae are valuable sources of natural polymers that may be utilized to create environmentally friendly packaging. Historically, the earliest materials utilized for food packing by ancient cultures were various natural materials, such as plant and animal parts, shells, pottery, and others [58]. Foods such as green bell peppers, guavas, blackberries, pineapples, cheese, strawberries, and shrimp were also used in edible packaging [48].

3. Edible films and coatings

According to estimates, the global edible coating and film market in 2020 was USD 2.06 billion. The Food Safety Act of 1991 requires that the framework regulations EC 1935/2004 be followed when using food packaging and other contact packaging materials. According to this law, no dangerous substances should be released into food items by packing materials in amounts that might endanger human health [2].

3.1 Edible films

Flat-layered sheets are used as food covers that can be eaten with the dish and may be detached [59]. Films can be used to make wraps, pouches, bags, capsules, and casings [5]. Edible films are prepared first and then applied on food for packaging (**Figure 1**) [1]. Film-forming materials must possess filmogenic qualities and be biopolymers [3]. The choice of plasticizers and solvents is based on how well they work with the chosen polymer. Solvents that dissolve polymers and change the physical and barrier properties include water, alcohol, and others [60]. In order to reduce water loss, stop leaks, and lessen food contamination and spoiling, hydrophobic coatings are also placed on the inside surfaces of packing films [61]. There are different types of formation processes of edible films, like wet and dry processes [14, 62].

3.1.1 Wet process

To create a film, the wet technique involves homogenizing the film-producing ingredients with a solvent and then drying them. Biopolymers are dissolved in solvents in first step. Then, matrix substances are incorporated with additives and enhanced the heat and pH of the solutions to make them more soluble. A surface that is flat is covered with a film-making fluid, which is then left to dry at an appropriate temperature and humidity level. Food products can be wrapped with the generated

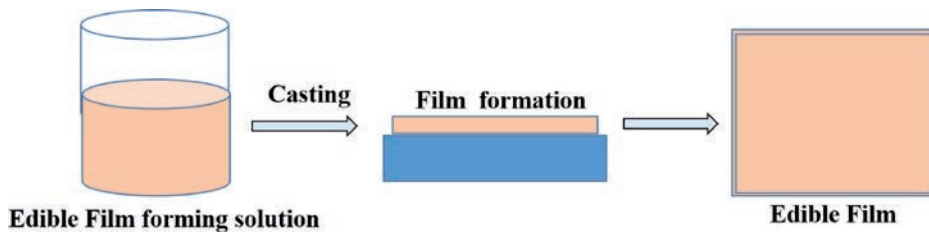


Figure 1.
Edible film formation.

film. During the casting process, the film-forming fluid is transferred onto a teflon-covered glass plate or a prefabricated mold. A mold-attached polymer film is created by solvent evaporation during the drying stage [3, 63].

3.1.2 Dry method

The thermoplastic tendency at low moisture content is used in a dry procedure to transform the additional ingredients into films [64]. This method is diverse and includes the different processes.

3.1.2.1 Extrusion process

In this process, three main steps are i. Feeding, ii. Kneading, and iii. Heating [65]. In addition to using less energy and time to manufacture the material, this method offers superior physical qualities. It is a popular commercial method that provides excellent performance at a fair price [1, 3].

3.1.2.2 Compression molding method

It is regarded as a sustainable process because of its quick formation and minimal energy requirements. The material within the film-making mold is heated and compacted until it solidifies. Another element that affects the film's characteristics is time related to the processing. Prior to the primary thermoforming process, the film-forming material is often prepared using this stage in conjunction with the extrusion method [3].

3.1.2.3 Injection molding method

The pressure of injection, heating of mold, and prior to injection pressure heating are the parameters of this three-stage process, which includes filling, packing, and cooling [66].

3.1.2.4 Electrospinning method

The process is generally carried out as jet starting, extension, and solution hardening. A syringe or capillary tube is one of the components of an electrospinning process that transfers solution to a high-voltage battery, which then produces nanofiber and collects the solution with the aid of a collector [1, 67].

3.1.2.5 Thermoplastic method

The thermoplastic process constantly shapes the materials using high temperatures, shear pressures, and minimal water, enabling the production of films on a commercial basis [68].

3.2 Edible coatings

The food items are effectively coated by the edible coating (EC) materials. Covering, dipping, and spraying are the examples of processes (**Figure 2**); moreover following drying, the food develops an edible coating that may be eaten or removed [5]. The powder, emulsion, or liquid suspension solution can be employed on food surfaces. There are different types of preparation methods of edible coatings.

3.2.1 Dipping method

This method is traditional and widely used [63]. It entails dipping an item directly into a liquid coating solution, taking it out, and then letting it air dry to generate a membranous coating that covers the outer structure of food items [3].

3.2.2 Spraying method

This approach is best suited for items with broad surfaces using pressure (60–80 psi) to cover the food-related item's outer structures and surfaces [66].

3.2.3 Fluidized bed method

Putting an extremely thin coating on dried particles that have very low sizes (density) is known as fluidized bed processing. A fluidized bed that rotates is filled with the tiny particles that need to be coated. Centrifugal force and airflow work together to efficiently offset the overall force imposed on the food particles [65, 69].

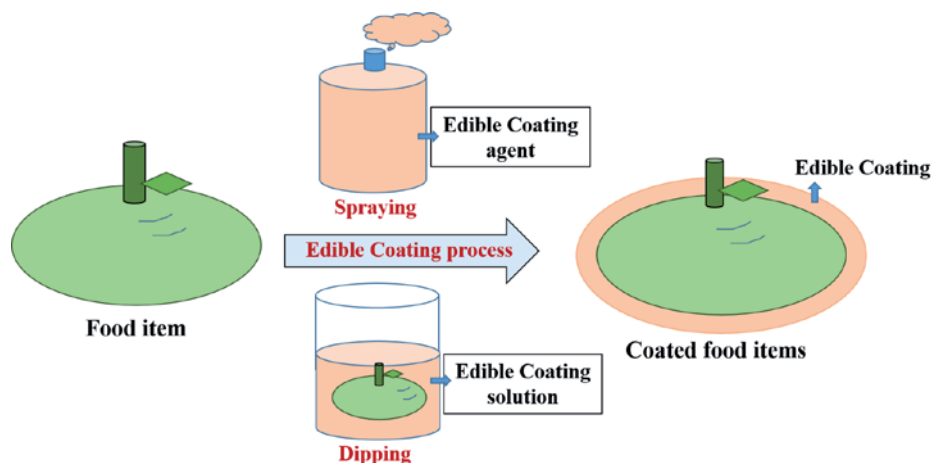


Figure 2.
Edible coating process of food item.

3.2.4 Drum coating method

Drum coating is one method for adding a significant thin and thick coating to a harder object (nut). It is used on salt and oil nuts, which improves their flavor and palatability while delaying oxidation. This coating technique aids in delaying the absorption of moisture in chocolate [1].

3.2.5 Pan-coating method

The pan-coating technique is suitable to create thin coverings and thick coverings of coating on hard, almost spherical particles that may give the coated product more tastes while halting the loss of lipids and moisture. This process involves placing the object to be coated inside a huge rotating bowl, which serves like a pan. Employing a ladle and a spray, the coating solution is poured into a rotating pan having food items for surface coating [69].

4. Edible packaging related to beverages

Beverages are being packed by edible packages. Drinks are frequently enclosed in coatings or films. Alginate capsules create a liquid container that forms a barrier that keeps the liquid inside for beverage packaging. A product's surface can be directly coated with the edible materials to provide protection. But many edible materials dissolve readily in water and have a short shelf life, moreover that can cause allergies while using natural ingredients in edible packaging [5]. Biomaterials such as seaweed, chitosan, gum, starch, and other materials are used by Patil et al. [70] to make edible straws. Injection molding, screw extrusion, rolling up, and other techniques are used to prepare them. Paper, plastic, and PLA straws are inferior to edible straws. These chemical-free edible straws go well with a variety of drinks and beverages [70]. Biodegradable edible cups have been created to collect the hot drinks. Material of the cups (cookies) was thick and could be taken in a hand. The drink can be kept in the edible cup for 20 minutes to 1 hour. Under the influence of drink, the cup remained unchanged [71]. Wheat flour, cocoa bean, coffee, palm oil, sodium bicarbonate, and sugar had been used by Anand et al. [72] for the formation of edible cups for coffee. Each cup has volume 180 ml (weight 22 g) and it was baked in an industrial oven for about 30 minutes. Eating cups have been suggested as a way to reduce plastic pollution and littering caused by the annual waste of 500 billion drinking cups [72].

Wu et al. [25] created an edible packaging film using a mixture of gum ghatti, carboxymethyl starch, and κ -carrageenan that dissolves quickly in water. This film has been applied in instant coffee powder packaging, where the film also increased instant coffee's (solid beverage) stability [25]. The strength performance of film was boosted when sodium alginate (SA) was added to potato starch (PST); moreover, fruit and vegetable juices were incorporated in PST/SA films that demonstrated the excellent antioxidant properties and good visual appeal [73]. Using the solvent-casting approach, polysaccharide-centered edible films were created using jambolan and grape juices by Chambi et al. [74]. This film demonstrated good flexibility and resistance to mechanical force [74]. Green tea extract was added to edible film of soy protein and antimicrobial activity was observed [75].

5. Benefits and drawbacks

Edible packaging materials decompose naturally and can be eaten or thrown away without harm. Frequently, the integrated composition contains vitamins and plant extracts that are good for health, improving the health of the customer. Industries related to food, medicine, nutraceuticals, agrochemicals, etc., are utilizing the edible films. Edible packaging is available in a number of forms, including films, coatings, soluble strips, flexible pouches, microcapsules, straws, cups, and capsules. Edible packaging opens the door for packaging the materials that are easily damaged (fruits and vegetables). Less use of traditional packaging improves the environmental effect and lowers waste output [29, 73].

There are some limitations while using the edible packaging, such as the fact that new edible wrappers are more costly than synthetic packaging. They would be used to wrap foods within a secondary synthetic package while delivering and preserving food. They would not be employed exclusively, where unhygienic circumstances during food handling may arise. Developers, however, believe the nutritional and environmental advantages will offset the increased cost. Edible packaging occasionally has an odd flavor and poor mechanical qualities. To prevent hygroscopicity and microbiological growth, edible packaging needs to be carefully chosen [1]. It could be necessary to use antimicrobial agents. Some ingredients employed in edible packaging, such as beeswax, may trigger allergic responses in people. There is a dearth of information regarding edible film and coating equipment, materials, and application methods [29].

6. Future perspectives and conclusions

In order to prevent food waste and environmental contamination, the significance of sustainable and long-lasting packaging materials has increased dramatically. Bio-based products flourish in the excess, such as bioplastics and wood-based paperboard. But there is still a long way to go before petroleum-based products in the packaging industry can be replaced with bio-based ones. An eco-friendly, inventive, and green solution that has the potential to replace synthetic packaging is edible packaging. Edible packaging is a significant way to boost the life of food-related items. Biopolymers of natural sources are used to construct edible packages. By decreasing weight loss, water transpiration, and the barrier against gas transmission, edible packaging is useful for storing the characteristics and sensory qualities of many food-related substances. Because of its superior barrier qualities, composite packaging is preferred over edible coatings that are made from a single polymer. A variety of edible packaging techniques are employed, including composite packaging, active packaging, etc. Moreover, nanotechnology is being used in packaging because of its superior mechanical, thermal, optical, and antibacterial qualities. Edible packages preserve color, flavor, and other inherent qualities. Active ingredients like plant extracts and essential oils can function as organic antimicrobials by preventing the growth of dangerous microorganisms in food products. Moreover, every additive has a unique purpose or impact on edible packaging. The industrial community has been increasingly interested in the idea of smart food packaging, but factors like cost, processing needs, energy usage, mean conventional packaging cannot be fully replaced. To comprehend layer-by-layer packing, commercial application, edibility, the scaling-up process, and other topics, more research is required.

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Emerging Trends for Innovative Wines

Paola Domizio, Alice Vilela and Antonio Morata

Abstract

The wine sector is currently undergoing a changing scenario, strongly influenced by global warming, new international market taxes, a decline in consumption among young people, and policies regarding alcohol consumption. Several strategies can help to overcome these issues among them (i) the use of new biotechnologies to control pH, improve sensory profile, and reduce additives in wines from warm areas (bio-acidification, bioprotection, use of non-conventional yeasts as non-*Saccharomyces*); ii) the production of low alcohol and non-alcohol wines, and grape-derived beverages of high quality, with a good sensory profile and stability, by use of new fermentation biotechnologies, innovative dealcoholization technologies, and emerging non-thermal technologies to improve the stability of these wine products; iii) the use of emerging yeast derivatives from *Saccharomyces* and non-*Saccharomyces* to improve quality and stability of wines.

Keywords: non-*Saccharomyces*, dealcoholized wines, grape-derived beverages, bioprotection, emerging non-thermal technologies, yeast byproducts

1. Introduction

The wine sector is a millennial industry that humans have developed since the Neolithic era [1]. The production of fermented beverages from grapes, as well as the stabilization and aging of wines, has been an essential part of the food industry, contributing to culture, quality of life, passion, art, environmental protection, and added value to the Mediterranean diet for centuries. Even though wine is currently affected by exaggerated threats like the toxicity of ethanol (difficult to understand in the context of moderate consumption and associated with a healthy diet), the allergenicity of sulfites (though wines have very moderate contents compared to other food products), and the decrease in consumption, especially among young people that prefer other beverages.

However, even in this challenging and dynamic context, numerous innovations have been incorporated into the wine industry. The use of traditional minority varieties to differentiate from the conventional international varieties, moreover, to look for better varieties that can be more suitable for the unbalanced composition produced by global warming [2]. The planting of resistant varieties (PIWIs) multi-crossed with *Vitis vinifera* is aimed at maintaining the maximum sensory profile of the grape [3].

The application of ancient techniques, such as extended skin maceration in white wines, as seen in Georgian traditional orange wines, is a trend [4]. Additionally, ancestral natural sparkling wines are fermented in bottles with the residual sugars of fermentation [5]. The soft extraction of skins in extremely pale rosés and moderate maceration in reds to achieve more balanced phenolic loads and a better elegance [6]. Partial dealcoholized wines, also known as 0.0, are a trend highly demanded by wine lovers who prefer to consume reduced alcohol amounts or are unable to drink alcohol due to health, pregnancy, religious, or cultural reasons [7].

Emerging biotechnologies, such as the use of non-*Saccharomyces* yeast, focus on improving the sensory profile to achieve better-balanced wines or enhancing stability through bioacidification [8] or bioprotection [9]. Some of these biotechnologies can also be used to improve wine quality from grapes affected by global warming. New strategies for aging wines are also employed, such as biological aging on lees, the use of different barrel sizes to mitigate the impact of barrels, or the use of alternative woods like chestnut, acacia, or others [10, 11]. All these innovations are summarized in **Table 1**.

Use of emerging non-thermal technologies to reach microbial and physicochemical stability in grapes and wines [12]. Physical non-thermal technologies eliminate spoilage microorganisms from grapes and wines, facilitating fermentative processes, the implantation of non-*Saccharomyces* starters, the extraction of phenols and aromas,

Technology	Innovation	Description	Advantages	Impact	Reference
Viticulture	Minority varieties	Use of non-conventional traditional varieties	New sensory profiles, better adaptation to global warming	Competitiveness, differentiated wines, and adaptation to new consumers	[2]
	Resistance to fungal diseases, low need for pesticides	Hybrids by back-crossing or reciprocal crossing with genes of resistance	Reduction of pesticides and labor costs	Sustainability and quality	[3]
Winemaking	Orange wine	Ancient technique of white winemaking with skins extended maceration	Good long-term evolution, especially sensory profile, higher flavonoid content	Differentiated wines, currently very appreciated by some consumers	[4]
	Ancestral sparkling	Natural sparkling wine in which the CO ₂ pressure is reached by the bottling of the base wine at the end of fermentation, with just the residual grape sugars.	In a scenario of global warming, it is not necessary to add extra sugar, which would increase the ethanol content.	Attractive to some consumers. Without external sugar addition. Better foamability.	[5]

Technology	Innovation	Description	Advantages	Impact	Reference
	Soft extraction	Use of slight macerations to achieve pale roses and light reds with reduced body and softer tannin.	More fashionable colors according to new market trends.	Attractive for new markets and more valued by consumers. In the case of reds, there is less challenging tannicity due to the lower phenolic load.	[6]
	Dealcoholized wines	Partial or complete dealcoholization by physical or biological techniques	Production of low-alcohol or 0.0 wines. High-quality wine with healthy polyphenols and lower alcohol content.	Fits the requirements of many consumers who cannot take alcohol due to health, religion, or culture.	[7]

Table 1.
Emerging trends in innovative wines.

and also improving wine stability. Moreover, these technologies can serve as an alternative to chemical additives, enabling clean labels. Some of the more efficient methods are high hydrostatic pressure (HHP), ultra-high pressure homogenization (UHPH), pulsed electric fields (PEF), ultrasound (US), and pulsed light (PL).

Among all these technologies, we will delve deeper into the following due to their versatility and potential applications in the context of global warming.

2. Emerging biotechnologies

Enologists and winemakers have spent the last century eliminating wild yeasts by using sulfites to better implant *Saccharomyces cerevisiae*, thereby achieving better performance and reliability in fermentation, which results in a safer process. In the current century, interest in non-*Saccharomyces* yeasts has grown steadily to produce more differentiated wines, with new features and improving the imbalances in grapes from warm regions. The use of non-*Saccharomyces* offers significant advantages, including pH control through bioacidification, which produces fresher and more stable wines [13, 14]. Additionally, it enhances aroma through the production of esters [15] or benzenoids [16] and facilitates the release of varietal aromas such as terpenes [17] or thiols [18].

2.1 Bioacidification and *Lachancea thermotolerans*

Recently, *Lachancea thermotolerans* [19] has emerged as a key tool for efficiently controlling pH during fermentation, resulting in fresher wines that are less prone to spoilage and exhibit better sulfite effectiveness due to a higher fraction of molecular SO₂ [8, 20–23]. The use of *L. thermotolerans* has also been described for acidification in beers [24], such as to produce fruity, sour lambic beers [25], and ciders to produce

more flavorful cider spirits [26]. The use of *L. thermotolerans* allows the production of wines with lower ethanol content, more suitable for the current health trends (0.2–0.9% of reduction [22, 27, 28]), with a fresh taste that fits with the new rosés and white wine types, and that helps to improve grapes affected by global warming. That is because the production of lactic acid by the lactate dehydrogenase enzymes (LDHs) is done despite sugars, therefore reducing the potential alcohol of grapes (Figure 1).

Moreover, *L. thermotolerans* has been described as low producer of volatile acidity (<0.4 g/L, [27, 28]) and even with capacity to decrease it [29], with a high production of succinic acid in some strains (>1 g/L, [27, 28]) and influence in the release of thiols (>x2, [18]). All these features contribute to its potential to produce innovative and fresh wines, respectful of varietal aromas and grape quality, with a mineral profile. Additionally, lowering the pH makes the sulfites used as an antioxidant and antimicrobial more effective, as the higher molecular SO₂ content allows winemakers to reduce the total amount of this concerning additive in wines while maintaining or even enhancing the level of protection.

2.2 Bioprotection and *Metschnikowia pulcherrima*

Bioprotection has been recently defined by the International Organization of Vine and Wine (OIV) as: “the use of oenological microorganisms, or their derivatives, to control the spoilage microorganisms and/or to avoid oxidations, to reduce chemical additives and to preserve the sensory quality of wine” [30]. Therefore, bioprotection is a handy tool to eliminate or reduce the use of chemical additives in controlling spoilage microorganisms [31, 32] and oxidative processes, as well as utilizing natural products.

Several oenological yeasts have been studied for bioprotection applications, including *L. thermotolerans*, which utilizes pH control and killer toxins [8, 33], *M. pulcherrima*, which produces pulcherrimin and killer toxins [33, 34], and *T. delbrueckii*, which exhibits antimicrobial and antioxidant capacities [35, 36]. Some of them also offer interesting advantages in terms of biocompatibility, as seen in the cases of *L. thermotolerans* and *M. pulcherrima* [37]. It has been reported that the simultaneous use of *L. thermotolerans* and *M. pulcherrima* is positive by the protective effect of *M. pulcherrima*, reducing the effectiveness of sulfites in the inactivation of

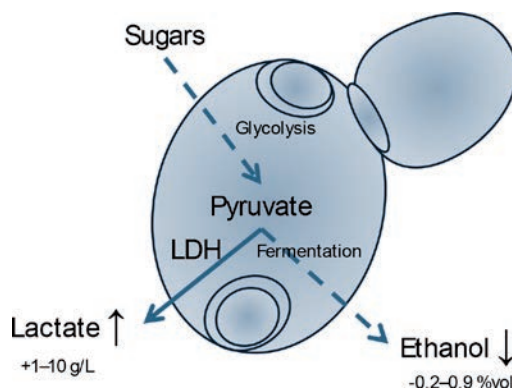


Figure 1. Formation of lactic acid by *Lachancea thermotolerans* and its influence on global fermentation balance.

L. thermotolerans, the antimicrobial control obtained by bioacidification by *L. thermotolerans* and killer toxins/pulcherrimin by *M. pulcherrima*, the antioxidative effect by O₂ consumption and iron chelation by *M. pulcherrima*, and the positive sensory impact of the aroma, taste, and freshness in wines. Therefore, new wine profiles can be made from flat grapes of warm areas using *L. thermotolerans*/*M. pulcherrima* cocktails. Additionally, all these advantages are accompanied by the total or partial substitution of sulfites with yeast bioprotection.

Furthermore, as *M. pulcherrima* exhibits respiratory metabolism and has very low fermentative power, with a final alcohol production of around 1% vol, it can be utilized as a biotechnological tool for producing low-alcohol wines.

2.3 Bio-production of low-alcohol wines

The demand for low-alcohol ($\leq 10.5\%$ vol) and non-alcoholic wines (0.0%–0.5% vol) is increasing due to health concerns, shifting consumer preferences, and the impact of climate change on grape sugar content. Biotechnological innovations are at the forefront of producing these wines, focusing on yeast selection, fermentation strategies, and process optimization to reduce ethanol while maintaining wine quality.

Incorporating non-*Saccharomyces* yeasts (e.g., *Lachancea thermotolerans*, *Starmerella bacillaris*, and *Williopsis saturnus*) alongside or instead of traditional *Saccharomyces cerevisiae* can lower alcohol content, increase glycerol, enhance aroma complexity, and improve mouthfeel in wines and other grape beverages. These yeasts also contribute to biocontrol and enzymatic activities that enhance the quality and safety of the product [38–44].

Utilizing non-*Saccharomyces* yeasts, such as *Metschnikowia pulcherrima*, *Torulaspora delbrueckii*, and *Hanseniaspora uvarum*, in either sequential or mixed fermentation processes alongside *Saccharomyces cerevisiae* can significantly reduce ethanol production while simultaneously enhancing the aromatic complexity and overall sensory profiles of the final products. Research by Contreras et al. [45], Varela et al. [46], Maturano et al. [47], and Fan et al. [48] highlights the transformative potential of these yeasts in the winemaking process.

Contreras et al. [45] evaluated 48 non-*Saccharomyces* isolates to find strains that could produce wine with lower ethanol concentrations under limited aeration alongside *S. cerevisiae*. Two strains, *Torulaspora delbrueckii* AWRI1152 and *Zygosaccharomyces bailii* AWRI1578, achieved reductions of 1.5% (v/v) and 2.0% (v/v) in ethanol concentration, respectively, compared to the *S. cerevisiae* anaerobic control.

Varela et al. [46] demonstrated that the non-conventional wine yeast species *Metschnikowia pulcherrima* and *Saccharomyces uvarum* can produce wine with reduced alcohol levels. *M. pulcherrima* resulted in wines with 1.0% v/v less ethanol, while *S. uvarum* showed a 1.7% v/v reduction compared to *Saccharomyces cerevisiae*. The volatile aroma compounds differed significantly, with *M. pulcherrima* wines having higher concentrations of ethyl acetate, esters, higher alcohols, and sulfur compounds. Sensory evaluations indicated that *M. pulcherrima* wines exhibited red fruit and fruit flavor notes, resembling *S. cerevisiae* wines, while *S. uvarum* wines were characterized by not-so-pleasant sensory descriptors, barnyard, and meat aromas.

Furthermore, certain non-*cerevisiae* strains of *Saccharomyces*, including *S. uvarum* and *S. bayanus*, have been noted for their diminished fermentation activity under specific conditions. In winemaking, *S. bayanus* is particularly prized for its role in

producing vibrant sparkling wines; however, under particular fermentation conditions, it can also play a critical role in regulating alcohol production, as detailed by Varela et al. [49].

In an intriguing study conducted by González et al. [38], a co-inoculated fermentation featuring both *S. bayanus* and *S. cerevisiae* demonstrated the ability to effectively modify metabolic pathways. This interaction led to the enhanced production of glycerol and organic acids, resulting in a richer flavor profile and a notable decrease in the wine's ethanol content.

Additionally, a diverse array of other *Saccharomyces* species, namely non-*cerevisiae* yeasts, including *S. uvarum*, *S. kudriavzevii*, *S. eubayanus*, *S. paradoxus*, and *S. mikatae*, offer promising alternatives for producing low-alcohol wines, thereby expanding the possibilities within the realm of modern winemaking (refer to **Table 2** for a comprehensive overview). Moreover, accompanied by the ethanol reductions, the wines presented higher concentrations of interesting flavor compounds such as higher alcohols and glycerol (**Table 2**).

Several studies investigate genetically modified yeast strains to redirect sugar metabolism associated with ethanol production, thereby promoting the synthesis of glycerol as an alternative to ethanol. These modifications include altering the activity of pyruvate decarboxylase to inhibit ethanol production [38, 50, 60].

The relative simplicity of the yeast genome allows for its modification. A logical strategy to achieve low-ethanol wine would involve limiting the expression of

<i>Saccharomyces</i> spp.	Ethanol reduction	Grape variety	Increased concentration in:	References
<i>S. kudriavzevii</i>	1.9–3%	Tempranillo, Macabeo, Synthetic grape must	1. Higher alcohols (2-phenyl-ethanol, isobutanol)	[51, 52]
<i>S. eubayanus</i>	0.4%	Sauvignon blanc, Macabeu; Synthetic grape must	1. Higher alcohols (2-phenylethanol); 2. Glycerol	[53, 54]
<i>S. uvarum</i>	0.5–1.7%	Trebbiano, Chardonnay, Pinot, Shiraz, Merlot	1. Higher alcohols (2-phenylethanol); 2. Esters (2-phenylethyl acetate, ethyl 2-methyl butanoate); 3. Glycerol; 4. Volatile acid (2-methyl butanoic acid).	[46, 48, 49, 55, 56]
<i>S. paradoxus</i>	0.3–0.6%	Chardonnay, Grignolino	1. Higher alcohols (1-propanol, hexanol, 2-phenylethanol, cis-3-hexenol)	[57, 58]
<i>S. mikatae</i>	0.5%	Chardonnay; Synthetic grape must	1. Higher alcohols (2-phenyl-ethyl alcohol, 4-hydroxybenzene ethanol); 2. Glycerol	[54, 59]

Table 2.

Ethanol reduction in wines produced with *Saccharomyces* non-*cerevisiae* yeasts and the metabolites that effectively increased in concentration. Adapted from Testa et al. [50].

the enzyme alcohol dehydrogenase (ADH), as illustrated in **Figure 2**. This enzyme catalyzes the final step in the production of ethanol during alcoholic fermentation. However, this approach has proven impractical, as strains devoid of ADH are unable to grow under anaerobic conditions and produce elevated levels of acetic acid and acetaldehyde [38, 61–63]. Consequently, it became necessary to identify novel targets to redirect metabolism from ethanol production toward alternative end-products [64].

Moreover, as described in the article by Afonso et al. [60], one other method to reduce ethanol production is by modifying the expression of triose-phosphate isomerase (Tpi1). This enzyme catalyzes the conversion between dihydroxyacetone phosphate and glyceraldehyde 3-phosphate. Deleting the Tpi1 gene can lead to high glycerol levels and lower ethanol yield, but it may also hinder growth in glucose environments due to decreased NADH production. A complete loss of TPI1 activity would likely impair yeast growth; however, a partial reduction could enable the production of low-alcohol beverages. This can be achieved by altering regulatory genes, such as Gcr1 and Gcr2, or by mutating genes like Reb1, Rap1, and Grc1, which also affect TPI1 activity (**Figure 2**).

Additionally, avoiding glucose repression has been explored as a means to create low-alcohol wines. Using a chimeric glucose transporter created from HXT and Hxt7 in yeast strains lacking transporters Hxt1-7 results in a respiratory phenotype and lower ethanol production, particularly in low-sugar (5%, w/v) media. This approach shifts metabolism from the Pasteur effect, where fermentation produces ethanol under low oxygen, to the Crabtree effect, which allows fermentation even with high sugar concentrations [60].

A different approach involves the expression of non-yeast genes in yeasts (**Figure 2**). Reducing the content of sugars in grape juice before fermentation can be achieved by glucose oxidase (GOXp), an oxygen-dependent dehydrogenase that

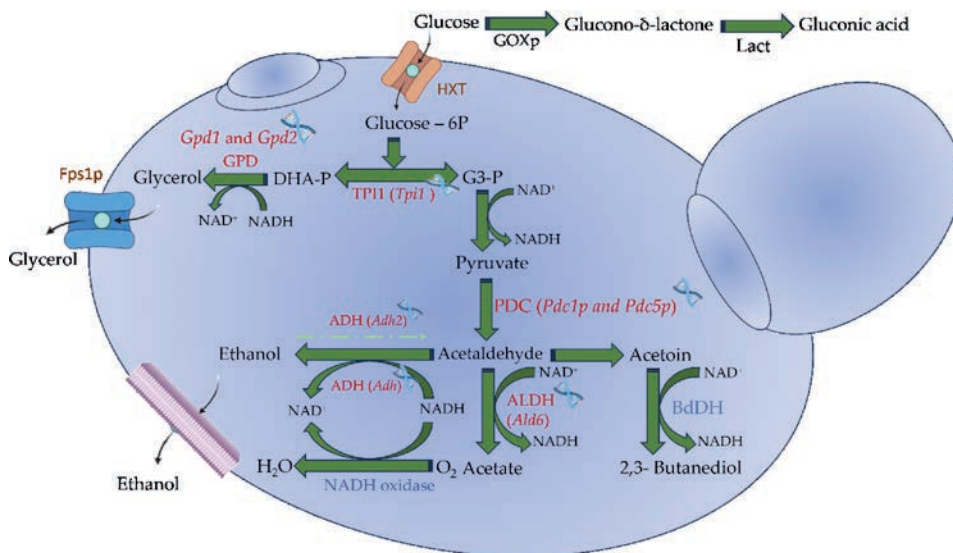


Figure 2. Main target-specific enzymes and genes in yeast cells that may lead to lower ethanol yields. HXT—hexose transporter; Fps1p—aquaglyceroporin; GPD—glyceraldehyde 3-phosphate dehydrogenase; TPI1—triose-phosphate isomerase; PDC—pyruvate decarboxylase; ADH—alcohol dehydrogenase; and ALDH—aldehyde dehydrogenase. GOXp—glucose-oxidase and Lact—lactonase are expressions, in yeasts, of non-yeast genes. Retrieved from Afonso et al. [60].

catalyzes the first step of a two-step process associated with converting glucose to gluconic acid [65]. Besides treating grape juice with GOX to reduce the sugar content, a strategy that has several limitations, even though it can reduce ethanol production by up to 40% [66]. Microvinifications of Chardonnay juice samples resulted in wines containing 1.8–2.0% less alcohol, possibly due to the use of glucose to produce D-glucono- δ -lactone and gluconic acid by GOX [67].

However, regulatory constraints on genetically modified organisms (GMOs) limit the use of these yeasts in winemaking, and consumer acceptance of GMOs remains mixed.

So, other strategies have been pursued. Immobilized kefir cultures, both wet and freeze-dried, have demonstrated high operational stability and efficiency in producing semi-dry, low-alcohol wine, even at elevated temperatures, with good sensory acceptance [68, 69]. Nikolaou & Kourkoutas [68] The study evaluated the fermentation efficiency of both wet and freeze-dried immobilized kefir cultures on natural supports for producing low-alcohol wine at high temperatures (above 30°C). The immobilized kefir culture was compared to free cells in repeated batch fermentations over 3 months, demonstrating high operational stability. It was found to be suitable for simultaneous alcoholic and malolactic fermentation of low-alcohol wine at temperatures up to 45°C. The study reported high ethanol productivity (approximately 6%, v/v) and malic acid conversion rates of up to 71.6%, suggesting that the industrial sector could adopt this method. Furthermore, the authors noted that the new products were of high quality and received approval from a sensory panel. The results suggest significant industrial potential for this technology in semi-dry low-alcohol wine production at 37°C and in creating novel wine products with a sweet (liqueureux) character at 45°C.

Limited aeration or semi-anaerobic conditions during fermentation with specific yeast strains can further reduce the ethanol content and positively influence wine flavor [45, 70]. Careful control of fermentation parameters (temperature, inoculation timing, and yeast ratios) is crucial for maximizing ethanol reduction without compromising wine quality [47].

As referred to before, the use of non-*Saccharomyces* yeasts during fermentation or even *Saccharomyces non-cerevisiae* can be an option to reduce alcohol content in wines. Moreover, some commercial *S. cerevisiae* strains also have this ability. Therefore, studies are ongoing aiming to use yeasts as a potential approach to reduce alcohol content in wines post-fermentation [60].

Research has demonstrated that specific yeast strains can utilize acetic acid during refermentation, improving sensory qualities by reducing acidity in wines [71–75]. Notably, ethanol content also decreased during deacetication. Vilela-Moura et al. [71] found that ethanol was reduced by 37.5% under aerobic conditions and by 13.5% under limited aerobic conditions. Furthermore, the use of immobilized yeasts in double-layer alginate-chitosan beads resulted in a reduction of ethanol content of 6–11.2% [75]. Understanding the pathways of ethanol degradation and the metabolic capabilities of yeasts could impact the composition of wines in post-fermentation, potentially providing strategies to address the effects of climate change on viticulture.

3. Emerging non-thermal technologies

One of the main problems with the use of non-*Saccharomyces* yeasts is their implantation; most of them are weaker fermentative yeasts than *Saccharomyces*, with

slower growth rates and are more sensitive to nutrient deficits, as well as less competitive under enological conditions. Furthermore, many non-*Saccharomyces* are very sensitive to sulfites. Therefore, the optimal use of these non-conventional yeasts requires ensuring a suitable implantation, which can be achieved by eliminating the wild microbiota. Traditional thermal techniques have a deleterious effect on the sensory quality of grape juice or crushed grapes. In contrast, the use of alternative, emerging non-thermal technologies is gentle on the grape sensory profile [12]. High-pressure

Technology	Description	Antimicrobial	Oxidation	Extraction	Reference
HHP—high hydrostatic pressure	Use of pressures of 400–600 MPa transmitted by a hydraulic fluid (water) during 2–10 min. Discontinuous OIV approved.	High effectiveness against yeast at $P > 300$ MPa, variable with bacteria (500–600 MPa). Very gentle with sensory fraction.	Variable control of oxidative enzymes.	Highly effective in the accelerated extraction of anthocyanins, tannins, and varietal aroma compounds.	[76–78]
UHPH—Ultra-high-pressure homogenization	Continuous pressurization at >200 MPa (usually 300 MPa). Continuous. OIV approved.	Extremely practical and can even reach sterilization, depending on the in-valve temperature—very low residence time (< 0.2 s) and minimal thermal effect.	Highly effective against PPOs, causes denaturation through nano-fragmentation. Inactivation exceeds 90%.	Very effective in releasing anthocyanins, aroma, and nutrients from colloidal particles from skins.	[77, 79]
PEF—Pulsed electric fields	Application of high-intensity electric fields 15–40 kV/cm during a few μ s and evenly spaced a few hundred μ s. Continuous. Approval for extraction as an antimicrobial by the OIV is under discussion.	Very effective against yeasts and bacteria, easily decreasing the initial counts by 3 log units.	Variable, but not especially effective in the control of PPOs.	Intense poration that helps to release anthocyanins, phenols, and aroma compounds from skins	[80–82]
PL—Pulsed light	Use of high-intensity xenon flashes with a duration of a few μ s and evenly spaced a few hundred μ s. Continuous.	Very effective in controlling wild microorganisms on the grape surface. Low penetration capacity of UV-visible-IR radiation	Variable.	Some effect, but weak extraction.	[83, 84]

Table 3.
 Emerging non-thermal technologies to eliminate wild microbiota, to control oxidation, and to speed maceration.

techniques (HHP or UHPH) and pulsed techniques (PEFs or PL) have demonstrated high efficiency in eliminating wild microorganisms while preserving sensory quality (**Table 3**). Many of them are also very effective at accelerating the extraction of compounds from grape skins during the treatment process [85].

Therefore, all these emerging non-thermal technologies can be utilized to enhance the application of new biotechnologies, producing fresher and more complex wines, while mitigating the inconveniences of global warming, promoting their

Wine type	Non-Saccharomyces (NS)	Bioacidification	Bioprotection	Pressure HHP-UHPH	Pulsed PEF-PL
Fresh red wine in warm areas	A more complex aroma, release of varietal compounds, and a better structure.	Better pH and fresher profile. Less SO ₂ . Better color stability.	Lower SO ₂ and additives. Microbial and oxidative protection.	Better color and phenol extraction. Optimal microbial stability.	Better color and phenol extraction. Microbial control.
Rosés	Aroma complexity, development of floral nuances. Creamy body.	Fresh profile. Long color stability with low SO ₂ contents.	Reduction of chemical additives.	Color and microbial stability. Control of oxidation.	Microbial stability.
Whites	Aroma depth with floral and fruity profiles. Good mouth structure	Better freshness. Enhancement of minerality. Paleness.	Control of oxidation with low contents of SO ₂ .	Spoilage control. Inactivation of oxidative enzymes	Better microbial control.
Low alcohol	Use of aerobic NS to reduce alcohol. Use of NS to increase aromatic complexity in physically dealcoholized wines.	Better pH and fresher profile. Less SO ₂ . Better color stability.	Control of oxidation and reduction of chemical preservatives.	Control of oxidation and reduction of chemical additives (SO ₂ , DMDC)	Better color and phenol extraction. Microbial stability
Non-alcoholic (0.0)	Use of NS to increase aromatic complexity and texture in physically dealcoholized wines.	Better pH and fresher profile. Less SO ₂ . Better color stability.	Control of oxidation and reduction of chemical preservatives.	Control of oxidation and reduction of chemical additives (SO ₂ , DMDC)	Better color and phenol extraction. Microbial stability
Aromatized wine-derived products (tea, flowers, and seeds)	Use of NS to increase aromatic complexity and texture.	Sour refreshing profile. Less SO ₂ . Better color stability.	Control of oxidation and reduction of chemical preservatives.	Better extraction of flavor compounds from grapes and other components. Control of oxidation. Microbial stability.	Better extraction of flavor compounds from grapes and other components. Microbial stability.

Table 4.
Opportunities of emerging technologies for innovative wines or wine derivatives.

implementation, and reducing the use of chemical additives. Additionally, they can be used to produce non-alcoholic (0.0%) or low-alcohol wines, increasing the possibility of designing new wines or wine-derived beverages for new consumers and a changing landscape due to global warming (**Table 4**). Currently, macerations with flowers, spices, tea, and various other vegetal parts are being studied for designing healthier beverages that are attractive to new, younger consumers or in emerging countries with increasing wine consumption, such as Asian regions.

4. Emerging yeast derivatives from *Saccharomyces* and non-*Saccharomyces* yeasts

Yeast derivatives (YDs) are preparations obtained from yeast cells, primarily *Saccharomyces cerevisiae*, but also from non-*Saccharomyces* species [86]. They are widely utilized in the food industry as flavoring agents and have seen significant expansion and diversification in the oenological sector. The increasing volume of scientific publications over the past two decades underscores the expanding interest in and relevance of YDs within the winemaking industry (**Figure 3**).

Indeed, YDs have been identified as a promising biotechnological tool for ensuring wine quality while aligning with consumer demand for environmentally sustainable practices and health-conscious information.

Yeast derivatives are produced by growing yeast colonies on sugar-rich substrates under aerobic conditions. This is followed by inactivation, which can be achieved through thermal means or pH changes. After inactivation, various processing techniques are applied, such as autolysis, plasmolysis, hydrolysis, or physical disruption [87]. The final products are then concentrated or dried, typically into powder form (**Table 5**).

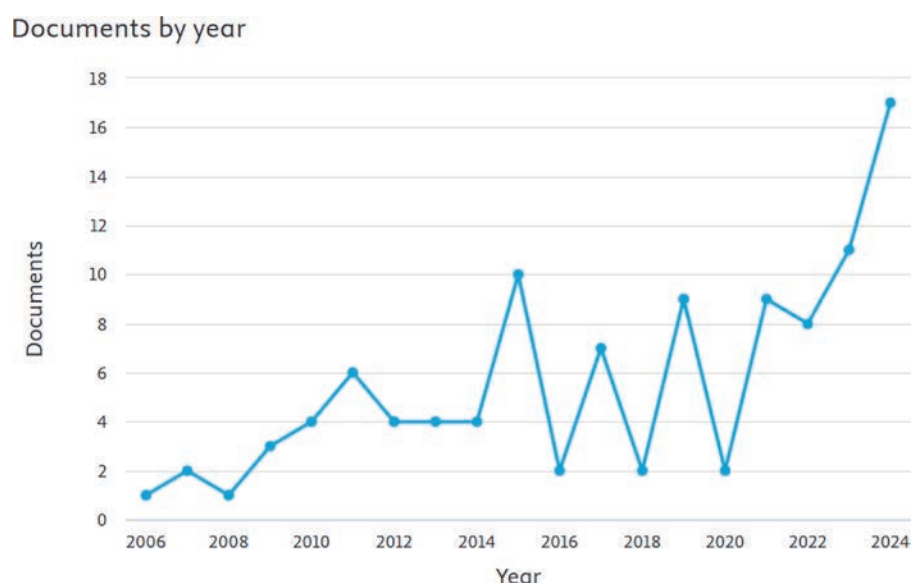


Figure 3. Scopus database search with the combination of terms “wine and yeast derivatives” as query statement to highlight the relevant literature over the past two decades.

Yeast derivatives (YDs)	Production technique	OIV resolutions & international code of oenological practices	Main oenological applications
Inactivated dry yeast (IDY)	Cells inactivated by heat and/or by a pH change, without allowing autolysis or cell rupture to occur	RESOLUTION OIV-OENO 459-2013 - Insoluble fraction $\geq 60\%$ w/w of dry matter. Total nitrogen content $< 10\%$ of dry matter. - Ammonia nitrogen content $< 0.5\%$ of dry matter - Content of free and soluble amino acids and small peptides in glycine equivalent $< 10\%$ of dry matter II.2.2.9 Treatment using inactivated yeasts with guaranteed glutathione levels - Addition at the start of maturing or during storage of wines II.2.3.2 Fermentation activators - Addition to the harvest or the must, before or during the alcoholic fermentation II.3.4.21 Malolactic fermentation activators - Addition at the end or after the alcoholic fermentation	- Support the rehydration of active dry yeast (ADY). - Improve yeast vitality and promote a more efficient fermentation process. - Support yeast/LAB growth, thus preventing stuck/sluggish fermentations. - Facilitates the elimination of harmful or unwanted substances, such as ochratoxin A (OTA). - Enhances wine's resistance to oxidation by reducing oxygen consumption and supplying natural antioxidants like glutathione (GSH), particularly with GSH-enriched YDs (OIV-OENO 603-2018) - Improve color stability by releasing polysaccharides that interact with phenolic compounds - Contribute to a smoother mouthfeel by adsorbing phenolic compounds (particularly larger proanthocyanidin polymers, often associated with astringency) - Improve and balance the aromatic profile of wine by boosting desirable aroma compounds and minimizing off-flavors - Enhance the foam stability of sparkling wines
Yeast lysates (YL)	Obtained through a process involving thermal inactivation followed by an incubation step that allows for spontaneous or enzyme-induced degradation of the cell content	RESOLUTION OIV-OENO 496-2013 - Dry matter $< 80\%$ - Total nitrogen content $< 12\%$ of dry matter. - Ammonia nitrogen content $< 0.5\%$ of dry matter. - Amino acid content, in glycine equivalent, ranging between 10 and 20% of dry matter II.2.3.2 Fermentation activators - Addition to the harvest or the must, before or during the alcoholic fermentation II.3.4.21 Malolactic fermentation activators - Addition at the end or after the alcoholic fermentation	- Used as nutrients at the beginning and during alcoholic fermentation - Used as malolactic fermentation enhancers - Used to promote the rehydration of active dry yeasts (ADY) - Increase the wine's aromatic intensity (although they may impart a slight yeast-like odor note) - Increase sensations of structure/body, mouthfeel sweetness, and reduce bitterness in wine - Enhance foam stability in sparkling wines

Yeast derivatives (YDs)	Production technique	OIV resolutions & international code of oenological practices	Main oenological applications
Yeast hulls (YH) (also known as "yeast ghost")	Obtained through a process that involves the separation and concentration of the insoluble cell wall fraction after cell autolysis or mechanical disruption	RESOLUTION OIV-OENO 496-2013 - Carbohydrates > 40%, (of which at least 60% are mannans and glucans). - Soluble fraction < 10% of the dry mass. - Dosage limit: 40 g/L/hL II.2.3.4 Treatment with yeast ghosts (Hulls) - Addition to the must, to the fermenting must, or to the wine II.3.4.21 Malolactic fermentation activators - Addition at the end or after the alcoholic fermentation	- To prevent or manage stuck fermentation - To adsorb - Fatty acids (toxic to yeast) - Ochratoxin A (toxic to humans) - Metals (Cu, Fe) - Off-odors (e.g., H₂S)
Yeast protein extract (YPE)	Obtained through a process involving cell lysis and the selective extraction of soluble intracellular proteins and peptides	II.3.2.14 Fining using yeast protein extracts - Addition to wines during clarification process RESOLUTION OIV-OENO 452-2012 - Total protein content > 50% of the dry product. - A minimum of 50% of the total proteins with molecular weights > 15 kDa. - Amino nitrogen content, in glycine equivalent, ranging between 10 and 20% of dry matter - Maximal legal dosage limit: 60 g/hL for red wines, 30 g/hL for musts, white and rose wines.	Wines clarification and colloidal stabilization
Yeast mannoproteins (YM)	Obtained through a process involving the extraction of MP using either enzymatic processes or physicochemical techniques. In this process, whole yeast cells or yeast cell walls are utilized.	II.3.3.13 Treatment of wines with yeast mannoproteins - Addition to wines during stabilization process OIV-OENO 674-2022 - Percentage of insoluble dry matter $\leq 1\% \pm 0.5$	- Tartaric and protein stabilization* - Reduction of astringency - Improvement in mouth perception - Addition of complexity and aromatic persistence

*The only two properties recognized for mannoprotein extracts (MPEs) in OIV resolutions.

Table 5.
Yeast derivative products approved for use in winemaking.

Due to the vast array of production techniques currently available, a diverse range of products can be manufactured, each with its distinct composition. YDs final composition includes insoluble components of yeast cell walls and soluble compounds like peptides, amino acids, polysaccharides (especially mannoproteins), nucleotides, fatty acids, vitamins, and minerals.

Based on the soluble and/or insoluble compounds present in each YD product, it is possible to observe additive or subtractive effects in wine.

The additive effect is primarily attributable to the soluble compounds released into the medium by each type of YD, encompassing assimilable nitrogenous compounds (e.g., peptides and free amino acids), polysaccharides (e.g., mannoproteins), lipids, nucleotides, and nucleosides. Certain compounds can stimulate the growth of micro-organisms, effectively boosting the alcoholic fermentation process [87]. In agreement, yeast lysates (YL), inactivated dry yeast (IDY), and yeast hulls (YH), according to OIV standards, are primarily recognized for their role as fermentation activators.

Meanwhile, other soluble compounds play a crucial role in enhancing the colloidal stability of wine and improving its sensory qualities, including texture and mouth-feel. To this end, mannoproteins (MP) have long attracted significant scientific attention due to their diverse effects on wine [88–93]. Indeed, these compounds are widely used as additives in winemaking due to their ability to improve sensory characteristics and colloidal stability. However, despite numerous scientific studies highlighting the role of mannoproteins extracted from *S. cerevisiae* in enhancing protein stability, there are currently no commercial products on the market that specifically leverage this functionality.

Subtractive effect of YDs occurs, instead, when specific compounds are adsorbed onto yeast cell walls or sequestered within inactive yeast. This process can be beneficial, as it eliminates toxic substances like heavy metals [94], short and medium-chain fatty acids [95] that hinder microbial activity, along with undesirable compounds such as phenolic compounds and browning products in white wines [96–98], and binding unwanted volatile phenols like 4-ethylphenol [99]. Moreover, they can also reduce the presence of health-threatening toxins, such as ochratoxin A (OTA) [100, 101] or pesticides used in vineyards [102], thereby enhancing both the safety and overall quality of the wine. Additionally, specific YD, containing purified proteins, can interact with tannins, making them useful for wine fining through a subtractive effect (precipitation) that helps to reduce astringency and improve clarity [103].

Hence, winemakers can select from a broad spectrum of commercial innovative YD to be used throughout the entire winemaking process, tailored to their specific oenological objectives (Table 5).

However, it is essential to note that the production process has a significant impact on YD's final composition. For instance, conventional methods to produce yeast derivatives are primarily based on heat and enzymatic treatments. These processes can exert a considerable influence on the chemical composition and volatile profile of YDs, often resulting in a significant impact on odor [104, 105].

In recent years, the emergence of non-thermal technologies (e.g., ultrasound (US), high-pressure processing (HPP), and pulsed electric fields (PEFs)) has the potential to supersede conventional methods for producing yeast derivatives, thereby enhancing the quality of these products. For instance, high-pressure processing has been studied to induce autolysis. It has delivered promising results in the production of yeast derivatives, showing interesting volatile profiles and low levels of unpleasant odorous compounds [106]. Similarly, ultrasound-treated cells have led to increased polysaccharide release and have been shown to intensify fruity and floral aromas in

wines incorporating these treated cells [107]. Furthermore, applying pulsed electric fields (PEFs) to induce autolysis in *Saccharomyces* species offers a valuable technique for efficient extraction of mannoproteins [108].

Beyond the technique used to obtain different YDs, their composition and properties are also significantly impacted by the yeast strain, cultivation conditions, and growth stage [109]. Most YDs currently on the market for oenological use are primarily derived from *Saccharomyces cerevisiae* strains. Indeed, it was only recently that the OIV authorized YDs from not only *Saccharomyces* spp., but also non-*Saccharomyces* yeasts with the Resolution OIV-OENO 740-2024. Of note is the fact that this resolution serves to revise earlier resolutions (OIV-OENO 674-2022; OIV-OENO 452-2012; OIV-OENO 459-2013; OIV-OENO 496-2013; OIV-OENO 497-2013), thus encompassing non-*Saccharomyces* yeasts in the production of various types of derivatives for use in the winemaking process.

To date, interesting results have been obtained with the various YDs from non-*Saccharomyces* yeasts, such as *Hanseniaspora uvarum* [110], *Lachancea thermotolerans* [111], *Metschnikowia pulcherrima* [103, 111–113], *Saccharomyces ludwigii* [112, 113], *Schizosaccharomyces japonicus* [114, 115], and *Torulaspora delbrueckii* [107, 112, 113, 116, 117] for producing derivatives with specific properties like protein and color stabilization or enhanced antioxidant activity and polysaccharide content.

However, non-*Saccharomyces* YDs are still mainly in the research phase. Current discussions primarily focus on their potential or suitability for future industrial-scale applications.

5. Conclusions

Emerging biotechnologies and non-thermal technologies offer valuable solutions for modulating the sensory profiles and stability of new wines and derived beverages. These advancements address consumer demands for innovative sensory experiences, reduced chemical additives, and the preservation of the natural flavors inherent in grapes. Furthermore, these techniques facilitate enhanced stability in low-alcohol wines that contain residual sugars, even in the absence of chemical additives.

Yeast derivatives (YDs), encompassing both commercially available options and those currently in development, represent a novel and strategic asset for the winemaking sector. Due to their versatility and natural composition, YDs effectively align with the increasing demand for sustainable production methods that prioritize consumer health. In light of growing concerns surrounding environmental and human health, the judicious application of YDs can reduce reliance on traditional adjuvants, enhance the sensory attributes of wine, and improve the perception of its natural quality.

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Conflict of interest

The authors declare no conflict of interest.

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Perspective Chapter: Phenolic Composition and Antioxidant Activity of Prolonged Macerated White Wines – A Comparative Review with Conventional White and Red Wines

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Abstract

White wines produced through prolonged skin maceration, commonly referred to as “orange wines,” have attracted increasing scientific and oenological attention due to their unconventional winemaking practices and distinctive physicochemical and sensory profiles. Unlike conventional white wines, “orange” wines undergo extended contact between the grape must and skins, a process traditionally associated with red wine production. This technique results in a notable increase in phenolic content, including flavonoids and non-flavonoid compounds, which significantly contribute to the wine’s color, astringency, and oxidative stability. This chapter investigates the temporal evolution of phenolic compounds in long-macerated white wines by drawing on data reported in the scientific literature, employing a comparative framework that integrates reference profiles from conventional red and white wines. Phenolic profiles were analyzed over time using both spectrophotometric and chromatographic techniques, enabling a detailed characterization of their concentration and compositional changes. Particular attention was given to the antioxidant activity associated with these compounds to assess their functional significance. The findings support a more nuanced classification and characterization of orange wines within the broader wine typology, highlighting their intermediate properties between white and red wines. Moreover, the results underscore the role of maceration in modulating phenolic composition and antioxidant capacity, offering valuable insights for winemakers and researchers seeking to optimize wine quality and explore the health-relevant properties of wine constituents.

Keywords: orange wine, aging potential, bioactive compounds, winemaking, grape skin

1. Introduction

Maceration is a fundamental oenological process traditionally employed during vinification. In this process, grape solids—primarily skins, seeds, and occasionally stems—are maintained in contact with the must or fermenting wine. This technique facilitates the extraction and subsequent integration of key constituents such as volatile aromatic compounds, aroma precursors, phenolic compounds (including tannins and flavonoids), and anthocyanins, which collectively contribute to the organoleptic properties, color stability, and aging potential of the wine [1, 2]. Maceration can occur at various stages of the vinification process: before fermentation (pre-fermentative maceration), during fermentation (fermentative maceration), or following fermentation (post-fermentative maceration). A more traditional and less common approach involves an extended maceration that overlaps and often continues beyond fermentation. This technique, rooted in ancient winemaking practices, is characteristic of the production of so-called “orange wines” or “amber wines,” which are typically made from white grape varieties subjected to prolonged skin contact, resulting in wines with distinctive tannic structure, oxidative notes, and enhanced phenolic complexity [3–5]. This technique enhances the extraction of phenolic compounds, such as flavonoids and tannins, which are typically found in higher concentrations within red wines [6, 7]. This unique production process significantly influences the wine’s sensory characteristics and oxidative stability, aligning with the rising consumer and producer interest in “natural” winemaking practices, where minimal intervention and reduced use of additives such as sulfites are prioritized [3].

Phenolic compounds are widely distributed across various plant tissues, including edible parts such as fruits, seeds, leaves, stems, and roots [8]. These naturally occurring metabolites are synthesized exclusively by plants and are characterized by one or more aromatic rings bearing hydroxyl groups. Phenolic compounds are recognized for their diverse bioactivities, including modulation of oxidative and inflammatory stress, influence on macronutrient digestion, and prebiotic-like effects on the gut microbiota [9, 10]. In winemaking, phenolic compounds are of particular significance, as they play a crucial role in determining wine quality by contributing to its color, astringency, bitterness, antioxidant capacity, and aging potential [11]. Phenolic compounds, a diverse group of secondary metabolites present in grapes and wines, undergo extensive transformations during vinification. These compounds are generally classified into two main groups: flavonoids and non-flavonoids. Flavonoids include anthocyanins, which contribute to color; flavan-3-ols, associated with bitterness and astringency; and flavonols, which act as co-pigments and possess antioxidant properties. Non-flavonoids encompass phenolic acids—such as hydroxybenzoic and hydroxycinnamic acids—that influence aroma stability and browning reactions, as well as stilbenes like resveratrol, known for their health-promoting antioxidant and antimicrobial activities (**Figure 1**) [12, 13].

Winemaking practices exert a significant influence on the extraction, composition, and transformation of phenolic compounds in wine. Key oenological variables, such as the duration and conditions of maceration and fermentation, pressing techniques, aging processes (both in barrel and bottle), and overall vinification strategies, can substantially modulate the phenolic profile derived from grape skins, seeds, and stems [14].

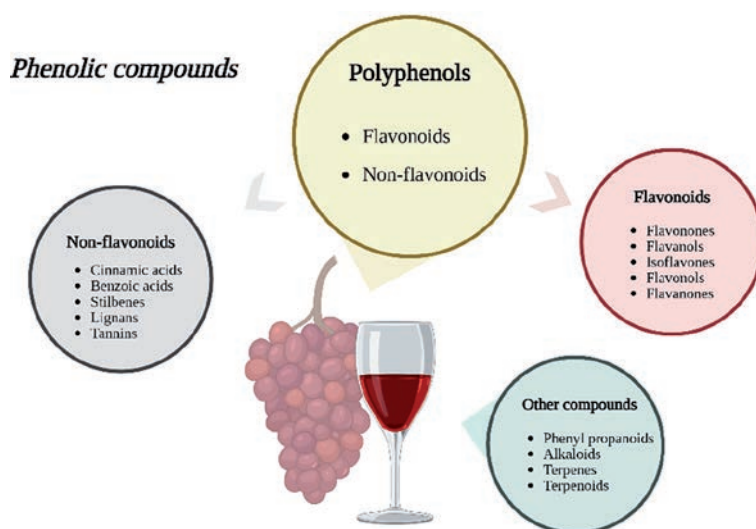


Figure 1.
 Classification of phenolic compounds commonly found in grapes and wines.

The antioxidant potential of these compounds is mediated through various mechanisms, including the scavenging of reactive oxygen species, chelation of redox-active metal ions, and inhibition of pro-oxidant enzymes [15]. However, the bioefficacy of phenolic compounds is contingent upon their chemical structure, concentration, and bioavailability, and the mere presence of such constituents in wine does not inherently translate to demonstrable health benefits from moderate consumption [16, 17]. Given that the antioxidant activity of phenolics is structure-dependent, the selection of appropriate winemaking techniques is critical [1]. In particular, maceration enhances the extraction of phenolic compounds and is a principal factor distinguishing red from white vinification. As such, optimizing oenological interventions represents a key strategy in modulating the functional and sensory attributes of wine [18].

This research seeks to elucidate the distinctions in phenolic compound profiles, both in terms of content and concentration, between conventional white and red winemaking practices and the traditional yet increasingly revitalized method known as “orange” winemaking. By focusing on the compositional outcomes of extended skin contact during white grape fermentation, the study aims to provide a comprehensive analysis of how this technique influences phenolic extraction and transformation. Particular attention is given to the resulting variations in antioxidant capacity. Furthermore, the investigation explores the broader metabolic implications of these compounds, intending to enhance the current understanding of their role in wine quality, oxidative stability, and potential health benefits.

2. Prolonged maceration in white winemaking: A comparative analysis with conventional techniques

2.1 Technological insights into the crafting of prolonged macerated white wines

In conventional white winemaking, the must is typically separated from the grape solids, skins, seeds, and stems, either before or shortly after the onset of

fermentation, resulting in minimal maceration. When employed, maceration in white wine production is primarily intended to enhance the extraction of volatile aromatic compounds, thereby contributing significantly to the final product's sensory profile and perceived quality [19, 20]. Although maceration also facilitates the release of phenolic compounds, this aspect has not been traditionally emphasized in white winemaking to the same extent as in red wine production, where the extraction of phenolics, particularly anthocyanins, plays a central role in defining both the color and structure of the wine [21]. The traditional winemaking practice originating from the Kakheti region of Georgia has recently attracted renewed global interest among both producers and consumers. This technique is characterized by an extended maceration period, during which the must remains in contact with grape skins, seeds, and stems for durations ranging from several weeks to multiple years [22]. A distinctive feature of this method is the use of qvevri (large, egg-shaped clay vessels buried underground), which serve as fermentation and maturation containers, contributing to the unique chemical and sensory profile of the resulting wines [23].

Analogous to red winemaking practices, the production of prolonged macerated white wines begins with the selection of grapes exhibiting optimal primary characteristics, including elevated phenolic content, well-developed and ripe tannins, and excellent phytosanitary conditions [3]. Following crushing, the must with the pulp and seeds directly into qvevri vessels, typically via a gravity-fed system. These traditional clay amphorae are buried underground, which ensures thermal stability and provides an optimal environment for a controlled fermentation process. Analogous to red wine vinification, a cap management technique involving twice-daily punch-downs is employed during fermentation [24]. This practice facilitates the extraction of phenolic compounds and assists in maintaining uniform temperature distribution, thereby preventing excessive thermal buildup that could compromise yeast viability and fermentation kinetics. Adhering to a philosophy of minimal oenological intervention, spontaneous fermentation is commonly favored. However, due to the inherent risk of sluggish or stuck fermentation under suboptimal conditions, microbial dynamics have been a subject of investigation [24, 25]. For instance, Capece et al. examined the yeast microbiota associated with wines produced via the traditional Kakhetian method. In their study, yeast isolates collected from wines aged for 1 year in 10 Georgian qvevris were all identified as *Saccharomyces cerevisiae*, with both flor and non-flor morphotypes detected, though flor yeasts predominated among the isolates [23]. Upon completion of alcoholic fermentation—typically signaled by the natural subsidence of the cap formed by grape solids—the qvevri vessel is hermetically sealed using a traditional dual-layer method. A flat stone lid is first placed over the vessel opening, followed by an outer seal composed of clay and sand. This sealing technique serves to minimize oxygen ingress and prevent external contamination, thereby ensuring a stable microenvironment conducive to the controlled maturation of the wine [26].

3. Phenolic enrichment in wines: Influence of winemaking approaches on compound concentration

Phenolic compounds play a pivotal role in determining the quality of wines, as they significantly influence key organoleptic properties such as color, astringency, bitterness, and overall mouthfeel. Effective modulation of phenolic content involves a complex interplay of viticultural and oenological practices. These include regulating

phenolic accumulation in the grape berry, strategic extraction during maceration, and their subsequent transformation throughout barrel or bottle aging [27]. Traditionally, the most pronounced distinction between red and white winemaking lies in the maceration-fermentation process, during which phenolic compounds are extensively extracted in red wines [1]. The growing interest in extended skin-contact white wines has introduced a novel dimension to white wine production. These wines challenge conventional paradigms by highlighting the underestimated role of phenolics in white

Country	Variety	Maceration period	Subclass	Analysis method
Croatia [28]	Malvazija istarska	16–21 days	Hydroxycinnamic acids	HPLC-UV-VIS
			Hydroxybenzoic acids	
			Flavan-3-ols	
Hungary [29]	Zeta	35 days	Flavan-3-ols	HPLC-UV/DAD
			Stilbenoid	
Georgia Italy Slovenia [30]	Rqatsitheli Khikhvi Ribolla Kakhuri Mtsvane Tsulukidzis tetra Rebula	n.s.**	Flavan-3-ols	HPLC-UV-VIS
Marlborough [31]	Pinot Gris (juice) × Thompson seedless (skins)	5 days	Hydroxybenzoic acids	HPLC-UV-VIS
			Hydroxycinnamic acids	
			Flavan-3-ols	
Croatia [4]	Malvazija istarska		Hydroxycinnamic acids	HPLC-DAD/FLD
			Hydroxybenzoic acids	
			Flavan-3-ols	
Italy Croatia [32]	Ribolla Gialla Tocai Friulano Malvazija Pinot Gris Sauvignon Blanc	n.s.**	Hydroxybenzoic acids	HPLC-UV-VIS
			Hydroxycinnamic acids	
			Flavan-3-ols	
			Stilbenoid	
Italy Austria Croatia Slovenia [33]	Several international and autochthonous	n.s.**	Hydroxybenzoic acids	HPLC-UV-VIS
			Hydroxycinnamic acids	
			Flavan-3-ols	
			Stilbenoid	

Country	Variety	Maceration period	Subclass	Analysis method
Serbian [34]	Commercial wines	n.s.**	Hydroxybenzoic acids	HPLC-UV-VIS
			Hydroxycinnamic acids	
			Flavan-3-ols	
Croatia [35]	Malvasia Istriana Chardonnay Rhine Riesling Sauvignon blanc Pinot gris	30 days to 6 months	Hydroxybenzoic acids	HPLC-DAD/ FLD
			Hydroxycinnamic acids	
			Flavan-3-ols	
			Stilbenoid	
Croatia [36]	Graševina	120 days	Flavonols	HPLC-UV-VIS
			Hydroxybenzoic acids	
			Hydroxycinnamic acids	
Italy [37]	Chardonnay	6–7 months	Flavan-3-ols	n.s.**
			Tannins	
Italy [38]	Bianchetta Trevigiana	190 days	Hydroxybenzoic acids	HPLC-UV-VIS
			Hydroxycinnamic acids	
			Flavan-3-ols	

**Pinot Grigio, Sauvignon, Chardonnay, Tocai, Friulano, Prociano, Ansonica, Ribolla, Malvasis, Picolit, Verduzzo, Malvazija, Traminer, Rebula, Jakot.*
***Not specified.*

Table 1.

Summary of studies focused on the determination and evaluation of phenolic compounds in prolonged macerated white wines.

wine expression and offer new perspectives on wine structure, complexity, and aging potential (Table 1).

3.1 Total phenolic content

The total phenolic content of extended skin-contact (or macerated) white wines has garnered increasing attention in recent years, as researchers aim to better understand the technological implications of prolonged maceration on phenolic extraction and wine composition. A comparative study involving 14 macerated and non-macerated white wines from the Friuli-Venezia Giulia region of Italy and Istria, Croatia, evaluated several grape varieties—including Ribolla Gialla, Tocai Friulano, Malvazija, Pinot Gris, and Sauvignon Blanc. In the macerated samples, total phenolic concentrations ranged from 1645 to 2103 mg/L. These values are

particularly significant as they approach, and in some cases overlap with, phenolic levels typically found in red wines, as reported in the literature: 282–1936 mg/L [14]; 544.4–1208.6 mg/L [39]; 2082–3184 mg/L [40]; 553–2668 mg/L [41]; and 621.7–3200.3 mg/L [42]. This observation highlights the substantial enrichment in phenolic content achievable through extended maceration in white winemaking, narrowing the compositional gap traditionally observed between red and white wines [32]. Further supporting this trend, a study on two Southern Italian white grape varieties—Verdeca and Minutolo—demonstrated even higher phenolic accumulation, particularly after 4 months of maceration. Peak concentrations reached 6670 mg/L for Verdeca and 5682 mg/L for Minutolo, followed by a slight decline at 6 months [5]. This reduction is likely due to the saturation of phenolic extraction, as well as the precipitation or re-adsorption of phenolic compounds onto grape skins—phenomena well-documented during prolonged maceration phases [43]. In another study, Bene et al. [29] observed a total phenolic content of 1632 mg/L in the Hungarian variety Zéta following a 5-week amphora maceration, reinforcing the impact of vessel choice and fermentation environment on phenolic outcomes. Moreover, a comprehensive investigation of six white grape varieties (Pinot Gris, Laški Rizling/Italian Riesling, Sauvignon, Šipon/Furmint, Chardonnay, and Riesling) subjected to a 107-day maceration revealed a wide phenolic range, from 884 to 5051 mg/L. These findings underscore the critical influence of grape variety on phenolic extraction and further illustrate the variability and potential of phenolic enrichment in skin-contact white wines [44]. A 2011 study comparing traditional Kakhetian and conventional European winemaking techniques highlighted the strong impact of production method on phenolic content. Wines made using the Kakhetian method—with prolonged qvevri maceration—showed significantly higher phenolic levels (1296–2290 mg/L) compared to those from European methods (210–456 mg/L) [30].

3.2 Non-flavonoids

Non-flavonoid phenolic compounds are significantly extracted in prolonged macerated white wines, similarly to red wines. Although colorless, they influence wine chemistry by stabilizing color (in reds), enhancing aroma (e.g., volatile phenolic acids), and offering bioactive properties—resveratrol being a notable example [45]. Recent research on skin-contact white wines has focused on hydroxycinnamic acids, hydroxybenzoic acids, and stilbenes, emphasizing their sensory and functional importance.

3.2.1 Hydroxycinnamic acids

Hydroxycinnamic acids represent the dominant class of phenolic compounds in grape juice and are the primary phenolics found in white wines. Commonly identified compounds include caftaric acid, fertaric acid, caffeic acid, p-coumaric acid, and ferulic acid, with some grape varieties also exhibiting the presence of sinapic acid [32, 34, 35].

3.2.1.1 Caffeic acid

In a study on Bianchetta Trevigiana wines, a notable decline in caffeic acid concentration was observed after 40 and 60 days in both macerated and non-macerated samples. This reduction is likely due to esterification with tartaric acid, resulting in the

formation of caftaric acid—a compound highly prone to oxidation and a key contributor to oxidative browning in white wines [38]. However, these results diverge from findings in other studies on prolonged maceration, where hydroxycinnamic acids, including caffeic acid, were shown to increase significantly over time. For instance, Ruzic et al. [32] reported caffeic acid concentrations of up to 5.4 mg/L in extended macerated white wines, a level comparable to those found in various red wines, such as Italian red wines (4.0–17.9 mg/L [46]), Greek Malagousia wines (0.6 mg/L–17.3 mg/L [47]), and Sicilian Nero d'Avola (4.2 mg/L [48]). The elevated levels of caffeic acid in skin-contact white wines are well-supported by findings from multiple studies. For instance, Malvasija istarska wines subjected to extended maceration and maturation in wooden barrels exhibited an increase of up to 90% in caffeic acid concentration compared to non-macerated controls [28]. In a comparative study involving 17 Croatian wines—both macerated and non-macerated—the macerated samples averaged 1.8 mg/L of caffeic acid, nearly three times higher than their non-macerated counterparts [35]. Similarly, an extensive analysis of 36 prolonged macerated white wines revealed caffeic acid concentrations ranging from 1.5 to 27 mg/L, with an average of 7.3 mg/L [33]. These results are consistent with data from a study on 20 Greek white wines, which reported caffeic acid levels between 2.6 and 33 mg/L [42], further confirming the substantial phenolic enrichment associated with prolonged skin contact.

3.2.1.2 Ferulic acid

Ferulic acid was detected in only a subset of wines, typically exhibiting an increasing trend during extended maceration. Concentrations ranged from 0.2 to 2.2 mg/L [28, 32, 35], aligning closely with values reported for certain Greek white wines, where levels ranged from 0.2 to 3.9 mg/L [42]. These findings are also consistent with concentrations observed in select Italian red wines such as Negroamaro, Montepulciano, and Nero d'Avola, which displayed ferulic acid levels between 0.1 and 0.2 g/L [49], highlighting its broader relevance across wine styles and varieties.

3.2.1.3 p-Coumaric and p-coutaric acid

p-Coumaric acid is a key hydroxycinnamic acid commonly found in grapes and wines. Extended skin contact during fermentation enhances the extraction of phenolic compounds, including p-coumaric acid, from grape skins, seeds, and stems. For instance, in a study on Malvasija istarska wines subjected to prolonged maceration, p-coumaric acid concentrations reached 2.3 ± 1.0 mg/L. Similarly, post-fermentative maceration of the same variety resulted in p-coumaric acid levels of 1.2 mg/L. These concentrations are noteworthy, as they fall within the range commonly reported for red wines from different Italian geographical regions (0.9–10.3 mg/L [50]) and Chile (0.9–3.6 mg/L [51]). Other studies support the trend of increased p-coumaric acid levels during post-fermentation maceration, with some reporting concentrations exceeding those typically found in red wines (1.2 mg/L [4]; 0.5–5.5 mg/L [31]; 0.1–1.4 mg/L [35]). The presence of p-coumaric acid in higher concentrations is significant not only for its contribution to the antioxidant capacity of the wine but also because it serves as a precursor to volatile phenols formed by spoilage yeasts like *Brettanomyces*, potentially influencing sensory outcomes [51].

p-Coutaric acid, an ester formed from p-coumaric acid and tartaric acid, is a naturally occurring hydroxycinnamic acid derivative found predominantly in grape

skins. In Croatia, the white grape variety Graševina was used to produce a wine with 120 days of skin maceration, during which p-coutaric acid levels increased significantly—by approximately 24% for the cis-isomer and 14% for the trans-isomer [36]. Comparable increases have been observed in Italian monovarietal long-macerated white wines, where p-coutaric acid concentrations ranged from 1.8 to 4.3 mg/L. Notably, a blend of three grape varieties yielded an exceptionally high concentration of 17.1 mg/L, a level similar to those found in Italian red wines, where values around 15.6 mg/L have been recorded [52]. When exposed to oxygen, p-coutaric acid is oxidized into reactive o-quinones, which polymerize into brown pigments, deepening the wine's amber hue [53]. This browning process, often embraced in orange wine styles, enhances visual richness and adds oxidative complexity, though it can also increase bitterness and astringency if not carefully managed.

3.2.1.4 Caftaric acid

Caftaric acid has been identified as the most abundant polyphenolic compound in nearly all studies conducted on long-macerated white wines. According to Milat et al. [36], the average concentration of caftaric acid in Croatian long-macerated white wines was 17.7 mg/L. Higher levels were reported in Italian macerated whites, reaching up to 53.1 mg/L, and in wines from Italy, Austria, and Slovenia, where concentrations were as high as 96.52 mg/L. In contrast, monovarietal wines generally showed lower concentrations, ranging from 4.5 to 33.1 mg/L [32, 33]. These values are consistent with findings in Spanish table wines (up to 53.5 mg/L) and Greek red wines, where caftaric acid concentrations varied widely between 4.3 and 106.7 mg/L [54]. Additional studies confirm that caftaric acid is the predominant hydroxycinnamic acid in white wines, with post-maceration concentrations ranging from 18.5 to 116 mg/L [55]. In the context of long-macerated white wines, where oxygen exposure is often deliberate, caftaric acid undergoes enzymatic oxidation mediated by polyphenol oxidase (PPO). This reaction produces reactive o-quinones, which can interact with other phenolic compounds, such as catechins, forming brown pigments. These pigments contribute to the distinctive amber or orange coloration typical of orange wines. Unlike in conventional white winemaking, this browning is not regarded as a flaw, but rather as a desirable stylistic element, enhancing the wine's visual depth, phenolic complexity, and oxidative character. The mechanisms behind caftaric acid oxidation and its impact on wine appearance and composition are well-documented in the scientific literature, particularly in studies focusing on oxidation processes during vinification and phenolic interactions in must and wine [56].

3.2.2 Hydroxybenzoic acids

Common hydroxybenzoic acids such as gallic acid, protocatechuic acid, vanillic acid, and syringic acid were found in higher concentrations in macerated white wines compared to traditionally made white wines [57].

3.2.2.1 Gallic acid

Gallic acid is one of the most prevalent hydroxybenzoic acids in wine, originating both from the grape itself and from the hydrolysis of hydrolyzable and condensed tannins during winemaking [45]. In studies focusing on prolonged maceration in white wines, gallic acid consistently emerges as a dominant hydroxybenzoic acid.

Notably, Beara et al. [34] identified a distinctive chemical profile in these wines, characterized by significantly elevated levels of gallic acid, reaching concentrations as high as 49.5 mg/L. Comparable increases have been reported in orange wines produced in Italy, Austria, and Slovenia using similar winemaking techniques, with gallic acid levels ranging from 0.9 to 41.1 mg/L. These values are noteworthy when compared to Croatian red wines such as Pinot crni (10.7 mg/L), Poštup (11.8 mg/L), and Merlot (11.1 mg/L) [58], underscoring the extent to which maceration elevates phenolic content in white wines. While several of these findings are based on analyses of commercial wines—limiting the ability to quantify exact increases—a Croatian study using controlled winemaking conditions reported an approximately tenfold rise in gallic acid concentration in macerated white wines compared to a non-macerated control [36]. Further insights come from a study on Bianchetta Trevigiana, where no significant difference in gallic acid concentration was observed between control and macerated samples within the first 40 days. However, after 100 days of maceration, gallic acid levels increased markedly in the macerated wine. This delayed rise suggests that the prolonged skin contact facilitates the hydrolysis of flavonoid-gallate esters, primarily located in grape skins, gradually releasing gallic acid into the wine matrix [38].

3.2.2.2 Protocatechuic, vanillic, and syringic acid

Besides gallic acid, other hydroxynamic compounds found predominantly in the wines were the protocatechuic acid, the vanillic, and the syringic acids. Protocatechuic acid (PCA) is a naturally occurring phenolic compound found in wines, originating mainly from the degradation of anthocyanins and other complex polyphenols during fermentation and aging. In white wines produced by prolonged maceration and maturation in wooden barrels, PCA levels were significantly higher than in standard wines. For instance, in Malvazija istarska wines, PCA concentrations were 14.9 mg/L in wines produced by prolonged maceration and maturation, compared to 3.4 mg/L in standard wines without maturation [28]. Similarly, higher concentrations of PCA were observed in macerated white wines such as Malvazija and Pošip. These wines exhibited increased antioxidant activity, correlating with the elevated phenolic content [32]. Similar patterns have been observed in Karaoglan red wines, with PCA concentrations reaching a peak of 9.5 mg/L after 10 days of maceration, followed by a modest decrease to 9.3 mg/L after 15 days. This slight decline is likely attributed to prolonged maceration, which may promote chemical transformations or the precipitation of phenolic compounds [6, 59]. Vanillic and syringic acids also exhibited an increasing trend in two studies conducted in Croatia. In several wines, the concentration of gallic acid was followed by that of vanillic acid, which showed significantly higher values compared to the control samples [28]. Notably, wines subjected to extended maceration and barrel maturation contained up to 12 times more vanillic acid. In the study by Korenika et al. [35], non-macerated wines exhibited vanillic acid concentrations approximately two times lower than their macerated counterparts. The highest concentration of vanillic acid in macerated wines was observed in blended samples, reaching 12.4 mg/L. These results are consistent with data from red wines of the Cabernet Sauvignon and Syrah varieties produced in San Francisco, where vanillic acid levels ranged from 4.4 to 44.4 mg/L [60]. Furthermore, a study conducted in high-altitude vineyards in Santa Catarina, Brazil, demonstrated that leaf removal timing in Cabernet Sauvignon grapevines significantly affects vanillic acid concentrations. Early defoliation, particularly at the buckshot and pea-sized berry stages, led to increased levels, reaching up to 7.6 mg/L. These findings underscore the critical role of canopy management practices in influencing wine composition [61].

3.2.3 Stilbenes

Stilbenes are a class of non-flavonoid polyphenolic compounds known for their potent antioxidant properties and potential health benefits, particularly in the prevention of cardiovascular diseases and inflammation-related conditions. Among them, resveratrol (3,5,4'-trihydroxy-trans-stilbene) is the most extensively studied. It occurs in both its aglycone (free) form and as glycosylated derivatives, most notably piceid (resveratrol-3-O- β -D-glucoside) [62].

Studies on “orange” wines have shown that resveratrol can be present at higher concentrations than in conventional red wines. Bene et al. [29] observed notably elevated levels of trans-resveratrol in Hungarian Zéta wines—both macerated and non-macerated—compared to traditional Georgian wines made using the Kakhetian method, which involves prolonged skin contact and fermentation in qvevri vessels. Among the samples analyzed, blended wines exhibited the highest trans-resveratrol concentration, reaching 1.95 mg/L. These values exceeded those reported for Merlot wines from Sicily (1.3 mg/L [48]) and fell within or above the range typically found in various international red wines (0.1–2 mg/L [63]). Notably, trans-resveratrol was not detected in all non-macerated wines; however, in those where it was present, the average concentration (0.5 mg/L) was approximately half that observed in the macerated counterparts [32]. These findings were further supported by Korenika et al. [35], who observed that a blend of Malvasia, Sauvignon Blanc, and Pinot Gris had the highest trans-resveratrol concentration among the macerated wines evaluated in their study. In addition to trans-resveratrol, elevated levels of cis-resveratrol and resveratrol-3-O-glucoside have also been detected in several studies. Concentrations of cis-resveratrol ranged from 0.7 to 5.3 mg/L, while resveratrol-3-O-glucoside was found at levels between 0.3 and 0.9 mg/L [33, 35].

3.3 Flavonoids

Flavonoids are a diverse group of secondary plant metabolites, with over 4000 compounds identified to date and nearly 2000 known to occur widely across plant species. They can be categorized into several major subclasses, including flavonols, flavones, anthocyanins, flavan-3-ols (such as catechins), and flavanones [64]. In grapes, the concentration and composition of flavonoids are primarily determined by genetic factors (such as grape variety), but they are also influenced by environmental conditions, viticultural practices, and the degree of berry ripeness at harvest [65]. In white wines produced through prolonged maceration, elevated levels of flavonols (e.g., quercetin, myricetin) and flavan-3-ols (e.g., catechin, epicatechin) are often observed due to extended contact with grape skins and seeds during fermentation. These compounds contribute to a richer and more complex phenolic profile, enhancing attributes such as bitterness, astringency, oxidative stability, and antioxidant potential. Moreover, they influence the wine's amber hue, fuller mouthfeel, and improved aging capacity [3].

3.3.1 Flavan-3-ols

3.3.1.1 Catechin and epicatechin

In prolonged skin-contact white wines, the predominant flavan-3-ols identified are catechin, epicatechin, and proanthocyanidins, which are extracted from grape

skins and seeds during extended maceration. A study conducted on Bianchetta Trevigiana wine in Italy provided further insight into how extended maceration influences phenolic composition. The research underscored the critical role of flavanols localization within grape tissues and their varying solubility in both aqueous and hydroalcoholic media. Flavan-3-ols demonstrated relatively stable extraction levels during the initial 40 days of maceration. However, a marked increase in their concentration was observed with prolonged maceration, reaching a pronounced peak around the 100-day mark. This trend highlights the dynamic behavior of phenolic compounds over time and the significance of maceration duration in shaping wine composition [38].

Complementary findings from Milat et al. [36], who studied the Graševina variety, reported a significant rise in catechin and epicatechin levels during maceration periods extending up to 190 days, with concentrations increasing up to fivefold. The study also explored the oxidative stability of these wines under air exposure for 24 and 48 hours. Interestingly, the composition of flavan-3-ol monomers and dimers remained largely unaffected by oxidation, with monomers continuing to dominate. Moreover, the mean degree of polymerization of flavanol fractions stayed consistently low and showed no significant changes during oxidative exposure or browning process [36]. Further investigations have demonstrated similar trends in skin-contact white wines when compared to red wines. For instance, a blend of Malvazija, Sauvignon Blanc, and Pinot Gris subjected to prolonged maceration exhibited catechin concentrations of 12.6 mg/L, closely aligning with those typically found in Greek red wines (11.6–13.4 mg/L) [66]. Ruzic et al. [32] also reported that most of the commercial wines included in their study—those produced with skin contact—showed catechin and epicatechin concentrations above 7 mg/L. In contrast, non-macerated white wines largely lacked detectable levels of these compounds. These results are in alignment with other commercial wines taken under study (1.8–22.7 mg/L) [33].

In contrast, Malvazija Istarska wines subjected to prolonged maceration followed by barrel maturation demonstrated a significant negative correlation between catechin and epicatechin concentrations and total maceration time. This decline is believed to result from condensation reactions involving acetaldehyde, as well as oxidative polymerization with glyoxylic acid. These processes likely lead to the formation of larger, less soluble phenolic structures, contributing to a reduction in monomeric flavan-3-ols during maturation [28, 67].

3.3.1.2 Proanthocyanidins

In the same study that reported a negative correlation between catechin and epicatechin concentrations and the total duration of maceration, proanthocyanidins showed an opposite trend. Their concentration increased significantly with prolonged maceration, exhibiting more than a fourfold rise compared to wines produced using conventional winemaking techniques followed by barrel maturation [28]. Notably, both Proanthocyanidin A and B were detected in commercial “orange” wines—white wines made using extended skin contact—originating from Austria, Italy, Croatia, and Slovenia. Concentrations of Proanthocyanidin A ranged from 1.1 to 70.5 mg/L, while Proanthocyanidin B levels varied between 0 and 34.9 mg/L [33]. A particularly striking comparison emerged in a study evaluating the effects of traditional and Kakhetian winemaking methods on white grape varieties. In the case of the Rkatsiteli variety, the Kakhetian method—characterized by extensive

skin contact and amphora aging, resulted in a 15-fold increase in proanthocyanidin concentration compared to the same variety produced via conventional techniques. Similarly, the Khikhvi variety displayed exceptionally high proanthocyanidin levels, reaching 1097 mg/L—nearly 24 times higher than under traditional winemaking—and comparable to those found in red wines made with the same method, which ranged from 872 to 1203 mg/L [30, 68]. These findings underscore the profound influence of maceration duration, grape variety, and winemaking approach on the phenolic composition of skin-contact white wines.

3.3.2 Flavonols

Flavonols have received limited attention in studies focusing on prolonged maceration in white wines, despite their well-established functional role in red wines. These compounds contribute to antioxidant activity, enhance oxidative stability, and play a key role in color stabilization through co-pigmentation with anthocyanins. From a sensory perspective, flavonols influence mouthfeel by contributing to astringency and bitterness through interactions with tannins [69]. However, recent research on various Croatian white grape varieties has confirmed the presence of flavonols such as quercetin and quercetin-3-glucoside in nearly all wine samples. Notably, the highest concentrations were observed in wines produced from blended varieties, ranging from 1 to 3.4 mg/L. Furthermore, levels of quercetin and kaempferol in these white wines were comparable to those reported in Croatian red wines (3.6 mg/L [58]) and red Greek wines (1.7–4.9 mg/L [42]), suggesting that maceration techniques in white winemaking may yield flavonol concentrations similar to those typically associated with red wine production.

4. Antioxidant capacity in white wines via prolonged maceration techniques

Over the past decade, the health impacts of wine consumption have been extensively investigated, with particular emphasis on its potential protective effects against cancer and cardiovascular disease. A key area of focus has been the role of oxidative stress in the early stages of these conditions. It is well established that reactive oxygen species, byproducts of normal metabolic processes, can inflict damage on vital cellular components, including proteins, lipids, and DNA, thereby contributing to disease development [70]. Among the components of wine, polyphenols have attracted significant attention for their protective biological properties. Their molecular structure enables them to effectively scavenge and neutralize free radicals, thus mitigating oxidative stress [71]. Polyphenols have also been shown to inhibit the oxidation of low-density lipoprotein, reduce platelet aggregation, and exert anti-inflammatory effects through modulation of eicosanoid pathways [72]. Furthermore, they influence nitric oxide production, facilitating vascular relaxation, and have demonstrated growth-inhibitory activity in various cancer cell lines [73]. The concentration and composition of phenolic compounds in wine vary depending on grape variety, climate, soil characteristics, as well as oenological practices, including winemaking, aging, and storage conditions. Among natural antioxidants, red grape and its derived products, particularly wine, have attracted significant interest due to their high levels and diverse array of phenolic compounds, making them valuable sources of bioactive dietary polyphenols [10].

In Croatian Malvasia Istarska wines, antioxidant activity was found to be nearly six times higher on average in those produced through prolonged maceration and maturation compared to standard winemaking methods. These elevated levels are comparable to antioxidant capacities reported for certain Czech varieties, which range between 2.9 and 7.3 mmol/L [74]. These findings align with results from Prasnikar et al. [33], who observed an average antioxidant activity of 4 mmol/L in long-macerated commercial wines, with values varying widely between 0.1 and 11.9 mmol/L depending on the grape variety. Strong positive correlations were observed between antioxidant activity and the concentrations of total phenols, flavonoids, and proanthocyanidins in wines subjected to extended maceration and aging. Interestingly, this relationship also held true, albeit to a lesser extent, in non-macerated wines, highlighting the fundamental role of phenolic compounds in driving antioxidant potential regardless of winemaking technique [28]. Additionally, Ruzic et al. [32] highlighted that the enhanced antioxidant activity in long-macerated white wines was more closely associated with specific phenolics such as gallic acid, catechins, and resveratrol, emphasizing the importance of these compounds in the antioxidant profile of such wines.

In a comparative study encompassing wines from various European countries and Georgia, a significant disparity in antioxidant activity was observed. Wines produced using the traditional Kakhetian method in Georgia exhibited notably higher antioxidant activity compared to those made using conventional European methods. The study also revealed that wines with greater antioxidant capacity contained substantially lower total sulfite levels, suggesting a possible inverse relationship

Measurement method	Country	Concentration (mmol TE/L)	Concentration variations (%)	Reference
Randox TAS assay	Hungary	12	↑ 77.5	[29]
DPPH assay	Croatia	4.7	↑ 213.3	[28]
FRAP assay	Croatia	14.4	↑ 4173	[36]
DPPH assay		12.1	↑ 500	
ABTS assay		16.2	↑ 440	
ORAC assay		23.4	↑ 390	
ABTS assay	Croatia	n.s.*	↑ 100	[35]
ORAC assay	US Spain Georgia Greece	4.2–22.5	n.s.*	[76]
DPPH assay	Georgia Italy Slovenia	0.5–1.2	n.s.*	[68]
DPPH assay	Georgia	0.5–2.9 kg TE/L	n.s.*	[75]
ORAC assay		0.9–4 kg TE/L		

*Not specified.

TAS—total antioxidant status; DPPH—2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; FRAP—ferric reducing antioxidant power; ABTS—2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); ORAC—oxygen radical absorbance capacity; TE—trolox equivalent; US—United States of America.

Table 2.
Overview of antioxidant activity reported in studies of long maceration white winemaking.

between sulfite concentration and antioxidant potential in these wines [75]. In the study by Korenika et al. [35], a positive correlation was observed between maceration duration and both total phenolic content and antioxidant activity. This increase was attributed to more efficient extraction of polyphenols from the grape pomace during extended maceration. Wines subjected to long or prolonged maceration exhibited up to a twofold increase in antioxidant capacity compared to those produced using cold maceration or without maceration (**Table 2**).

5. Conclusions

The growing consumer interest in distinctive and unconventional wine styles has opened a compelling niche for “orange” wine, also known as qvevri wine, to establish a unique and influential presence within the global wine market. These wines, produced through prolonged maceration of white grape varieties, share certain oenological techniques with red wine production, especially in terms of skin contact and phenolic extraction. However, they are set apart by their amber-to-deep orange hue, elevated levels of phenolic compounds, and their complex sensory profiles, which often include pronounced astringency, oxidative notes, and enhanced aromatic intensity.

This chapter aimed to comprehensively evaluate and deepen the characterization of phenolic compounds in white wines produced through extended maceration. Special emphasis was placed on understanding the extraction dynamics and stability of key phenolic groups, such as hydroxycinnamic acid, hydroxybenzoic acid, flavan-3-ols, and proanthocyanidins, under prolonged skin contact conditions. By investigating their concentration patterns and interactions over time, the research seeks to elucidate how long maceration influences the phenolic profile and contributes to the unique structural, oxidative, and sensory attributes associated with “orange” wines.

Beyond tracing the evolution of phenolic compounds, this chapter focused specifically on their role in enhancing the antioxidant capacity of wines produced through extended maceration. Numerous studies have demonstrated that the elevated levels of phenolic compounds significantly contribute to the antioxidant potential of wines from various grape varieties. By examining the behavior of these compounds under prolonged skin contact, the research offers critical insights into the biochemical mechanisms underlying increased antioxidant activity in orange wines. This understanding not only highlights the distinguishing features of orange wines compared to traditional white and red styles but also provides valuable direction for winemakers seeking to fine-tune maceration techniques to boost oxidative stability and aging potential. Furthermore, the findings support the strategic positioning of orange wines in a growing market segment that values authenticity, minimal intervention, and health-oriented attributes.

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Chapter 7

The Global Grind: Past Trends and Future Brews of the Coffee Culture

Megha Ashawat and M.S. Ashawat

Abstract

Coffee as a beverage needs no introduction. This caffeinated drink has solidified its place as a global staple beverage. Its journey has taken a significant turn, with its consumption being affected by scientific advancements and findings, health-related discourse, consumer preferences, and global market dynamics. This chapter offers a layered exploration of how the tables have turned over the past centuries, driven by innovations, brewing technologies, and making coffee more than just a beverage. The scientific findings also unraveled the pharmacological aspect of the brown grounds. It was considered a source of energy, mixed with various spices and fats. Globalization has continued to shape coffee grounds to their fullest. From different cultural perspectives, our methodology will examine the dimensions that attempt to explain how traditional beliefs, histories, and regional proclivities influence the statistics. From traditional coffee ceremonies of Ethiopia to the minimalist coffee culture in Italy, we examine how these cultures have influenced consumption trends across the globe over the past centuries. It is a cultural influence now, a rooted narrative shifting lifestyle demands. There lies a much deeper dimension behind all the humongous statistics that deal with coffee from its social perception: How coffee and culture are experienced and appreciated, and (in some cases) even ritualized. By fusing recent scientific data with a culturally rich story, this chapter presents a whole new view of coffee as both a beverage and a cultural artifact. Its liveliness, adaptive nature, and human interaction have caused it to be one of the greatest mysteries yet covered in a simple cape.

Keywords: coffee, cultural influence, tradition, global beverage trend, health-related effects, globalization

1. Introduction

1.1 History

“A single cup of coffee contains centuries of rituals, evolution, resilience, and reinvention.”

Coffee, the famous caffeinated drink, is loved by many but understood by just a few. Although it is simple in appearance, it has woven its way into the deepest cultures around the globe. Beyond its unmistakable aroma lies its global narrative that spans continents, traditions, and time. Once a ritualistic elixir in Ethiopia is now an anchor and a scientific subject of great scrutiny.

Coffee first became known when the Yemen Sufis used it to stay awake in the evening prayers. Then, around the fifteenth century, a shepherd in Yemen recognized its remarkable properties. Originally used in rituals and ceremonies in old Yemen, coffee made its way to North Africa and the current regions of Turkey [1]. The drink, accompanied by fruits and brewed with cardamom, was a significant part of the conversations of the Turkish people. Reinvention became its second stage of development. From roasting the beans to the brewing technologies, everything was modernized. Coffee was then paired with energy supplements like fats and spices to provide adequate nutrients to the shepherds. In the wake of innovations, some coffee shops were now being established in Mecca and Medina in the Middle East [2]. Caffeine now instilled the fear of rebellion in the region and hence was banned by the Governor of Mecca in 1511. Not long after this, the famous “coffee” became popular in Italy and Europe. As time passed, so did coffee pave its way, and the aroma reached India. Owing to its stimulating effect, traders and exporters soon heard about the “black fashion” that gave energy. From there, coffee began to be exported to the Americas [3]. Despite its singular origin, the interpretations multiplied when the first cafe, “Florian,” was established in Venice. In the light of social demands, the cafes began to grow, and coffeehouses spread rapidly across France, England, and some parts of Germany. In the eighteenth and nineteenth centuries, they were the main hubs for literary, political, and academic discussions, and often referred to as “penny universities,” meaning that for the price of a penny, you could be part of a vibrant society [4].

2. Transition to significance

How did coffee evolve from a ritualistic drink into the global symbol of pharmacological value, commercial power, and social culture?

When eras changed, so did the brew. Originating from Yemen and Ethiopian regions, in the fifteenth century, it was mainly used by Sufis and priests to keep them awake during their long hours of prayer [5]. But as time progressed, people realized that this beverage was more than just an anti-sleeping tonic. Preparations like Qishr (made from boiling cherry husks in water) were used for medicinal purposes, too, but little did they know this simple beverage is going to skyrocket and change the entire course of the beverage industry [6]. Coffee commercially expanded from Dutch Java to Indonesia. From France to the Caribbean, and finally, the British colonies brought the aroma to India. Coffeehouses were now the main hub for discussions, private and professional meetings, academic, and social exchange. The cafes soon began to spread into espresso bars and started becoming the daily ritual across distinct cultures. By the seventeenth century, coffee dug its way into the medicinal industry, as the psychoactive effects of the bean came into light [7, 8]. Further research presented that the little bean does much more than just stimulate the brain. It was used in a variety of cases, like neuroprotection, diuretics, and, to an extent, asthma treatment. From the early fifteenth century to this day, coffee has been serving as the staple beverage of society. The transition to stand with water and tea as a drink has been great; coffee went from a ceremonial drink to a social giant.

3. The tale of two beans: Arabica vs Robusta

The popularity of coffee is mainly attributed to its invigorating effect, which is produced by two kinds of beans, Arabica and Robusta. Of course, there are types

Parameter	Arabica	Robusta
Scientific name	<i>Coffee arabica</i>	<i>Coffee canephora</i>
Origin	Ethiopia	Sub-saharan Africa
Altitude	1000–2000 meters	400–800 meters
Caffeine content	1.2–1.5%	2.2–2.5%
Flavor	Smooth, mild (generally used in specialty coffees, single-origin brews)	Strong, bitter (generally used in instant coffees)
Sugar content	5–9%	3–7%
Lipid content	15–17%	10–12%
Cultivating cost	Higher	Lower
Market share	60–70%	30–40%
Therapeutic value	In nutraceuticals and health drinks, due to its antioxidant properties	More common in energy drinks owing to their higher caffeine content and more stimulating effect

Table 1.
Comparison between Arabica and Robusta coffee varieties.

beyond these, too, but these two serve as the faces of the coffee industry and are known by many. While Arabica is milder and flavorful, on the other hand, Robusta is quite the opposite, with strong and more astringent flavors. As the name “Robusta” suggests, it gives an idea of robustness—a fitting description indeed, as this bean needs less care, thrives at lower altitudes, and is less vulnerable to pests than Arabica [9]. Coffee aficionados often debate the origin and flavor of beans between mild Arabica and robust Robusta; therefore, understanding their distinctions would enhance appreciation and selection (Table 1) [10].

4. Brewing the coffee

So, let us start from the raw plant to how it is served in our cups, aiming to stimulate the brain and boost endurance.

It all begins with growing the plant in the suitable regions called the “coffee belts,” which are listed in Table 2 [11]. Then, the harvesting is done either by hand for more precise selection or *via* machines. Then, it proceeds to dry the beans with cherry (refers to the fruit of the coffee plant) husk. The next steps include sorting beans based on their size, and the upper layer, called the parchment layer, is removed by hulling. Once completely dried, the beans undergo roasting to unlock the peculiar aroma and flavor. The heat is precisely controlled, which determines whether the coffee yields a dark, medium, or light profile. The beans are then subjected to grinding and brewing. However, this step differs significantly among different regions, classes, and societies. As time progressed, so did the brewing technologies throughout the map.

As we have extensively discussed the stats, let us now get into the chemistry of brewing for a bit of an adventure. Trigonelline is a natural compound found in coffee, formed when nicotinic acid undergoes enzymatic methylation. It contributes to about 3.5% of coffee’s bitterness and also plays an essential role in roasting, producing

Rank	Region	Per capita production (kg/person)
1.	Central African Republic	56.27
2.	Honduras (Central America)	30.69
3.	Vietnam (Southeast Asia)	19.47
4.	Guinea (West Africa)	18.60
5.	Brazil (South America)	15.03
6.	Costa Rica (Central America)	14.72
7.	Columbia (South America)	12.71
8.	India (South Asia)	0.25

Table 2.
Per capita production of different regions in descending order of their capacities.

aroma *via* breaking the actives. The chlorogenic acids present in the bean are responsible for the astringency and acidity of our cup of coffee [12].

5. Timelines of taste: Evolution of the brewing technologies

Dating back to the fifteenth century in Yemen, coffee was brewed by boiling cherry husks, and the special form was known as Qishr. Back then, coffee was mainly used as a ceremonial and ritualistic drink. Then, in the sixteenth and seventeenth centuries, around the Ottoman Empire, the beverage was prepared using a method called Turkish Ibrik, presenting drinkers with a fine grind and foamy texture. Percolators came in the eighteenth century in Europe to make the aroma and flavor richer. Then came paper filters and espresso machines in the twentieth century, courtesy of the Germans and Italians. Time passed quickly as innovations like the French Press, Aero Press, and Siphon took over the coffee industry and made brewing even easier. In the early 2000s, cold brew and nitro coffee came into play from the USA and Japan. Presently, we have sophisticated technology like smart brewers used globally, emphasizing artisanal qualities. From husks to high tech, coffee made its way through the ages. It is not just about the aroma, flavor, or commercialization but the sense of craftsmanship blended in every cup, making life more maneuverable [13].

6. Pharmacy in a cup: Coffee's chemistry

The story goes back to 1025, when the Persian physician Avicenna mentioned coffee as a medicine in his manuscript called “The Canon of Medicine.” Back then, it was used to make the skin glow and cover up body odor [14]. From Yemen's spiritual enclaves to Persia's apothecaries, coffee's medical reputation came into light in the early fifteenth century, when medical practitioners used it to boost endurance and relieve fatigue. However, the specific structure was determined centuries later, around the nineteenth century, when Friedlieb Runge isolated the compound as a white, bitter, crystalline powder in 1819. It was then that the practitioners started to unravel its therapeutic potential. Caffeine is known to be a great stimulant and psychoactive compound present in more than 50 different plant species. Some common

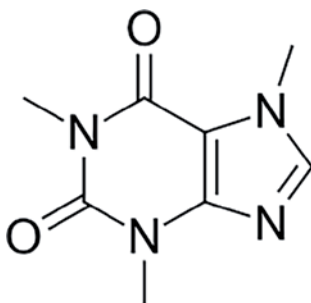


Figure 1.
1,3,7-trimethylxanthine (caffeine).

plant varieties include cacao and the tea plant. In addition to the varieties, caffeine also goes by many aliases; however, this nomenclature should not be confusing, as the name basically comes from the parts from which the compound is derived. For instance, guaranine from guarana berries, theine from tea leaves, etc. This naturally leads us to ask what the reason is behind caffeine's profound medical significance. The answer will be found in its chemistry [15]. Caffeine (1,3,7-trimethylxanthine), a methylxanthine derivative, is regarded as an alkaloid compound as it is the byproduct of nitrogen metabolism [13]. Caffeine is an amphiphilic compound, meaning it is soluble in both oil and aqueous solutions and which makes it easier to cross the blood-brain barrier (BBB). There, it antagonizes adenosine receptor types A₁, A_{2a}, A_{2b}, and A₃, resulting in enhanced alertness and faster reaction time (**Figure 1**) [16–18].

7. Hepatoprotective properties of coffee

Several studies have noted that the consumption of coffee is linked to liver enzymes that act as markers for hepatic damage. Coffee significantly decreased the enzymatic levels of aspartate aminotransferase (AST), alanine aminotransferase (ALT), and gamma-glutamyltransferase (GGT) [19]. Soon, another study contradicted the previous findings by subjecting Korean and Japanese immigrants to coffee. Kim et al. concluded that coffee and the enzymatic activities had an inverse relationship rather than a direct one. Although the study also suggested that coffee is a miraculous bean that can inhibit the hepatic damage caused mainly by alcohol. As time progressed, it was found that people with higher coffee consumption (3–4 cups a day) have reduced enzymatic levels [20]. As per the reports by the US Department of Agriculture (USDA) and the European Food Safety Authority, people consuming 2–4 cups a day of coffee containing around 400 mg of caffeine are not under any direct health risk [12].

8. Pharmacokinetics of caffeine

The pharmacokinetic parameters of caffeine are absorption, distribution, metabolism, and excretion. Starting with the first step is the absorption of the administered compound. Caffeine is 100% bioavailable, meaning it is completely absorbed. The gastrointestinal part absorbs almost 80% of the dose due to its higher stability in the GI environment.

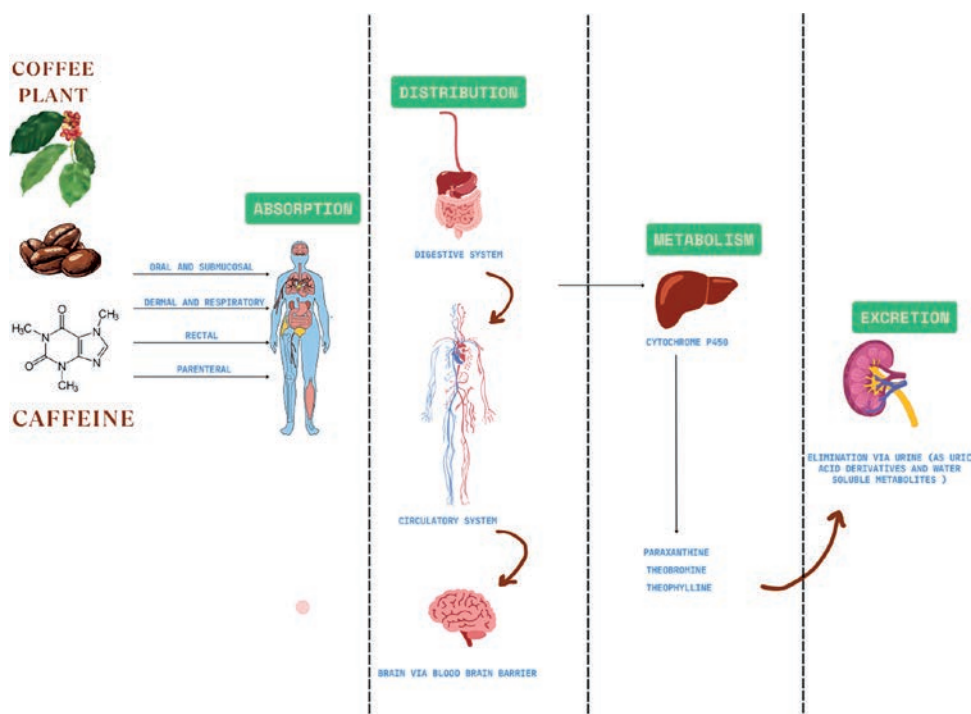


Figure 2.
Showcasing the absorption, distribution, metabolism, and excretion of coffee.

While the remaining 20% is absorbed through the stomach [21]. The purine structure of the compound contributes to the exceptional bioavailability. As the core is small and planar, it facilitates the passive diffusion through the membrane easily, accounting for its negligible first-pass metabolism [22]. Caffeine is then rapidly distributed throughout the body and does not accumulate in the tissues. Due to its highly lipophilic nature and low affinity toward proteins, it also swiftly passes through the blood-brain barrier [23]. The average volume of distribution of caffeine in infants is slightly higher than in adults, accounting for 0.8–0.9 L/kg and 0.6 L/kg, respectively [16]. The distribution of caffeine is independent of age, but depends on gender and the fat content of a person individually, and is significantly higher in women and obese people [15]. Now comes the degradation or metabolism of the compound. For caffeine, it is mainly three compounds: theophylline, theobromine, and paraxanthine. Primarily metabolized in the liver by the CYP450 enzymes, these are then converted into their further metabolites (as shown in the figure). Finally, the compound is swiftly excreted from the body with a half-life of 5 hours. Most of the percentage is reabsorbed in the renal tubules of the kidneys, and the remaining is excreted through urine (Figures 2 and 3) [21].

9. Coffee beyond cup: Multifaceted uses of coffee

Coffee as a beverage has many hearts and brains all around the world, but it is more than just a refreshing and stimulating drink. As eras and centuries change, so do their uses. Innovations are emerging and transforming the way we perceive coffee. Some of the diverse utilizations are described below as coffee in:

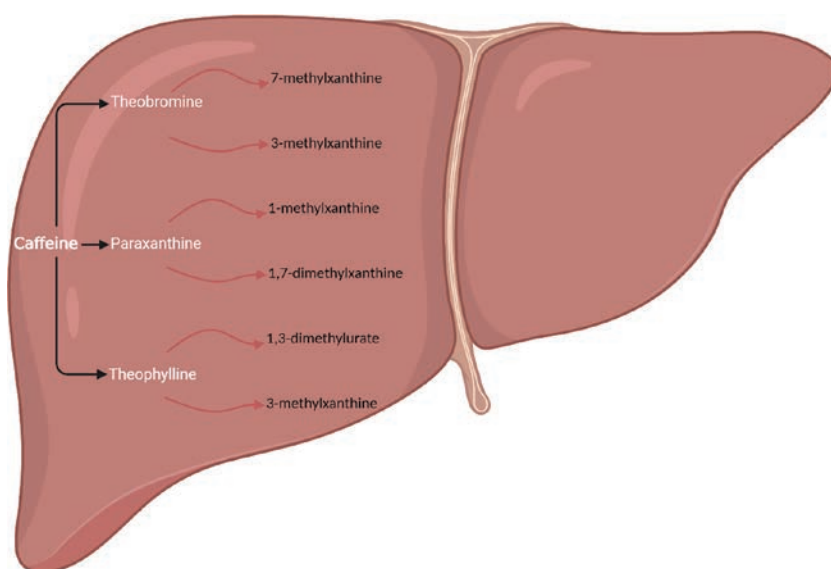


Figure 3.
 Key pathways of caffeine metabolism in the liver.

9.1 Astronaut nutrition

On average, a human in space has 6 hours of sleep, which accounts for the reduced alertness and performance. In space, humans needed to perform extensive and sophisticated teleoperational tasks, which were often compromised due to a lack of sleep [24]. The studies conducted determined the ratio of astronauts using caffeine as well as the impact of caffeine on sleep and alertness. Researchers used both blue light and mild doses of caffeine to increase alertness and enhance the performance of space humans. In essence, the findings suggested that when subject astronauts were exposed to blue light and administered caffeine, the ability to divide their attention to two separate teleoperations was significantly improved. However, using blue light and caffeine separately reduced the visual alertness from -9% to -13% [25].

9.2 Textile

As discussed in the previous sections, it is now an established fact that coffee is majorly consumed across the globe and thus produces significant solid waste known as Spent Coffee Grounds (SCG). Therefore, firms thought of utilizing this large industrial waste and turning it into a new source of fabric and an artistically applicable material. The leftover grounds are converted into yarn at high temperatures ($\sim 160^\circ$). Raw materials are then prepared by mixing processed coffee grounds and recycled polyester. The procedure consists of several extremely precise steps, like sieving, cleaning, and eliminating organic compounds from the final mixture [26]. After this, the method reaches its final steps: preparation of the master batch. These coffee fabrics are sustainable, gorgeous, innovative, and one of their kind. It is gentle to Mother Nature with minimal waste generated and pollutants released into the system.

9.3 Cosmetics

Each layer of the coffee bean unravels a new opportunity for us to use it in ways no one has done before. Its derivatives are employed in topical formulations because of their antioxidant properties. In studies by Al Dhahi et al., the main findings highlighted the use of different discarded parts of coffee after export. They found that these parts have antioxidant, anti-cellulite, sunshielding, and anti-inflammatory properties [27]. Caffeine, associated with UV protection and linked to a range of issues from ageing to serious skin cancer, holds great potential. Results suggest that coffee-based formulations can reduce wrinkles by 35% compared to untreated subjects. The cosmetic industry is increasingly turning to coffee formulations for topical applications. Male androgenic alopecia, which currently has only two FDA-approved treatments, has shown positive results with caffeine preparations. It inhibits the conversion of testosterone to dihydrotestosterone and remains available in hair follicles for up to 24 hours, even after washing [28].

9.4 Human microbiome

Consumers today have gotten smarter and demand high-nutrition food, and yet again, coffee has their back. For coffee enthusiasts, it is heaven as now the grounds also provide prebiotic effects [29]. The good prebiotic effects directly affect the gut and microbiota. The by-products are potentially investigated for the gut-to-brain axis, having a positive impact on neurological health [30]. A high content of dietary fibers, non-digestible polysaccharides, and compounds like melanoidins and chlorogenic acid has been shown to have a low digestive index and are therefore extensively fermented by gut microbes, leading to a lowered gastrointestinal pH and inhibited growth of pathogens. Chlorogenic acid (CGA) is isomerized while roasting the coffee beans, affecting its release. In unabsorbed form, it acts as a growth medium for probiotic bacteria like *Bifidobacteria* or *Lactobacilli*. CGA also affects neurological health by reducing inflammatory indicators. While melanoidins, due to their high molecular weight, remain undigested. It facilitates the growth of *Bifidobacteria*, a probiotic bacterium. However, it is highly dose-dependent, as at higher doses, it may have an antibacterial effect, causing our primary objective (to increase the good bacterial population) to shift in a different direction [29].

10. Emerging applications of coffee in innovative beverages

Coffee is no longer limited to conventional brews like espresso, cappuccino, and latte. In recent times, bioactivity and adaptive profiles have captured the hearts of millions. It motivated them to experiment and play with the flavors and richness to bring out the aroma. Some of the innovative coffee forms are described below.

10.1 Coffee Kombucha

It is a fermented beverage made by using brewed coffee in place of tea as the base, fermented with a symbiotic culture of bacteria and yeast (SCOBY). The fermentation not only lowers the pH but also enhances preservation with probiotic benefits, organic acids, and new flavors. Unlike tea-based kombuchas, coffee-based variants offer additional polyphenols and caffeine, which contribute to their antioxidant and stimulating effects [31].

10.2 Coffee-enriched energy drinks

With an increasing aversion among consumers to synthetic caffeine and sugary drinks, manufacturers are turning to natural caffeine sources, particularly coffee extracts and green coffee bean derivatives. These are often combined with adaptogens, B-vitamins, taurine, or electrolytes to develop performance-enhancing beverages that are cleaner and more bioactive. The drinks come with so many goodies and bonuses like enhanced cognitive abilities, energy, decisive power, neuromuscular coordination, and much more [8, 32].

10.3 Cascara

Cascara, also known as the “coffee cherry tea,” is a beverage made from dried husks of coffee cherries, which can be consumed as hot, cold infusions, or sparkling drinks. It was made from six samples of pulp, which are packed with antioxidants, polyphenols, and caffeine. It is also rich in dietary fiber, making it a good option for purgatives. Cascara is also entering the market with booming products like stress-relieving cascara tea, detox cascara tea, etc. It is also sustainable as it is produced from the by-products of coffee production, helping to reduce the production waste and pamper Mother Earth a bit [33, 34].

10.4 Functional waters

Now this is something tongue-catching. A bottle with coffee aroma, flavors, and the goodness of vitamins and antioxidants. Functional waters bridge the gap between tasteless nutrients with our loved coffee richness. It is infused with coffee fruit extracts from the pulp and skin of the bean. The extracts contain compounds like chlorogenic acid, proanthocyanidins, and trace amounts of caffeine. Reports suggest that coffee fruit extract enhances brain-derived neurotrophic factor, leading to the potential improvements in memory and cognition. They are low-calorie, rich in energy, and align with the market demand of consumers for hydration, taste, and health benefits all in one [35].

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Advancements in Mycotoxin Detection Technologies: Safeguarding Beverage Quality and Consumer Health

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Abstract

The global risk posed by mycotoxins in beverages, such as ochratoxin A (OTA), patulin (PAT), aflatoxins (AFs), and others, necessitates robust and rapid detection strategies to maintain product safety and public health. This chapter reviews recent analytical innovations spanning chromatographic, immunoassay, biosensor, and microfluidic platforms. Special emphasis is placed on portable, point-of-care systems utilizing novel recognition elements (aptamers, antibodies, MIPs), nanomaterials, and digital signal processing. Comparative performance metrics demonstrate that emerging biosensor systems can rival traditional high-performance liquid chromatography-mass spectrometry (HPLC-MS/MS) while offering greater speed and field applicability. Integration trends toward multiplexing, smartphone readouts, and AI-assisted interpretation are explored, alongside future directions for regulatory adoption and commercialization.

Keywords: mycotoxins, beverage safety, on-site detection, advanced detection techniques, beverages analysis, coffee mycotoxin screening

1. Introduction

In recent years, there has been an increasing global concern regarding the safety and quality of beverages due to the presence of mycotoxins, harmful secondary metabolites produced by various fungal species, predominantly *Aspergillus*, *Penicillium*, and *Fusarium*. These toxic compounds can contaminate a wide range of raw materials used in beverage production, including cereals, fruits, coffee beans, and grapes, leading to significant public health risks and economic losses. Mycotoxins such as aflatoxins (AFs), ochratoxin A (OTA), patulin (PAT), deoxynivalenol (DON), zearalenone (ZEN), and fumonisins are known for their carcinogenic, hepatotoxic, nephrotoxic, and immunosuppressive effects [1].

Despite improvements in food processing and storage technologies, mycotoxin contamination remains a persistent issue, particularly in beverages derived from agricultural products that are prone to fungal infection. The globalized nature of food trade, climate change, and variations in agricultural practices exacerbate the risk of contamination, making effective monitoring and detection strategies more critical than ever [2].

The health implications of chronic exposure to mycotoxins, even at low concentrations, are profound. For instance, aflatoxin B1 is classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen, while OTA has been associated with kidney damage and immunotoxicity [3, 4]. In vulnerable populations such as children, the elderly, and immunocompromised individuals, the effects can be even more severe. Furthermore, combined or synergistic toxicity, where multiple mycotoxins are present, can enhance harmful outcomes, complicating risk assessments and safety regulations [5].

From an economic perspective, the repercussions of mycotoxin contamination are equally significant. Contaminated batches of raw materials or finished beverages often result in product recalls, trade restrictions, and reputational damage for manufacturers. A report by the Food and Agriculture Organization (FAO) estimates that up to 25% of the world's food crops are affected by mycotoxins annually, with corresponding losses in the beverage industry reaching millions of dollars [6].

In response to these risks, international regulatory bodies have established maximum allowable limits for various mycotoxins in food and beverages. The European Union Regulation (EU) 2023/915 sets stringent limits on aflatoxins, OTA, and PAT in products like wine, fruit juices, and coffee. Similarly, China's GB 2761–2017 and U.S. FDA guidelines provide detailed specifications to safeguard consumer health [7]. However, ensuring compliance with these regulations demands the availability of rapid, sensitive, and reliable analytical methods. **Table 1** summarizes selected international regulatory limits for key mycotoxins across various beverage types, reinforcing the importance of sensitive analytical techniques.

Traditionally, detection of mycotoxins has relied on sophisticated laboratory-based methods such as high-performance liquid chromatography (HPLC), liquid chromatography-tandem mass spectrometry (LC-MS/MS), enzyme-linked immunosorbent assay (ELISA), and gas chromatography-mass spectrometry (GC-MS). While these techniques offer high sensitivity and specificity, they are often labor-intensive, time-consuming, and require costly instrumentation and skilled personnel. This makes them less suitable for routine screening or on-site applications, particularly in resource-limited settings [8].

Mycotoxin	Beverage matrix	Regulatory	Maximum limit
Aflatoxin M ₁	Milk, milk-based drinks	EU (Reg. 2023/915)	0.05 µg/kg
Patulin	Apple juice, cider	EU	50 µg/L
Ochratoxin A	Wine, grape juice, coffee	EU	2 µg/L (wine), 10 µg/kg (coffee)
Aflatoxins	Fruit juices, cereals	FDA	20 µg/kg
Deoxynivalenol	Beer	EU	200 µg/L

Table 1.
Regulatory limits of major mycotoxins in common beverages.

To overcome these limitations, recent years have seen a surge in research and development of innovative detection technologies that are faster, more portable, and user-friendly. Among these, biosensors, nanotechnology-based platforms, molecularly imprinted polymers (MIPs), microfluidic devices, and smartphone-integrated diagnostic systems are gaining prominence. These tools aim to bridge the gap between laboratory accuracy and field applicability, offering promising alternatives for real-time, on-site mycotoxin screening [9, 10].

Artificial intelligence (AI) and machine learning (ML) are also beginning to play transformative roles in this landscape. Data-driven approaches can enhance pattern recognition, improve detection sensitivity, and facilitate predictive modeling for contamination risk, all of which are invaluable for ensuring food safety in complex production and supply chain environments [11].

The convergence of analytical chemistry, material science, and digital technology marks a new era in mycotoxin detection, with direct implications for the beverage industry. As consumer awareness grows and regulatory scrutiny tightens, companies are under increasing pressure to adopt cutting-edge detection methods that not only meet legal standards but also build trust and transparency with consumers.

This chapter aims to provide a comprehensive overview of these advancements, starting with traditional detection methods and progressing through to state-of-the-art technologies. It will also explore the integration of AI and machine learning into analytical workflows, address the challenges of implementation, and discuss future directions in this rapidly evolving field.

2. Traditional methods for mycotoxin detection

Conventional detection methods have long been the cornerstone of food safety assessment, especially for detecting mycotoxins in beverages. Among the most widely used are thin-layer chromatography (TLC), high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), enzyme-linked immunosorbent assay (ELISA), and liquid chromatography-tandem mass spectrometry (LC-MS/MS). These last methodologies have set the benchmark for sensitivity, specificity, and accuracy in quantitative analysis, often detecting contaminants at parts-per-billion (ppb) levels [12].

2.1 High-performance liquid chromatography (HPLC)

Widely used high-performance liquid chromatography (HPLC) is one of the most established and widely used analytical techniques for detecting and quantifying mycotoxins in various food and feed products. It is renowned for its high sensitivity, precision, and reproducibility, making it a gold standard in regulatory laboratories [13].

In typical mycotoxin analysis using HPLC, the process begins with sample extraction and purification, often through solid-phase extraction (SPE) or immunoaffinity columns to remove interfering substances. The cleaned extract is then introduced into the chromatographic system, where separation of target mycotoxins occurs based on their interaction with the stationary and mobile phases. Commonly used columns are reversed-phase C18, which provide strong retention of nonpolar mycotoxins like aflatoxins, ochratoxin A, and zearalenone [14].

Detection methods used in HPLC for mycotoxins include UV or Diode-Array Detection (DAD), suitable for trichothecenes and ochratoxins. Also, Fluorescence Detection (FLD), especially effective for naturally fluorescent mycotoxins such as aflatoxins and ochratoxin A and offers a sensitive protocol for OTA detection and quantification [15]. Mass spectrometry (HPLC-MS/MS) offers high sensitivity and specificity for simultaneous multi-mycotoxin analysis.

Aflatoxins can also be detected in food commodities using HPLC with fluorescence detection (HPLC-FLD), although their native fluorescence is significantly diminished in the aqueous solvents typically used for reversed-phase chromatography. Fluorescence intensity can be enhanced either by adding cyclodextrins to the HPLC eluent before or after the column or by pre-column derivatization of the hemiacetal group with trifluoroacetic acid [16].

The most widely used techniques for detecting fumonisins and trichothecenes in food and feed are HPLC-MS and GC-MS, primarily because these mycotoxins lack natural fluorescence. HPLC with Diode-Array Detection (HPLC-DAD) is seldom applied in mycotoxin analysis, as it generally offers low sensitivity, which is inadequate for meeting regulatory limits typically set in the parts-per-billion (ppb) range. Nonetheless, UV detection has occasionally been reported for specific mycotoxins such as patulin, trichothecenes, zearalenone (ZON), and *Alternaria* toxins [17].

HPLC coupled with tandem mass spectrometry (HPLC-MS/MS) has become prominent for multi-residue analysis due to its capacity to detect trace levels of multiple mycotoxins in a single run, even in complex matrices [18]. However, HPLC does require time-consuming sample preparation, and the cost of instruments and consumables can be high. Moreover, skilled personnel are needed to operate and maintain the equipment and interpret the results [19].

2.2 Enzyme-linked immunosorbent assay (ELISA)

The enzyme-linked immunosorbent assay (ELISA) is a rapid, cost-effective, and widely used immunoassay technique for the detection and quantification of mycotoxins in food and feed matrices. It is based on the specific antigen-antibody interaction, which enables the identification of even trace levels of target compounds [20]. ELISAs are commonly employed for routine mycotoxin detection, as commercial test kits are available for nearly all major mycotoxins of concern.

In the ELISA technique, a mycotoxin-specific antibody is immobilized on a microplate. When a sample containing the target mycotoxin is added, it competes with an enzyme-labeled mycotoxin (conjugate) for binding sites on the antibody. After washing away unbound substances, a substrate is added that reacts with the enzyme to produce a measurable signal, typically a color change. The intensity of this color is inversely proportional to the amount of mycotoxin in the sample [20]. ELISA kits are commercially available for a wide range of regulatory-relevant mycotoxins, including aflatoxins, ochratoxin A, deoxynivalenol (DON), fumonisins, zearalenone, and T-2 toxin. They are particularly valued in screening applications, especially when processing large numbers of samples or working in resource-limited settings [21].

ELISA offers numerous advantages, such as low limits of detection (LODs), minimal sample volume requirements, high throughput, rapid processing, excellent sensitivity, ease of use, and minimal need for sample preparation, making it more popular than many other analytical methods. Its suitability for fast, sensitive analysis with high throughput and low sample volume further enhances its appeal [21].

However, ELISA methods also have limitations. One of the main concerns is cross-reactivity, where antibodies may bind to structurally similar, nontarget compounds, potentially causing false positives or inaccurate quantification [22]. Additionally, ELISA is less specific and accurate than chromatographic methods, making confirmatory testing using HPLC or LC-MS/MS advisable when regulatory decisions are involved. Recent developments have improved ELISA performance using monoclonal antibodies, multiplexing capabilities, and immunoaffinity columns for sample clean-up prior to analysis [23].

2.3 Gas chromatography-Mass spectrometry (GC-MS)

Gas chromatography-mass spectrometry (GC-MS) is a powerful analytical technique that combines the high-resolution separation capability of gas chromatography (GC) with the specificity and sensitivity of mass spectrometry (MS). While GC-MS is not as commonly used as HPLC for mycotoxin detection due to the nonvolatile and thermally labile nature of many mycotoxins, it remains an important tool, particularly for those that can be derivatized into volatile forms [24].

GC-MS is especially effective for detecting trichothecenes (e.g., deoxynivalenol and T-2 toxin), zearalenone, and fumonisins after appropriate chemical derivatization [25]. Derivatization often involves the formation of trimethylsilyl (TMS) or oxime derivatives, which increase volatility and thermal stability, enabling these compounds to be analyzed by GC [26].

The technique typically involves sample extraction and clean-up, often using solid-phase extraction (SPE) or immunoaffinity columns; derivatization to convert polar, nonvolatile mycotoxins into volatile forms; gas chromatographic separation; and mass spectrometric detection, where target compounds are identified based on their mass-to-charge ratios (m/z) and fragmentation patterns [26].

Recent advancements in GC-MS include tandem mass spectrometry (GC-MS/MS) and high-resolution GC-MS, which enhance sensitivity and are increasingly used for trace-level detection of multiple contaminants in complex food matrices [27].

Despite its strengths, GC-MS is time-consuming, requires elaborate sample preparation, and demands specialized training and equipment. Moreover, many of the most regulated mycotoxins (such as aflatoxins and ochratoxin A) are better suited for LC-based methods, as they are inherently nonvolatile and degrade at high temperatures.

2.4 Limitations of conventional techniques

While conventional methods such as HPLC, ELISA, and GC-MS have been instrumental in advancing mycotoxin detection, they are not without limitations. These challenges can affect accuracy, efficiency, and practicality, especially in resource-limited or field settings.

2.4.1 Time-consuming and labor-intensive procedures

Many chromatographic methods, especially HPLC and GC-MS, require lengthy sample preparation, including extraction, purification (e.g., solid-phase or immunoaffinity column clean-up), and sometimes derivatization (for GC-MS). This significantly slows down the analysis and requires skilled personnel [20].

2.4.2 Requirement for expensive and specialized equipment

Instruments such as HPLC and GC-MS are costly to purchase and maintain. Additionally, they demand technical expertise to operate, which may limit their use in low-resource laboratories and developing countries [28].

2.4.3 Matrix interference and cross-reactivity

ELISA-based methods, although user-friendly and suitable for high-throughput screening, are vulnerable to matrix effects that can interfere with antibody binding. Cross-reactivity with structurally similar compounds may lead to false positives or overestimation of toxin levels [29].

2.4.4 Limited detection spectrum

Many traditional methods are target-specific, meaning they are designed to detect only a limited number of known mycotoxins. This is problematic given the frequent co-occurrence of multiple mycotoxins in food and feed samples. Multi-toxin detection requires separate assays or sophisticated methods such as LC-MS/MS [30].

2.4.5 Lack of on-site applicability

Most conventional techniques are not portable, restricting their use to central laboratories. This is a major drawback when rapid, on-site screening is necessary to prevent contaminated products from entering the food supply chain [31].

2.4.6 Sensitivity and specificity issues

Although HPLC and GC-MS offer high sensitivity, their performance can be affected by complex food matrices, leading to signal suppression or enhancement. In

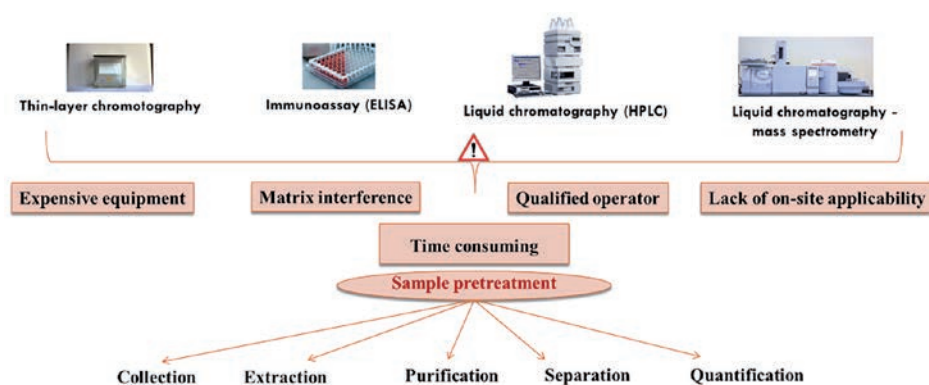


Figure 1.

Key limitations and challenges in conventional and advanced mycotoxin detection methods. This diagram illustrates the primary drawbacks associated with traditional and instrumental techniques for mycotoxin analysis, including the need for expensive equipment, susceptibility to matrix interference, the requirement for qualified operators, and limited on-site applicability. A significant bottleneck is identified as the time-consuming nature of sample pretreatment, encompassing steps from collection and extraction to purification, separation, and quantification.

contrast, ELISA methods, while convenient, typically lack the specificity and confirmatory power required for regulatory enforcement [29].

In summary, while traditional methods provide robust and reliable data, they are often limited by infrastructure requirements, operational complexity, and the need for skilled personnel, as mentioned in **Figure 1**. These constraints underscore the need for portable, rapid, and cost-effective alternatives that can complement or even replace laboratory-based techniques in real-world beverage monitoring scenarios.

3. Emerging technologies in mycotoxin detection

3.1 Biosensors: Principles and applications

Biosensors have emerged as a transformative technology in the field of mycotoxin detection, offering significant advantages in terms of sensitivity, speed, portability, and user-friendliness. At their core, biosensors consist of three main components: a biorecognition element (e.g., antibody, aptamer, or molecularly imprinted polymer), a transducer that converts the biochemical interaction into a measurable signal, and a signal processor that displays the result. In recent years, advances in material science, microfabrication, and surface chemistry have greatly enhanced the performance of biosensors for food safety applications [31].

In the context of beverages, biosensors are particularly well-suited due to their ability to detect low concentrations of mycotoxins in complex matrices like wine, juice, and coffee. Aptamer-based biosensors have gained popularity because of their high specificity, thermal stability, and the ability to be synthesized chemically at low cost. These single-stranded oligonucleotides can fold into unique three-dimensional structures that selectively bind to specific mycotoxins, such as aflatoxin B1 or OTA [15]. Immunosensors, which use antibodies as the biorecognition element, also remain widely used due to their high affinity and specificity. These sensors can be adapted for various formats, including colorimetric, electrochemical, piezoelectric, and fluorescence-based detection.

Electrochemical biosensors, in particular, have shown promise for real-time and on-site testing. They are capable of delivering results within minutes and often achieve detection limits in the low nanomolar or even picomolar range. This is highly valuable for beverage producers who require rapid screening methods to prevent contaminated products from entering the supply chain [32]. Furthermore, recent developments in nanomaterials, such as graphene and gold nanoparticles, have enhanced electron transfer processes and signal amplification, further boosting sensor performance [33].

The integration of biosensors with portable devices and smartphones is another emerging trend that facilitates user-friendly, decentralized testing. These systems can provide digital readouts, enable cloud-based data sharing, and even use machine learning algorithms to interpret complex signals. In the future, biosensor platforms may become a standard tool in quality control laboratories and even at the consumer level, thanks to their ease of use and reliability.

Despite their potential, biosensors still face challenges, including variability in sensor fabrication, limited shelf life of biorecognition elements, and the need for validation against established laboratory methods. Nevertheless, with continuous advancements and the push for sustainable, rapid, and cost-effective monitoring tools, biosensors are expected to play an increasingly central role in safeguarding beverage quality and consumer health.

3.2 Nanotechnology-enhanced detection platforms

Nanotechnology has increasingly become a cornerstone in advancing mycotoxin detection methods, offering unprecedented improvements in sensitivity, specificity, and miniaturization. The use of engineered nanomaterials, such as gold nanoparticles (AuNPs), quantum dots (QDs), carbon nanotubes (CNTs), and graphene derivatives, has enabled the creation of highly efficient sensing platforms tailored for beverage matrices. These materials exhibit unique optical, electrical, and catalytic properties that significantly enhance signal transduction and amplification [34].

In recent years, gold nanoparticles have gained traction due to their excellent biocompatibility, surface functionalization capabilities, and strong surface plasmon resonance. AuNPs are frequently employed in colorimetric assays for detecting aflatoxins and ochratoxin A, where the presence of the mycotoxin induces a visible color change, facilitating naked-eye detection or analysis with smartphone-based readers [32]. This feature makes AuNP-based assays particularly attractive for on-site or field applications, where laboratory infrastructure may be lacking.

Graphene and graphene oxide (GO) have also revolutionized the sensitivity of mycotoxin detection, particularly in electrochemical sensors. Their high electrical conductivity and large surface area provide an excellent platform for immobilizing recognition elements such as aptamers and antibodies. For example, graphene-enhanced field-effect transistor (FET) sensors have demonstrated detection limits in the picomolar range for OTA and AFs, even in complex matrices like coffee and wine [35]. Similarly, carbon nanotubes integrated with molecular recognition agents have shown potential for multiplexed toxin analysis, enabling the simultaneous detection of several mycotoxins in a single sample [36].

Quantum dots, with their size-tunable fluorescence and high photostability, are increasingly used in fluorescence-based sensors. Their capacity for multiplexing, coupled with high quantum yield, enables the development of ratiometric assays capable of detecting multiple toxins simultaneously. Recent studies have employed QD-labeled antibodies in sandwich immunoassays, achieving ultra-low detection limits with high reproducibility [37].

Moreover, magnetic nanoparticles (MNPs) are utilized for rapid sample preparation and pre-concentration, significantly enhancing assay sensitivity and reducing matrix interferences. When functionalized with mycotoxin-specific ligands, MNPs can selectively capture target analytes and facilitate their separation using external magnetic fields, thereby streamlining workflows in both field and laboratory settings [38].

Despite these advances, nanotechnology-based sensors face challenges including batch-to-batch variability, the potential cytotoxicity of some nanomaterials, and the need for standardization in manufacturing and analytical protocols. Nonetheless, the field is rapidly evolving, and with ongoing research and commercialization efforts, nanomaterial-based detection platforms are poised to become mainstream tools for safeguarding beverage safety. **Table 2** provides examples of nanomaterials applied in recent beverage-based mycotoxin detection platforms, highlighting their sensitivity and versatility.

3.3 Surface-enhanced Raman spectroscopy (SERS)

Surface-Enhanced Raman Spectroscopy (SERS) has emerged as a highly promising technique for the sensitive detection of mycotoxins in complex matrices such as beverages. Unlike conventional Raman spectroscopy, which often suffers from weak

Nanomaterial	Sensor type	Target mycotoxin	Matrix	LOD
Gold nanoparticles (AuNPs)	Colorimetric	Aflatoxins	Juice	0.5 ng/mL
Graphene oxide	Electrochemical	OTA	Wine	0.2 ng/mL
Quantum dots	Fluorescent	Patulin	Apple juice	1 ng/mL
Carbon nanotubes	Electrochemical	DON, ZEN	Beer	5 ng/mL
Magnetic nanoparticles	Pre-concentration	Multi-toxin	Grape juice	Enhances recovery ~90%

Table 2.
Recent applications of nanomaterials in beverage mycotoxin detection.

signal intensity, SERS enhances Raman scattering by several orders of magnitude through the use of metallic nanostructures, typically silver or gold nanoparticles, that amplify the electromagnetic field around the analyte [39].

This enhancement makes SERS exceptionally suitable for detecting trace levels of mycotoxins such as aflatoxins, ochratoxin A, and patulin, even without extensive sample pretreatment. In recent studies, researchers have functionalized metallic nanoparticles with specific antibodies or aptamers to improve the selectivity of the SERS platforms. These functionalized nanostructures can selectively bind to target mycotoxins, allowing for precise detection even in the presence of potentially interfering substances in beverages like wine, beer, or juice [32].

One of the key advantages of SERS is its rapid analysis time; results can often be obtained within minutes, making it well-suited for point-of-care or on-site testing applications. Moreover, SERS can be adapted to portable platforms, including hand-held Raman spectrometers coupled with smartphone interfaces, further enhancing its accessibility and practicality [40].

Several innovations have further improved the robustness and reproducibility of SERS for mycotoxin detection. For instance, the use of substrate engineering, such as the development of flexible or paper-based SERS-active surfaces, allows for more uniform signal enhancement and easier integration into disposable diagnostic formats [41]. Additionally, combining SERS with chemometric and machine learning tools has enabled more accurate interpretation of complex spectral data, reducing false positives and improving quantification accuracy.

Despite its potential, challenges remain in the commercialization of SERS-based mycotoxin detection. These include the stability of SERS substrates, variability in signal enhancement, and regulatory acceptance of the method for official control purposes. Nevertheless, as nanofabrication techniques and machine learning models improve, SERS is expected to become an increasingly vital tool in ensuring the safety and quality of beverages.

3.4 Portable and rapid diagnostic devices

The demand for rapid, user-friendly, and cost-effective mycotoxin detection tools has driven significant progress in the development of portable diagnostic devices. These systems are particularly advantageous for field applications and real-time quality control in beverage production lines, where timely decision-making is critical. Portable diagnostic devices often combine biosensing technology with microfluidics, smartphone integration, or miniaturized readers, allowing for efficient on-site testing without the need for extensive laboratory infrastructure [31].

Lateral flow immunoassays (LFIA) are among the most established portable tools for mycotoxin detection. These paper-based devices use capillary action to transport a liquid sample across test lines that contain immobilized antibodies. The presence of a target mycotoxin produces a visible line, indicating a positive result. LFIA have been commercialized for various mycotoxins, including aflatoxins, OTA, and patulin, and are commonly used for screening fruit juices, wines, and milk-based beverages [42].

Recent advancements have significantly improved the analytical performance of portable diagnostics. For example, the integration of nanomaterials such as gold nanoparticles and quantum dots has enhanced signal visibility and sensitivity. Smartphone-based readers equipped with optical sensors can now quantitatively analyze test line intensity, providing semiquantitative results that correlate well with laboratory standards (Jin et al., 2023). Additionally, paper-based microfluidic devices have enabled the creation of multiplexed formats, capable of detecting multiple toxins simultaneously within minutes.

Electrochemical devices have also gained momentum as portable solutions. These systems, often powered by screen-printed electrodes and handheld potentiostats, offer low detection limits and the ability to interface with mobile apps for data logging and cloud storage. In combination with AI algorithms, some platforms can now interpret raw sensor data, identify toxin profiles, and deliver actionable insights to producers in real time [43].

Furthermore, the concept of repurposing existing consumer devices, such as personal glucose meters, thermometers, or pressure sensors, has led to creative diagnostic tools for mycotoxins. These systems rely on enzymatic or electrochemical signal transduction and provide a low-cost alternative for widespread deployment, especially in developing regions.

Despite their growing popularity, portable diagnostic devices face challenges, including shelf life of biorecognition elements, environmental stability, and the need for rigorous validation. However, as sensor miniaturization, smart data processing, and material innovations continue, these platforms are set to play a pivotal role in the proactive surveillance of mycotoxins in beverages.

4. Advanced analytical techniques

Mycotoxin detection in diverse food matrices often demands highly sensitive and selective methods due to the complex composition of foods and the typically low concentrations of contaminants. The challenge is especially pronounced in beverage matrices, which can range from water-like clarity to viscous dairy substitutes. Unlike solid foods, beverages (e.g., milk, juices, beer, and wine) present relatively homogeneous matrices, but their high water content and presence of sugars, ethanol, proteins, or lipids can still interfere with analyses. Advanced analytical techniques have been developed to isolate and identify mycotoxins in beverages with greater accuracy. These techniques build upon traditional methods by enhancing sensitivity, specificity, and throughput, ensuring that even trace levels of toxins are detected to protect consumer health. This section discusses three key advanced methods: liquid chromatography-tandem mass spectrometry (LC-MS/MS), immunoaffinity columns with multiplex assays, and molecularly imprinted polymers (MIPs), highlighting their principles and specific applications for detecting mycotoxins in beverages. To contextualize the evolution of mycotoxin detection technologies, **Table 3** compares key performance attributes of conventional and emerging methods.

Method	LOD range	Time to result	Multiplexing	On-site use	Remarks
LC-MS/MS	<1 ng/L	3–6 hours	Yes	No	Gold standard; high sensitivity and specificity
ELISA	~1–10 ng/mL	1–2 hours	Limited	Yes (portable kits)	Fast and cost-effective; risk of cross-reactivity
GC-MS	~10 ng/L	4–8 hours	Limited	No	Suited for volatile/derivatized toxins
Biosensors (Electrochemical)	~0.1–10 ng/L	<30 minutes	Yes (platform-dependent)	Yes	Real-time; can be smartphone-integrated
SERS	<1 ng/L	<10 minutes	Yes	Yes (portable)	Ultrasensitive; requires nanostructured substrate
Lateral flow assay	~10–50 ng/mL	5–15 minutes	Limited	Yes	Ideal for screening; semiquantitative

Table 3.
Comparative performance of traditional vs. emerging mycotoxin detection methods.

4.1 Liquid chromatography-tandem mass spectrometry (LC-MS/MS)

Liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) is widely regarded as the gold standard for mycotoxin analysis, offering unparalleled sensitivity and the ability to simultaneously quantify multiple toxins in a single run [44]. In LC-MS/MS, a liquid chromatograph first separates mycotoxins from other matrix components, and then a tandem mass spectrometer detects and fragments the target molecules, providing structural identification and quantification based on unique mass-to-charge signatures. This technique has high selectivity and sensitivity, making it ideal for complex beverage samples where regulatory limits are often in the low parts-per-billion (ppb) range or lower.

Recent studies have leveraged LC-MS/MS to perform multi-mycotoxin screening in beverages. For example, Pavlenko et al. [45] developed a UHPLC-MS/MS method to analyze 22 mycotoxins in plant-based milk substitutes [45]. Their survey of 72 commercial drinks found that 64% contained at least one mycotoxin (with up to 16 co-occurring toxins in a single sample). Such findings underscore the importance of multi-residue methods like LC-MS/MS in beverages, where co-contamination is common. Likewise, Rausch et al. [46] validated an LC-MS/MS method for 41 free and modified mycotoxins in beer, achieving limits of quantification as low as 0.04 µg/L (40 ng/L) for some analytes [46]. This high sensitivity enabled the detection of mycotoxin contaminants in ~76% of beer samples in their study, including masked mycotoxins (metabolites like deoxynivalenol-3-glucoside) that might evade simpler assays. These examples illustrate LC-MS/MS's capability for broad-spectrum mycotoxin monitoring in beverages.

One major advantage of LC-MS/MS is its robustness across different beverage types. With appropriate sample preparation (e.g., dilution, solvent extraction, and sometimes concentration), laboratories have successfully applied LC-MS/MS to a wide range of drinks, from clear apple and grape juices to alcoholic beverages like beer and wine, and

even opaque liquids like milk or plant-based smoothies. Typically, beverages require less intensive clean-up than solid foods, but matrix effects (ion suppression/enhancement) can still occur due to sugars, acids, or fermentation byproducts. To address this, methods often employ matrix-matched calibration or internal standards (including isotopically labeled mycotoxins) to correct for any signal suppression. For instance, Rausch et al. [46] used standard addition in beer samples to compensate for matrix effects ranging from 67% to +319%. Such strategies ensure quantitative accuracy when measuring sub-ppb toxin levels in complex beverage matrices.

LC-MS/MS has also become central to regulatory compliance testing for mycotoxins. Its sensitivity and confirmation capabilities meet strict criteria set by authorities. Many nations have established maximum levels for mycotoxins in beverages (e.g., aflatoxin M₁ in milk at 0.05 µg/kg in the EU, patulin in apple juice at 50 µg/L, and ochratoxin A in wine at 2 µg/L), and LC-MS/MS methods are routinely used to verify that products remain below these limits. Because tandem MS can confirm the identity of toxins *via* their fragmentation patterns, the technique reduces false positives and is admissible as a confirmatory method under regulations [47]. In practice, this means an initial screening (perhaps by a rapid test) can be followed by LC-MS/MS to definitively quantify any mycotoxin found. **Table 4** below showcases a few applications of LC-MS/MS in beverage testing, demonstrating its versatility and performance.

In conclusion, LC-MS/MS remains the gold standard for mycotoxin analysis and continues to evolve in terms of speed, sensitivity, and automation. Its combination with chemometric tools and AI-based data analysis may further improve its applicability in the food and beverage industry.

4.2 Immunoaffinity columns and multiplex assays

Immunoaffinity columns (IACs) are a powerful sample preparation tool that uses antibodies immobilized on a solid matrix to selectively capture mycotoxins from complex samples. Traditionally, IACs have been used for single-analyte clean-up; for example, columns specific to aflatoxin M₁ in milk or ochratoxin A in wine allow these toxins to be concentrated and separated from the bulk matrix, greatly improving detection limits. Recent advances, however, have led to multi-analyte immunoaffinity columns capable of binding several mycotoxins at once, as well as the development of multiplex immunoassays that can detect multiple toxins in parallel.

Matrix	Target mycotoxins	Method performance
Plant-based “milk” (almond, oat, etc.)	Mycotoxins (AFs, DON, ZEA, ENNs, etc.)	UHPLC-MS/MS, co-occurrence of up to 16 toxins in samples; LODs generally <1 µg/L.
Beer (various styles)	Mycotoxins (including modified forms)	LC-MS/MS, LOQs 0.04–75 µg/L; 76% samples positive for ≥1 toxin.
Apple juice and grape juice	Aflatoxins, OTA, Patulin (multi-target)	HPLC-MS/MS, recoveries ~80–100%; used for routine EU compliance monitoring.
Wine (red, white)	Ochratoxin A, AFs, others	LC-MS/MS with minimal clean-up (dilute-and-shoot for degassed wine); LODs ~0.01–0.1 µg/L.

Abbreviations: AFs = aflatoxins; DON = deoxynivalenol; ZEA = zearalenone; ENNs = enniatins; OTA = ochratoxin A; LOD = limit of detection; LOQ = limit of quantification.

Table 4.
Examples of LC-MS/MS applications for mycotoxin detection in beverages.

One example is the VICAM “6-in-1” immunoaffinity column, which contains a mixture of antibodies to capture aflatoxins (B_1 , B_2 , G_1 , G_2), ochratoxin A, deoxynivalenol (DON), zearalenone (ZEN), and fumonisins from a single sample loading [48]. Such a column can be applied to a beverage like beer, which might be susceptible to multiple *Fusarium* toxins (DON, ZEN, fumonisins) as well as storage molds (aflatoxins, OTA). Andronaco et al. [48] demonstrated that using a multi-mycotoxin IAC in craft beer analysis enhanced recovery and purity of extracts, thereby improving the accuracy of subsequent HPLC-MS measurements. By binding the targeted toxins and allowing other matrix components (proteins, sugars, etc.) to be washed away, these columns reduce matrix interferences and concentration steps in one go. This not only lowers detection limits but also saves labor and time, since a single IAC replaces multiple separate clean-up steps. For routine quality control in breweries or juice production, multi-analyte IACs enable efficient screening of multiple contaminants with minimal sample handling. Furthermore, IACs can be used in tandem with automation: for instance, in fully automated LC systems, beer or wine samples can be loaded onto IAC cartridges online, purified, and injected into the LC-MS without manual intervention. The result is a more scalable and high-throughput analysis pipeline suitable for industry needs.

In addition to sample prep columns, immuno-based techniques have evolved to simultaneously detect multiple mycotoxins in one assay. Traditional enzyme-linked immunosorbent assay (ELISA) formats are typically single-analyte, but newer approaches use antibody arrays or versatile labels to achieve multiplexing. One strategy is the microarray-based immunoassay, where different capture antibodies are spotted at distinct locations on a small device. Sooksimuang et al. [49] developed a microarray lateral flow immunoassay (μ LFA) that can detect five regulated mycotoxins at once (aflatoxin B_1 , T-2 toxin, ZEN, DON, and fumonisin B_1) [49]. In this system, antibody spots specific to each toxin are arrayed on a strip; when the sample (e.g., an extract of rice or potentially a beer sample) flows through, each toxin in the sample binds to its corresponding spot. A portable reader then quantifies signals from each spot, allowing simultaneous quantification of all five toxins on-site. Notably, the detection limits achieved (0.56–1.89 $\mu\text{g/kg}$ for the five mycotoxins) were well below regulatory limits, highlighting that immunoassays can be both sensitive and multiplexed. While that particular study was in a rice matrix, the principle applies to beverages after a suitable extraction or dilution—for instance, a similar multiplex LFA could be used on a grain-based beverage or a dilute beer sample.

Another multiplex immunoassay approach used lateral flow strips with multiple test lines, where each line is coated with antibodies for a different toxin. Such multiplex LFDs (lateral flow devices) have been reported for combinations like aflatoxin B_1 + fumonisin or DON + ZEN [50]. The challenge in designing these is avoiding cross-reactivity and ensuring each test line develops distinctly if its target is present. By carefully selecting highly specific antibodies (or antibody fragments, nanobodies) and even using colored or fluorescent nanoparticle labels that emit at different wavelengths for different toxins, researchers have achieved one-step tests that screen for several mycotoxins simultaneously. For example, a multiplex fluorescent immunostrip might use red-emitting beads for aflatoxin and green-emitting beads for OTA so that a single strip, read under a fluorescence scanner, can independently quantify both toxins if present.

Beyond immunochromatography, multiplex ELISA kits and bead-based assays have been developed. In a multiplex ELISA, wells can be coated with mixtures of antigens or antibodies, or different beads (each with a unique signature, like color or

size) can be coated with different toxin conjugates. A flow cytometric microsphere assay has been reported where microspheres of distinct fluorescence serve as carriers for different mycotoxin protein conjugates, enabling detection of multiple mycotoxin antibodies in one run [51]. These advanced immunoassays often rely on instruments (plate readers, cytometers), but they significantly increase throughput—a single assay can replace multiple separate tests, which is valuable for monitoring beverages that might contain various contaminants (e.g., a cornmeal-based beverage could have aflatoxins, fumonisins, and zearalenone concurrently).

Crucially, immuno-based techniques generally offer rapid and field-deployable detection. Unlike LC-MS/MS, which requires lab instrumentation, immunoassays can be used in on-site screening (see Section 6.3) by plant managers or inspectors. For instance, a dairy processor might use a lateral flow strip test for aflatoxin M₁ on raw milk, and a brewery could use a quick kit for DON in beer grain extract. New multiplex kits mean that comprehensive screening is becoming possible even outside the lab; a single device could check a cider for multiple mycotoxins before fermentation, for example. However, multiplex immunoassays require careful validation: antibodies must maintain high specificity to avoid cross-reactivity, and the assay's sensitivity for each toxin must meet regulatory thresholds. So far, results are promising; Sooksimuang et al. showed accuracies between 77% and 127% recovery for all five toxins in their multiplex test [49], indicating reliable quantitation.

In summary, immunoaffinity-based technologies enhance mycotoxin detection in beverages in two complementary ways: (a) improving sample clean-up and concentration through multi-analyte IACs and (b) enabling multiplexed, rapid detection through advanced immunoassay platforms. These tools increase the throughput and scope of testing, making it feasible to routinely monitor a wide spectrum of mycotoxins even in resource-limited or on-site scenarios. When combined with instrumental analysis (e.g., using IAC clean-up before LC-MS/MS or using immunoassay as a prescreen), they form an integral part of advanced analytical strategies for ensuring beverage safety. **Table 5** outlines notable examples of multiplex detection systems, emphasizing their potential for high-throughput mycotoxin analysis in beverages.

4.3 Molecularly imprinted polymers (MIPs) for selective detection

Molecularly imprinted polymers (MIPs) represent an emerging class of synthetic recognition elements that can selectively bind mycotoxins, analogous to how antibodies bind their antigens. MIPs are crafted by polymerizing functional monomers in

Platform type	Target toxins	No. of analytes	Detection format	Time
Microarray Lateral Flow (μLFA)	AFB ₁ , ZEN, DON, T-2, FB ₁	5	Colorimetric (multi-spot)	17 min
Multiplex ELISA	AFs, OTA, ZEN	3–6	Enzymatic	~2 hrs
SPR-based biosensor	OTA, AFB ₁	2	Optical resonance	~10 min
Electrochemical aptasensor array	AFB ₁ , DON, ZEA	3	Electrochemical	<20 min
Fluorescent immunostrip (dual-color QDs)	OTA, AFB ₁	2	Fluorescence	<10 min

Table 5.
Emerging multiplex detection platforms for mycotoxins in beverages.

the presence of a target analyte (the “template” molecule). The template induces the formation of complementary binding sites in the polymer matrix; after the template is removed, these cavities remain, with shape and chemical functionality tailored to rebind the target molecule with high specificity [52]. In essence, MIPs are plastic antibodies, robust, reusable, and stable even under harsh conditions of pH, temperature, or organic solvents, which might denature real antibodies. This makes MIPs particularly attractive for mycotoxin detection in various foods and beverages, where they can be used either as solid-phase extraction sorbents or as recognition elements in sensors.

One key application of MIPs in beverage analysis is their use in selective solid-phase extraction (SPE). Just as immunoaffinity columns use antibodies to capture toxins, MIP-SPE cartridges use imprinted polymer particles that bind the mycotoxin of interest. For example, researchers have developed MIPs specific for ochratoxin A (OTA) and applied them to clean up wine samples prior to analysis [53]. Unlike biological receptors, these polymer sorbents can be washed with stronger solvents to remove matrix impurities and then eluted with a solvent to release the concentrated toxin. This improves detection limits and reduces interference. A study introduced a novel SPE column using an MIP to extract aflatoxins (B₁, B₂, G₁, G₂) from cereals [54], and similar approaches have been extended to beverages like beer, red wine, and grape juice [55]. The imprinted polymer in these cases was engineered to have high affinity for the planar aflatoxin molecules, allowing it to discriminate those toxins from other compounds in alcoholic beverages. By employing MIP-SPE, an efficient recovery of OTA from beer and wine with minimal matrix effect was reported, demonstrating that MIPs can parallel the performance of immunoaffinity clean-up for certain analytes while being more stable and cost-effective (polymers can be mass-produced and stored long-term) [56].

In addition to extraction, MIPs have spurred the development of MIP-based sensors for mycotoxins. These sensors integrate the polymer as the recognition layer on a transducer, such as an electrode in an electrochemical sensor or a quartz crystal in a piezoelectric sensor. When the target mycotoxin binds into the MIP's cavities on the sensor surface, it causes a measurable change, for instance, an electrochemical current change or a frequency shift. A variety of transduction mechanisms have been explored: voltametric, capacitive, fluorescent, and even surface-enhanced Raman scattering signals can be modulated by binding events [54]. The advantage of MIPs here is that they enable direct, reagentless detection, unlike immunoassays that often require labeled secondary antibodies or enzyme substrates. An MIP sensor can often be used repeatedly by simply washing off the analyte after measurement.

A notable example is a molecularly imprinted electrochemical sensor for OTA in apple juice reported in 2023. Kaya et al. [57] constructed a sensor where an OTA-imprinted polymer film was deposited on a carbon fiber electrode enhanced with MnCO₃ nanostructures [57]. The MIP provided selective binding sites for OTA, and the nanostructured electrode amplified the electrochemical signal. This sensor achieved a linear detection range of 1×10^{-11} to 1×10^{-9} M and an impressive detection limit of 2×10^{-12} M (approximately 0.8 ng/L). In practical terms, this allowed detection of OTA well below 1 ng/L, and tests in spiked apple juice showed ~100% recovery of OTA with a rapid 5 min analysis time. Such sensitivity rivals that of large-scale instruments, illustrating the potential of MIP-based sensors as portable, highly sensitive detectors for mycotoxins. Moreover, the stability of the MIP meant the sensor could be reused multiple times with minimal loss of performance, and it remained stable in the acidic apple juice matrix where biological receptors might degrade.

Beyond electrochemical sensors, researchers have developed MIP-based optical sensors, which incorporate a signaling element whose emission changes upon binding the toxin. A fluorescent MIP sensor for aflatoxin B₁ using carbon quantum dots, achieving a distinct ratiometric fluorescence change when the toxin was captured [58]. Similarly, MIPs have been coupled with surface plasmon resonance (SPR) chips for real-time detection: an SPR sensor can be coated with an OTA-imprinted polymer, and when OTA in a wine sample binds, the refractive index change at the surface produces an SPR signal. Although SPR is very sensitive to large molecules, the detection of small molecules like mycotoxins *via* SPR-MIPs may require nanomaterial enhancements or competitive formats. Nonetheless, these approaches highlight how MIPs offer flexibility; they can be tailored to various detection platforms, many of which are amenable to miniaturization for on-site use.

While highly specific in theory, early MIPs sometimes suffered from incomplete template removal or nonspecific binding to molecules similar to the target. Recent progress has addressed these issues: advanced polymerization techniques (e.g., sol-gel imprinting, core-shell MIPs) produce more homogeneous binding sites, and control experiments with non-imprinted polymers (NIPs) are used to ensure that observed sensor signals are truly due to specific binding. For example, Li et al. [50] note that a drawback of MIPs can be nonspecific adsorption, especially with small molecules, but careful use of NIP controls and optimization of polymer composition can enhance MIP selectivity and affinity to the level required for analytical use. Indeed, many MIP sensors now report selectivity comparable to antibody-based methods, with the benefit of being tolerant to conditions that would denature antibodies [58].

In beverage analysis, MIPs are being explored for field deployment. One can envision an inexpensive MIP-coated test strip or a USB-stick-sized MIP sensor that a winery could use to check OTA in wine barrels or a coffee producer could use to test green coffee extract for ochratoxin. The stability of MIPs (no cold chain needed) and their reusability align well with such uses. Already, some commercial SPE products incorporate MIP technology for mycotoxins, and prototypes of MIP sensors are being evaluated for online monitoring in brewing processes (e.g., real-time DON sensing during beer filtration).

In summary, molecularly imprinted polymers provide selective, durable, and cost-effective alternatives to biologically based detection elements. They also overcome some of the drawbacks of biological receptors, such as sensitivity to degradation and storage requirements. In the context of beverages, MIPs can be used to selectively extract mycotoxins from drinks (improving downstream detection by LC-MS or HPLC) or to directly sense toxins *via* smart sensor devices. Their continued development is a key aspect of advanced analytical techniques, promising to expand the toolkit for safeguarding beverages against mycotoxin contamination.

A comparative overview of major mycotoxin detection technologies is illustrated in **Figure 2**, highlighting key trade-offs among traditional and emerging methods in terms of analytical performance, speed, portability, and suitability for field use.

This radar chart evaluates six key technologies used in mycotoxin detection: LC-MS/MS, GC-MS, ELISA, biosensors, Lateral Flow Immunoassays (LFIAs), and Surface-Enhanced Raman Spectroscopy (SERS). Performance was scored on six criteria: sensitivity, time to result, multiplexing capability, portability, cost-effectiveness, and on-site applicability. LC-MS/MS and GC-MS exhibit high analytical sensitivity and multiplexing ability but are limited by cost and portability. In contrast, biosensors and SERS offer more balanced performance with strong potential for field deployment and real-time diagnostics, whereas LFIAs are optimized for speed and screening in low-resource settings.

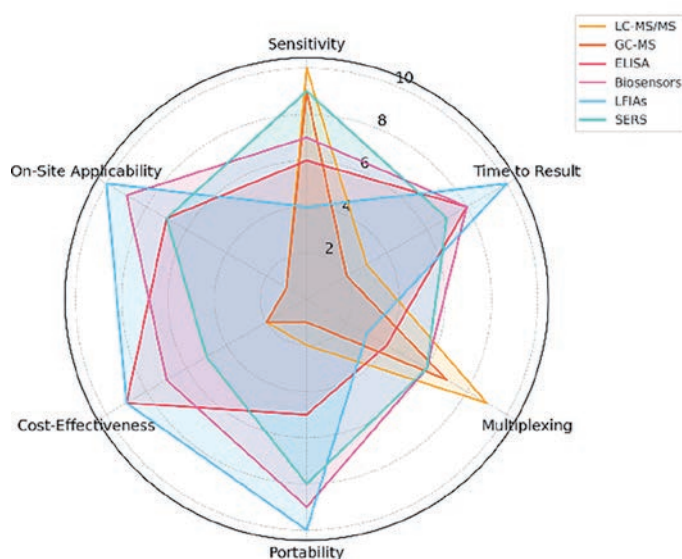


Figure 2.
 Comparative performance of mycotoxin detection technologies based on analytical and operational metrics.

5. Integration of artificial intelligence and machine learning

5.1 Data-driven approaches for mycotoxin prediction

Artificial intelligence (AI) and machine learning (ML) have emerged as transformative tools in food safety, especially in the context of predicting and managing mycotoxin contamination. These technologies allow researchers and industry professionals to analyze vast and complex datasets related to weather patterns, agricultural practices, storage conditions, and contamination history to forecast the risk of mycotoxin presence in beverage supply chains [59].

Predictive models built using supervised learning algorithms, such as support vector machines, random forests, and neural networks, have been developed to estimate mycotoxin levels in raw materials before they reach processing facilities. For instance, models trained on environmental and crop yield data have been able to predict aflatoxin outbreaks in maize with high accuracy [60]. Such systems can help beverage manufacturers make informed sourcing decisions and implement proactive quality control measures.

In the laboratory setting, AI-driven data interpretation enhances the analysis of chromatographic and spectrometric outputs. Automated pattern recognition algorithms are used to identify spectral features associated with specific mycotoxins, even in complex matrices like juice or wine. This reduces the likelihood of human error and accelerates decision-making [61].

Additionally, unsupervised learning techniques like clustering and principal component analysis (PCA) assist in the discovery of hidden trends in multi-toxin datasets, which can inform both regulatory strategy and risk assessment. The integration of AI not only improves the precision of detection technologies but also supports a broader shift toward smart manufacturing in the beverage sector.

5.2 Machine learning in analytical method optimization

Machine learning (ML) plays a critical role in optimizing analytical procedures for mycotoxin detection, from sample preparation to signal processing. Techniques such as genetic algorithms and deep learning have been used to enhance method development by selecting the most relevant parameters for sensor calibration, extraction efficiency, or matrix effect correction [62].

For example, ML can fine-tune the composition of molecularly imprinted polymers (MIPs) by modeling how different functional monomers interact with a target toxin, thereby reducing experimental trial and error [54]. In biosensor design, reinforcement learning frameworks can help identify optimal electrode configurations and material choices to achieve maximal signal-to-noise ratios.

Spectral deconvolution and noise filtering in optical or electrochemical assays also benefit from ML algorithms that improve signal clarity and interpretation. These enhancements are particularly relevant in low-resource settings, where rapid and accurate diagnostics are essential but laboratory capacity is limited.

Furthermore, ML is being embedded into commercial software that accompanies portable diagnostic devices, enabling real-time decision support and remote data monitoring. As such, machine learning is not just a research tool but an enabler of practical, scalable solutions in the beverage industry.

6. Challenges and future perspectives

As advanced analytical methods for mycotoxin detection in beverages continue to evolve, several overarching challenges remain. Ensuring sensitivity and specificity in new methods, achieving cost-effective and scalable deployment, enabling on-site and real-time monitoring, and fostering global collaboration for standardization are critical for translating technical advances into practical food safety solutions. In this section, we discuss these challenges and future perspectives, emphasizing how emerging technologies must not only be scientifically sound but also feasible and reliable in real-world beverage industry settings. To effectively translate technical advances into practical food safety solutions, several critical challenges must be addressed, as depicted in **Figure 3**.

6.1 Sensitivity and specificity of emerging methods

A fundamental challenge for any mycotoxin detection method is achieving the required sensitivity (limit of detection) and specificity (ability to distinguish the target toxin from other substances). Regulatory limits for mycotoxins in beverages are very low (often in the microgram-per-kilogram or liter range), so methods must detect trace amounts with high confidence. Traditional chromatography-based methods (HPLC, LC-MS) generally have excellent sensitivity and specificity [50], but many emerging methods, such as certain biosensors or rapid assays, still struggle to reach comparable performance.

One issue is that newer biosensors or portable assays sometimes exhibit insufficient sensitivity relative to laboratory techniques. For instance, simple immunochromatographic strips may have visual detection limits in the tens of $\mu\text{g/L}$, which could be above the strict maximum levels for some toxins [63]. Consider an on-site optical biosensor for patulin in apple juice: if its detection limit is $20 \mu\text{g/L}$, it would

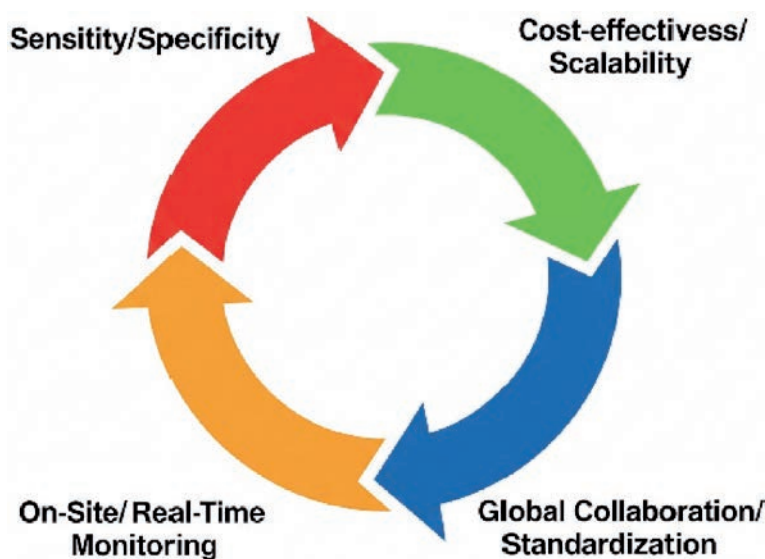


Figure 3.
 Key challenges in mycotoxin detection and future perspectives. This figure illustrates the interconnected primary challenges in developing and implementing advanced mycotoxin detection methods, including achieving optimal sensitivity and specificity, ensuring cost-effectiveness and scalability, enabling on-site and real-time monitoring, and fostering global collaboration for standardization.

barely meet the EU limit of 50 µg/L and might miss lower-level contamination that a laboratory method could catch. Therefore, a future focus is on signal amplification strategies to boost sensitivity in field-deployable assays. Approaches like enzyme or nanoparticle amplification, use of ultrasensitive transducers (e.g., surface-enhanced Raman tags or electrochemiluminescent readouts), and ratiometric sensing (using dual-signal outputs to self-calibrate) are being explored [63]. Ratiometric sensors, for example, provide two signals (perhaps two fluorescence colors or dual electrochemical peaks) where the ratio is indicative of toxin concentration; this can correct for environmental noise and significantly improve accuracy and lower the detection limits. Indeed, Li et al. [50] highlight that single-signal sensors can suffer from poor reproducibility due to instrument or environmental variations, and dual-signal designs can greatly enhance both sensitivity and reliability.

Specificity is another concern. Cross-reactivity can plague immunoassays if antibodies bind structurally similar compounds, and nonspecific adsorption can affect MIP sensors, as mentioned. For emerging multiplex assays, specificity is even more critical—each analyte must be distinguishable without interference. Advances in antibody engineering (e.g., producing monoclonal antibodies with ultra-high affinity and specificity or using recombinant fragments) and in MIP synthesis (as discussed in Section 4.3) aim to maximize selective recognition. Additionally, alternative biorecognition elements like aptamers (synthetic DNA/RNA binders) are being investigated; these can have very high specificity and can be engineered against toxins that are poor immunogens. Aptamer-based sensors for mycotoxins have shown promise, sometimes achieving sensitivities in the low ppt range with excellent specificity, for example, for aflatoxin B₁ or OTA [54]. However, aptamers can be sensitive to matrix effects, and integrating them into user-friendly devices is an ongoing area of research.

Another aspect of specificity is distinguishing multiple co-occurring toxins. As methods move toward multiplex detection, there is a risk of signal overlap or misidentification. Ensuring specificity in multiplex format might involve using unique signal tags for each toxin (as in multiplex LFA, where different colored nanoparticles correspond to different toxins) [64] or computational analysis of sensor data (for instance, deconvoluting overlapping electrochemical peaks). The data processing algorithms accompanying advanced sensors are thus part of the solution; machine learning is being applied to pattern recognition in sensor arrays to improve specificity and even detect “unknown” mycotoxins by their signal patterns [44]. In the future, intelligent sensors might self-validate their specificity by cross-checking multiple sensing channels.

Finally, any new method's sensitivity and specificity must be validated against established references. This leads to the practice of method validation and inter-laboratory comparisons. A challenge is that not all emerging methods have well-defined protocols for validation; unlike LC-MS, which has standardized performance criteria (linearity, recovery, precision, etc.), a novel biosensor might require custom validation approaches. To ensure reliability, researchers are increasingly performing side-by-side comparisons of new assays with LC-MS/MS on real beverage samples [65]. Such studies provide confidence that the new method can match the “gold standard” in detecting low-level contamination. In summary, while significant progress has been made, ensuring that emerging mycotoxin detection methods are as sensitive and specific as needed remains an important focus. Continued refinement of recognition elements, signal amplification, and validation will drive these methods to maturity.

6.2 Cost-effectiveness and scalability

Advanced mycotoxin detection technologies face significant challenges related to cost and scalability, which hinder their widespread adoption in industry. While highly effective in research settings, many methods are either too expensive or impractical for large-scale implementation. Costs stem from both the initial investment in equipment and the ongoing expenses for consumables, reagents, and skilled labor. Techniques like LC-MS/MS, though precise, are costly and resource-intensive, whereas newer options such as immunoassays and sensors offer lower per-test costs but often involve specialized materials like nanomaterials that are difficult and expensive to mass-produce [50].

To overcome these barriers, future advancements must focus on developing cost-effective manufacturing strategies, such as roll-to-roll printing, scalable nanoparticle synthesis, and low-cost 3D printing, that support mass production. Scalability also depends on throughput. Beverage companies require rapid, high-volume testing capabilities that traditional methods may not provide. Emerging solutions such as multiplex assays, automated analyzers, and lab-on-a-chip devices offer faster processing and parallel testing, aligning better with industrial needs.

The cost of consumables and environmental concerns also affect method viability. Traditional assays consume large volumes of solvents, while newer sensor-based approaches use fewer resources. However, many rapid tests are single-use, making a low cost per test essential. Reusable devices, like regenerable electronic tongues or molecularly imprinted polymer (MIP) sensors, could provide more sustainable alternatives by reducing long-term costs [57].

Integrating multiple tests into a single system also enhances cost-effectiveness. Devices that screen for various hazards simultaneously, including mycotoxins and

pathogens, add greater value and operational efficiency. Some spectral sensors already perform such multipurpose screening, serving as cost-effective initial filters [66].

Equitable access to these technologies globally is critical. High-end instruments are often inaccessible to small producers or developing countries. Therefore, robust, low-cost methods, such as paper-based assays or smartphone-interfaced readers, are needed to ensure global food safety. Open-source platforms and local fabrication of detectors may offer practical solutions.

6.3 On-site testing and real-time monitoring

A major advancement in food safety is the shift from centralized laboratories to on-site testing and real-time monitoring, especially for detecting mycotoxins in beverages. On-site testing enables producers to test samples directly at the facility or in the field, avoiding delays associated with external lab analysis. Real-time monitoring adds another layer, allowing for continuous or high-frequency detection during storage or production. These approaches enhance responsiveness by enabling the immediate identification and isolation of contaminated products, provided the detection methods used are fast, portable, and accurate [67].

Traditional tools like lateral flow strips and portable ELISA kits have long enabled simple, rapid testing. Now, more advanced technologies, including handheld biosensors and smartphone-based devices, are expanding on-site capabilities. Smartphones can act as portable readers, detecting changes in color or fluorescence on test strips. Additionally, microfluidic lab-on-a-chip devices, compact enough to fit in a pocket, can process beverage samples through integrated reaction channels, delivering results *via* a connected phone or reader. These devices often include wireless capabilities, facilitating remote monitoring [68].

In continuous beverage production, real-time sensors are especially useful. For example, a sensor inside a grape juice tank could detect patulin accumulation before packaging. Similarly, during beer brewing, sensors might monitor for mold markers in storage or fermentation tanks. Technologies like fiber optic biosensors or electrochemical sensors with immobilized receptors (antibodies, aptamers, or MIPs) are under development for this purpose. While continuous sensing remains challenging due to potential fouling or drift, semi-continuous systems, sampling at intervals, are more feasible for now.

Recent advancements include portable multiplex readers, such as a 17-minute assay that enables simultaneous detection of multiple mycotoxins with minimal sample preparation. Such technologies make sophisticated field-based testing a practical reality. In beverages, these methods typically require only simple filtration or dilution prior to testing [49].

Looking ahead, innovations like smart packaging and inline pipeline sensors could allow for continuous monitoring of contaminants during product shelf life or processing. While still conceptual, these systems align with the broader industry as automated quality control [19].

However, widespread adoption depends on regulatory acceptance, as current on-site methods are mostly used for preliminary screening. To fully realize their potential, portable systems must prove reliable enough to inform official safety decisions. With continued progress, real-time mycotoxin detection may become standard practice in beverage production worldwide.

6.4 Global collaboration for standardization and implementation

Mycotoxin contamination is a global issue affecting international food and beverage supply chains. Ensuring safety requires more than advanced analytical methods; it demands harmonized standards, shared data, and international collaboration. A key challenge lies in the inconsistency of regulations and testing capabilities across countries. Some nations lack legal limits for specific mycotoxins, particularly in newer beverages like plant-based milks, and not all regions have access to high-end detection technologies. As such, global standardization and collaborative implementation strategies are crucial moving forward [7].

International organizations such as Association of Official Analytical Collaboration (AOAC) International, International Organization for Standardization (ISO), and European Committee for Standardization (CEN) are working to establish validated standard methods for mycotoxin analysis. Emerging techniques, including LC-MS/MS and rapid sensors, must undergo multi-laboratory validation studies to gain global acceptance. Collaborative testing, where multiple labs analyze identical samples, helps ensure consistency. The development of certified reference materials (CRMs), such as milk powder with known aflatoxin M₁ levels, also enhances cross-border comparability and calibration reliability [69].

Global data sharing further supports understanding of contamination trends. Surveys conducted in countries like Latvia and Spain offer insight into mycotoxin prevalence in beverages. Networks like INFOSAN and the MycoKey consortium facilitate the exchange of findings and best practices. These shared data sets enable joint risk assessments and better-informed international standards. Harmonization of regulatory limits is particularly important to avoid trade disputes; what is acceptable in one country might be rejected in another. Over time, collections like Codex Alimentarius help promote uniform safety thresholds, even for currently unregulated compounds such as enniatins [7].

Addressing capacity gaps is another essential component. Many developing countries struggle to access or maintain sophisticated equipment. Technology transfer, training, and aid programs can bridge these gaps, enabling broader adoption of rapid tests or portable kits. The future may also include cloud-based analysis tools, where remote users upload data for real-time interpretation *via* AI, increasing equity in food safety management [70].

Emerging tools like blockchain offer innovative means for traceability and transparency. Embedding test results into an immutable digital ledger can validate safety at each supply chain stage, reducing redundant testing and supporting smoother trade.

7. Conclusion

7.1 Summary of key advancements

This chapter reviewed the progression of mycotoxin detection technologies, emphasizing how significant advancements have reshaped the landscape of mycotoxin detection in beverages. While traditional techniques such as LC-MS/MS, HPLC, ELISA, and GC-MS remain foundational for confirmatory analysis due to their accuracy and sensitivity, emerging technologies have introduced transformative possibilities. These include biosensors, nanotechnology-based platforms, molecularly imprinted polymers (MIPs), and advanced spectroscopic techniques

like Surface-Enhanced Raman Spectroscopy (SERS). The integration of Artificial Intelligence (AI) and machine learning (ML) into analytical workflows further enhances the speed, accuracy, and predictive capacity of these tools, enabling real-time, in situ testing across diverse beverage matrices.

7.2 The role of innovation in ensuring beverage safety

Innovation has moved mycotoxin detection beyond centralized laboratories, offering robust tools for on-site, rapid, and multiplexed analysis. Smart diagnostic systems, leveraging aptamers, nanomaterials, portable devices, and smartphone interfaces, are now capable of detecting multiple toxins simultaneously with high specificity and low detection limits. Furthermore, the adoption of AI-driven modeling and decision support systems allows for early risk prediction and supply chain optimization. These innovations directly contribute to enhanced food safety, reduced economic losses, regulatory compliance, and increased consumer trust in beverage quality.

7.3 Future directions for research and industry adoption

The future of mycotoxin monitoring in the beverage industry lies in integrating advanced sensing technologies with intelligent data systems. Key research priorities include enhancing the selectivity and stability of recognition elements (e.g., aptamers, MIPs), expanding the use of multiplex and point-of-care devices to detect co-occurring mycotoxins, developing low-cost, scalable platforms suitable for resource-limited environments, validating emerging methods through harmonized international protocols, and incorporating continuous monitoring systems and blockchain-based traceability solutions for transparent quality assurance.

To bridge the gap between laboratory performance and field applicability, industry adoption must align with regulatory standards, affordability, and usability. Collaborative global efforts, including standardized testing, open-access databases, and training programs, are critical to achieving equitable food safety worldwide. As the beverage industry embraces digital transformation, the proactive integration of these technologies will be essential to ensuring resilient, efficient, and safe production systems.

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The beverage industry is as old as human history, with traditional products such as wine, beer, tea, and coffee with thousands of years of history and tradition. At the same time, it is a modern and dynamic sector, full of innovation and new opportunities. This book compiles recent advances in the beverage industry, focusing on innovations in traditional products, sustainability, the use of emerging technologies for processing and preservation, regulatory frameworks, and health and safety. It provides a comprehensive analysis of the key factors involved in the production of both traditional and innovative beverages, emphasizing health and sustainable practices.

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