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REWIEV ARTICLE

ETHICAL DILEMMAS IN FOOD LABELING: THE UNDISCLOSED PRESENCE OF ALCOHOL AND ITS IMPACT ON VULNERABLE CONSUMERS

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ABSTRACT

Despite the existence of some consumer protection legislation that mandates the declaration of alcohol content in food products when it reaches a certain threshold, current regulations appear insufficient to fully protect consumers from the consequences of excessive consumption of these products. The marketing of non-alcoholic drinks has increased significantly in the last decade leading to increased consumption, especially among schoolchildren, adolescents and pregnant or lactating women. This paper presents recent studies examining the presence and effects of ethanol in a range of foods, including baked goods, fermented beverages such as kombucha, and condiments such as soy sauce. The ethanol content in these products varies widely and can have unintended consequences, particularly for children, pregnant women, individuals with alcohol use disorders, and people with certain health conditions. In addition, the labeling and classification of low-alcohol or non-alcoholic beverages remains challenging, as definitions and regulations vary significantly across regions. Understanding the complex interrelationships surrounding ethanol in food is crucial for informed consumer decisions and the development of evidence-based health policy.

Keywords: *ethanol-containing food, soft drinks consumption, non-alcoholic beverages, food labeling, health policy*

INTRODUCTION

Ethanol, commonly known as alcohol, occurs in a wide range of food products either as an intentional additive or as a by-product of fermentation. The deliberate addition of ethanol to foods is a common practice aimed at enhancing flavor, aroma or microbial stability. For instance, some bakeries and confectionery industries incorporate small quantities of alcoholic beverages or ethanol into cakes and bread products to improve sensory attributes and prolong shelf life [1]. Although ethanol has a lower boiling point than water and is expected to evaporate during baking or cooking, research has shown that a significant proportion may remain in the final product. Depending on cooking time, temperature, and method, residual ethanol can range from 2.6% to as high as 85% of the originally added amount [2]. This percentage may be even higher in uncooked dishes or those that require temperatures below the boiling point of ethanol [3].

Recent years have witnessed a global surge in consumer demand for low- and no-alcohol beverages, commonly referred to as “NoLo” products. These include beers, wines, spirits, and ready-to-drink cocktails that contain minimal or no ethanol. According to a survey by Euromonitor International, non-alcoholic beverage consumption increased steadily between 2011 and 2021, from 508 billion to over 800 billion liters [4]. In Europe, the market for low- and no-alcohol drinks was estimated in 2022 to account for around 2.5 billion liters and a total market value of €7.5 billion [5]. Similar growth has been observed in other regions: the Chinese non-alcoholic beverage market reached approximately USD 204 billion in 2022, with energy drinks alone accounting for nearly 3 billion liters [6]. Globally, the non-alcoholic beverage industry was valued at USD 1.18 trillion in 2020 and is projected to reach approximately USD 2.17 trillion by 2026 [7]. In the United Kingdom, a 2020 consumer survey identified “NoLo” beverages as one of the

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fastest-growing trends among young adults aged 18 to 24 [8].

The increasing popularity of these beverages reflects not only health consciousness but also evolving social and cultural attitudes regarding alcohol consumption. Consumers are demonstrating greater awareness of the potential risks associated with alcohol use, including impaired cognitive function, liver disease, and long-term addiction. People are therefore seeking alternatives that align with healthier lifestyles and personal values [9, 10]. This shift presents both opportunities and challenges for food and beverage manufacturers, public health authorities, and regulators. While the development of "NoLo" products caters to changing consumer demands, ensuring accuracy in alcohol labeling and disclosure remains crucial for maintaining transparency and consumer trust. Understanding these social and cultural dynamics provides valuable insights into what drives the growing demand for "NoLo" beverages.

Certain population groups, such as children, pregnant or lactating women, and individuals with specific medical conditions, are particularly sensitive to even trace amounts of ethanol [11-13]. For these groups, unintended exposure through mislabeled or inadequately controlled food products poses potential health concerns. Consequently, clear and standardized labeling regulations that specify ethanol content in all food and beverage products are essential. In addition, the use of sensitive and validated analytical techniques is necessary for effective monitoring and regulatory compliance.

This review evaluates current literature on the presence and variability of ethanol content across different food categories, regulatory frameworks governing alcohol disclosure in food labeling, potential health effects of unintended exposure, and the ethical considerations associated with consumers' right-to-know.

NATURAL SOURCES OF ETHANOL IN FOOD

Ethanol is produced naturally as a by-product of fermentation in many foods, with levels varying widely depending on the substrate, microbiota, time, and temperature. Spontaneous fermentation occurs under anaerobic conditions, where microorganisms generate energy through ethanol fermentation. Unlike industrial fermentation using selected starter cultures, spontaneous fermentation depends on autochthonous microbiota, including wild yeasts and bacteria naturally originating from raw materials, fruit surfaces ("bloom"), processing equipment, and the surrounding environment [14]. The process continues until alcohol concentrations reach levels typically toxic to the microorganisms' own membranes (approximately 2-4% Alcohol by Volume (ABV)) [15] (see Figure 1).

Vinegar, which is one of the primary condiments around the world in preparing and cooking some foods, is basically a diluted solution of acetic acid and is produced by fermenting raw materials containing starch or sugar such as grapes, apples and other fruit juices. Other types of vinegar include malt vinegar, rice vinegar, and beer vinegar. Two steps are involved in the vinegar production process [16]. In the first step, yeast produces ethanol from the simple sugars present in the raw materials. In the second step, bacteria oxidize ethanol and convert it to acetic acid. Industrial vinegar is produced by fermenting alcohol (such as spirits, wine or cider) to produce acetic acid. As such, it is not unusual that vinegar contains some ethanol. Analysis of ethanol in 140 samples of industrial (used as raw materials in large-scale manufacturing) and domestic vinegar (vinegar produced for household or kitchen use, typically sold in retail stores for individual consumers), showed that the average content of ethanol was 1.01% ABV for domestic brands and 0.176% ABV, for industrial brands [17]. Another study reported ethanol concentrations of 0.228% ABV in commercial apple vinegar and 0.170% ABV in commercial rice vinegar products [18]. A very varied ethanol content ranging from 0.01% to 0.94% ABV was also reported for different types of vinegar [19]. Considerably lower ethanol concentrations, ranging from 0.007% to 0.018% ABV, were reported in samples of Palestinian fermented apple vinegar [20]. The presence of ethanol

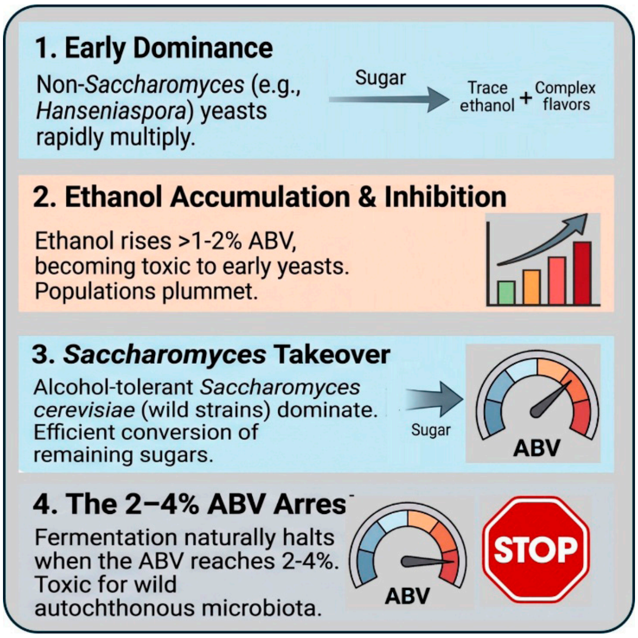

Figure 1. Sequential phases of spontaneous natural fermentation, illustrating the transition from non-*Saccharomyces* dominance to *Saccharomyces cerevisiae* takeover and the eventual 2-4% ABV arrest threshold

in vinegar leads to the formation of ethyl acetate, which is a product of ethanol and acetic acid reaction. Ethyl acetate is accused of being responsible for the low acceptance of Cortina, the taste and smell of vinegar [21].

Kombucha is produced through the fermentation of sweetened tea by a symbiotic culture of acetic acid bacteria and yeasts [22]. Ethanol concentrations reported in commercial kombucha products vary substantially among studies and product types, ranging from 0.07% to 1.63% ABV in commercial brands [23], 1.12% to 2.0% ABV in commercially available samples [24], and 1.62% to 2.21% ABV in flavored kombucha products [25]. Furthermore, more than 31% of surveyed Canadian kombucha products exceeded 1% ABV, with a maximum reported concentration of 3.62% ABV [26]. During fermentation, ethanol concentration reached 0.52% ABV on day 6 and peaked at 0.67% ABV on day 8 [27].

Prior to baking, sourdough dough may reach ethanol concentrations of approximately 1.7% ABV (≈60 mmol per 100 g flour); however, ethanol is largely volatilized during baking, resulting in essentially negligible levels in the finished product [28]. Canned salmon exhibited ethanol concentrations ranging from below the detection limit to 0.0075% ABV, with levels increasing markedly as spoilage progressed. However, ethanol content did not consistently correlate with microbial load, indicating that part of the ethanol formation may also arise from non-microbial (chemical) processes [29].

As for fruits, the degree of fruit ripening significantly influences ethanol concentration. No ethanol was detected in unripe hanging palm fruits, whereas ripe hanging fruits contained approximately 0.6% ABV ethanol, ripe fallen fruits about 0.9% ABV, and over-ripe fallen fruits up to 4.5% ABV ethanol [30]. Fresh ripe pineapple contained 0.48% ABV ethanol, increasing to 1% ABV after 10 days of storage [31]. Similarly, ethanol concentrations in citrus products have been reported to range from 0.009% ABV to 0.09% ABV [32]. Bananas stored at room temperature may also develop ethanol concentrations of up to 0.4% ABV as a result of spontaneous fermentation processes [13]. Fruit juices from the German market showed low levels: grape juice ≤ 0.086% ABV, apple juice ≤ 0.066% ABV, orange juice ≤ 0.073% ABV [13]. Fruit juices generally contain ethanol below 0.5% ABV, the threshold proposed by FAO legislation [33, 34]. Turkish fruit juices and energy drinks showed ethanol contents far below 0.3% ABV [35].

Kimchi contains only trace ethanol (~0.01% ABV) [36], probably due to lactic fermentation. Similarly, Miso (soy/cereal paste) produces only very small amounts of ethanol (trace to ~0.1% ABV) [36], with rice/barley miso higher than soybean miso. Tempeh (soy fermented with Rhizopus) yields negligible ethanol (only trace detection) [37]. Boza (cereal beverage) typically contains ≈0.5-2% ABV [38]. Gochujang (Korean red pepper paste) contained ethanol at 1.73-1.95% ABV [36]. Four fermented corn dough products from Ghana ranged from 0.007% to 0.14% ABV [39]. The majority of kefir types contain 0.5-2% ABV ethanol depending on the brand [40].

Temperature plays a critical role in modulating ethanol formation during storage. In kombucha, storage at room temperature led to a marked increase in ethanol concentration, rising from 0.51% ABV to 1.3% ABV over three weeks, whereas refrigeration at 4°C effectively suppressed this increase, maintaining comparatively stable levels [41]. A similar temperature-dependent pattern was observed in fresh grape juice, where ambient conditions rapidly accelerated ethanol production, increasing from an initial 0.00029% to 2.11% ABV within one day and further to 5.60% ABV after 10 days [31].

ADDITION OF ETHANOL DURING MANUFACTURING

Ethanol is widely used in food processing, including as a solvent, preservative, flavor carrier, and processing aid, and its deliberate addition to food products is a common industrial practice [42]. Although ethanol has a lower boiling point than water and is expected to evaporate during heating, research shows that significant proportions may remain. Depending on cooking time, temperature, and method, residual ethanol can range from 2.6% to as high as 85% of the originally added amount [2], with higher retention in uncooked dishes or those prepared below ethanol's boiling point [3]. A case report described a defendant claiming consumption of 900 g of Stollen (German Christmas cake) containing Strohrum to explain a blood alcohol concentration of 1.19 per mille (‰); the study confirmed that noticeable alcohol remains after baking [3].

Adding ethanol to bread after baking at 2-3% ABV increases shelf-life, though levels > 2% ABV impart unpleasant flavor [43]. Analytical testing reveals significant variance in ethanol concentrations across different bakery products. American-style burger rolls exhibited a level, reaching 0.128% ABV, closely followed by French-style milk rolls at 0.121% ABV. In contrast, standard bread varieties contained substantially lower concentrations, ranging between 0.014% ABV and 0.029% ABV [13]. Italian "pancarrè per tramezzini" (sandwich bread) was found to contain up to 2% ABV ethanol on a dry weight basis [44]. Analysis of fifteen different bread and cake samples revealed ethanol levels ranging from 0.007% ABV to 1.9% ABV [45]. Further comparative studies categorize these concentrations by product type [46]: Bread: 0.009% ABV – 0.67% ABV, Short Cake: 0.002% ABV – 1.6% ABV, Pyramid Cake (Baumkuchen): 0.004% ABV – 0.59% ABV, Sponge Cake: 0.007% ABV – 0.01% ABV. Downey's original Jim Beam Kentucky bourbon cake contained up to 1.662% ABV ethanol [47].

Ethanol is frequently utilized in commercial soy sauce production as a functional additive to enhance aromatic profiles and extend shelf stability. However, the final concentration remains highly variable, as it is fundamentally determined by specific manufacturing parameters such as fermentation temperature, carbohydrate sources, salt concentrations, and the overarching production methodology [48].

Regional and stylistic variations in soy sauce fermentation produce substantial differences in ethanol content. Conventionally brewed soy sauces commonly contain appreciable ethanol concentrations generated during yeast fermentation, frequently reaching approximately 2-3% ethanol (ABV) in traditionally fermented products. In contrast, tamari soy sauce, which is traditionally produced with little or no wheat, has often been described as containing little or negligible ethanol because the reduced carbohydrate availability limits alcoholic fermentation [49]. However, analytical studies demonstrate that ethanol concentrations in commercial tamari products can vary considerably depending on formulation and fermentation practices. For example, a recent study comparing Japanese soy sauces reported ethanol concentrations of approximately 0.58 ± 0.02% ABV in organic tamari and 0.91 ± 0.24% ABV in conventional tamari products [50]. Other surveys of commercial soy sauces detected ethanol concentrations up to 2.15% ABV across different soy sauce categories [51]. These findings indicate that although tamari is often expected to contain lower ethanol levels than wheat-containing soy sauces, measurable ethanol may still be present depending on fermentation conditions, carbohydrate composition, microbial activity, and post-processing treatments.

Chinese soy sauces manufactured via high-temperature, low-salt solid-state fermentation retain only minimal amounts due to significant evaporation during the process [52]. Korean soybean sauces have been recorded with relatively low concentrations between 0.044% ABV and 0.15% ABV [36].

Quantitative analyses of commercial brands reveal a broad range of alcohol content, with findings spanning from non-detectable levels to 2.4% ABV [53], while other reports cite standard concentrations reaching as high as 2-3% ABV [54].

Ethanol represents a primary constituent of the volatile flavor profile, accounting for 42.3% of total volatile organic compounds (VOCs) generally [55] and exceeding 60% in specific Chinese varieties [56]. Comparative data further highlight significant regional disparities in the ethanol share of total VOCs, measured at 8.4% in Philippine toyo, 34.7% in Chinese jiangyou, and 60.51% in Japanese shoyu [57].

Analysis of various processed food categories reveals a broad spectrum of ethanol concentrations [53]. Recorded levels ranged from 0.0034% to 0.1366% ABV in fish-based products and up to 0.0286% ABV in cheese-based items. Furthermore, ethanol was identified in instant dried noodles at 0.007% to 0.023% ABV, ginseng-based products at 0.0147% to 0.0550% ABV, and mayonnaise at levels reaching 0.0266% ABV. The highest concentrations among these categories were observed in rice-based cakes, which contained between 0.0224% ABV and 0.565% ABV ethanol.

A large-scale survey of 811 food items, including Black Forest gateau, various chocolate products, fruit juices, lemonades, honey, and non-alcoholic beverages, concluded that the alcohol content in many common foods is frequently underestimated [58]. The study suggests that isolated instances of higher ethanol concentrations can result in a non-negligible cumulative alcohol intake for consumers.

RELEASE FROM PACKAGING

The deliberate incorporation of ethanol in active packaging systems provides a highly relevant model for understanding its mass transfer behavior. A primary example is the preservation of intermediate-moisture bakery products, such as sweetbread and rye bread, which are highly susceptible to fungal spoilage (e.g., *Rhizopus stolonifer*) and physical degradation (staling). These products can be protected using active packaging sachets or integrated polymeric films designed to emit ethanol vapor at controlled rates [59]. In active packaging applications, ethanol emitters are frequently co-formulated with synergistic volatile compounds (such as essential oils containing carvacrol or thymol) or deployed alongside chemical oxygen scavengers to simultaneously inhibit microbial proliferation and oxidative degradation [60]. Importantly, the minimum inhibitory concentration (MIC) of ethanol vapor in the headspace required to exert effective fungistatic activity depends on the water activity (a_w) (the amount of unbound water available to support microbial growth and chemical reactions) of the product. Published data indicate that ethanol emitters are most effective in products with $a_w < 0.92$, which explains their primary application in bakery and dried fish products rather than high-moisture foods. Furthermore, an initial burst-release pattern has been documented empirically: headspace ethanol concentrations peak during the first 3-6 hours after packaging and then decline to a quasi-steadystate level (approximately 2-3% ABV), after which antimicrobial efficacy must be sustained through continued diffusion from the carrier matrix [61].

Food-grade ethanol is typically adsorbed onto an inert carrier matrix, such as silica gel or starch copolymers, and enclosed within a selectively permeable polymeric film. Common film materials include ethylene-vinyl acetate (EVA) copolymers and low-density polyethylene (LDPE). The release kinetics are fundamentally governed by the permeability coefficient of the enclosing film, the ambient temperature, and the concentration gradient between the emitter and the package headspace [62]. The EVA content in the LDPE/EVA film matrix plays a particularly critical role in modulating release rate. Studies on volatile antimicrobial agents (linalool, carvacrol, thymol) released from LDPE/EVA films demonstrate that an optimum EVA concentration (approximately 10% w/w) minimizes the rate of antimicrobial agent release, thus extending the duration of protective headspace concentrations. The polarity of the EVA hydroxyl groups favors absorption of polar volatile compounds, including ethanol, making EVA an effective binding matrix for controlled release applications. Diffusion coefficients (*D*) for small volatile molecules in such polymer matrices are typically on the order of 10^{-9} to 10^{-11} cm^2/s depending on temperature and polymer polarity [63]. The transfer of ethanol from an active packaging system to a food matrix is a multistage process [64]. It begins with the permeation of ethanol vapour from the emitting material through a selectively permeable polymer film into the package headspace, driven by the concentration gradient and described by Fick's first law of diffusion. This is followed by the accumulation of ethanol within the headspace until a near-thermodynamic equilibrium is established between the emitting source and the gas phase. Finally, ethanol is transferred from the headspace into the food matrix through sorption processes, which are governed by the gas-food partition coefficient (K_gas/food) [65]. For polar, volatile solvents such as ethanol, the gas-food partition coefficient is strongly influenced by the water content of the food. High-moisture foods act as significant thermodynamic sinks because ethanol is highly miscible with water, resulting in a low K_gas/food value and therefore greater net absorption of ethanol from the headspace. Conversely, high-fat matrices, which are thermodynamic sinks for lipophilic compounds, are less favorable sinks for ethanol due to its polar character. This polarity-driven partitioning behavior has been confirmed by studies using LDPE migration into food simulants of varying ethanol-water compositions [66].

However, a critical knowledge gap arises from the lack of precise quantification of ethanol transfer into the food matrix from active packaging systems. Unregulated accumulation of ethanol can lead to organoleptic degradation, imparting undesirable off-flavors or alcoholic odors that exceed consumer sensory thresholds [67]. Furthermore, precise quantification is necessary from a regulatory perspective to ensure that absorbed ethanol does not result in undeclared alcohol content exceeding regional statutory limits [59].

HEALTH COMPLICATIONS

It has been evidenced that alcohol in food interacts with its components leading to changes in the biological functions of food [68]. Absorption of nutrients could also be impaired by ethanol through damaging the absorbing cells in the stomach and intestines [69]. Decreased absorption of certain essential nutrients such as folate, vitamins B_6, B_{12}, A, and some lipotropes when ethanol-containing foods are consumed has been reported [70]. Mixing alcohol with foods and beverages has the potential to increase lipid peroxidation and induce cytochrome P450 2E1 and DNA lesions [71]. Also, ethanol could be considered an indirect co-carcinogenic substance by providing affordable chemical conditions for some carcinogens to penetrate the mucosa of upper aerodigestive organs, especially among cigarette smokers [72]. A study suggested that schoolchildren who consume foods mixed with ethanol are exposed to an average daily intake of 10.3 mg ethanol/kg body weight, which is nearly double the warning level for children's use [73]. In addition, the so-called higher alcohols (also known as fusel oils or fusel alcohols) which occur in fermented beverages are more than often not undeclared on alcoholic beverages [74].

Energy drinks are popular especially among youth. Adding alcohol to energy drinks resulted in increased intoxication and amplified effects of depression [75]. Studies conducted on energy drinks mixed with alcohol found that mixing alcohol with energy drinks poses higher risks than alcohol alone [76]. Laboratory studies on both humans and animals have shown that these mixed drinks cause decreased feelings of intoxication, increased euphoria, and increased desire to drink [77]. When you consume pre-mixed beverages or use energy drinks as a mixer, your body gets deceived into believing it is not weary, while the fact is that your body is more intoxicated than you may realize [78]. Caffeine can counteract the depressive effects of alcohol by masking them, making consumers feel more alert than they otherwise would [79]. Because of this, people may consume more alcohol and get more inebriated than they realize, which increases the likelihood that they will experience alcohol-related issues [78].

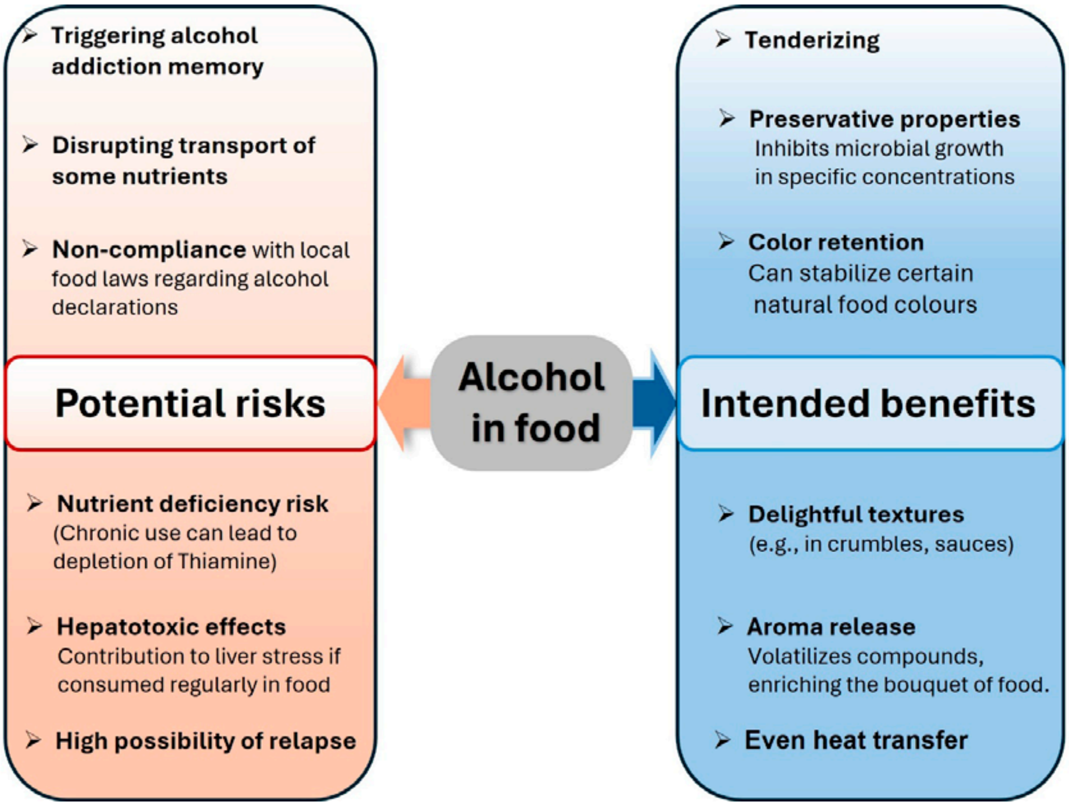

Figure 2. Most frequent negative and positive aspects of mixing alcohol with food (based on Herdiana et al., 2025 [42])

Recovering alcoholics or people suffering from various diseases are among vulnerable categories and any alcohol in food might present a risk of relapse [80]. This may be due to the activation of the so-called addiction memory which is caused by stimuli that can produce an addictive desire – also called craving [81]. The danger of activating the addiction memory through an alcohol-free beer (which usually contains up to 0.5% ABV alcohol) does not arise from the alcohol itself, but from the cognitively associative proximity of non-alcoholic beer to alcohol-containing beer – i.e. both via the gustatory (tastes similar) and the optical component (looks like a normal beer). An alcohol content of up to 0.5% ABV is sometimes found unlabeled as a by-product in fruit juices due to natural fermentation [82]. Figure 2 summarizes the pros and cons of mixing alcohol with food.

Drinking a "non-alcoholic" beverage with the same appearance, aroma, and flavor as alcohol may cause cognitive and behavioral effects that are similar to those of alcohol [83].

Grimm et al. [84] analyzed data collected by Dragonfly, a children's educational magazine in USA, and found that around 53% of the study sample (children aged 8-11) consume soft drinks on a daily basis. Figure 3 shows the frequency of carbonated soft drink consumption among adolescents aged 12–15 years, by region (based on original data published by Yang et al. [85]).

Although, the average adult's daily intake of ethanol-containing foods does not lead to acute alcohol toxicity, even low doses of ethanol intake may render the consumer susceptible to chronic health problems and several toxicological concerns [11, 73].

The German Federal Institute for Risk Assessment (BfR) warned that Alcopops, Premix, or 'Ready to drink' are barely perceived as alcoholic drinks in terms of flavor due to the presence of the fruit juice or lemonade-like scent [86]. These product characteristics can result not only in drinking behavior that is inappropriate for alcoholic beverages with the consequence of unintentionally high alcohol

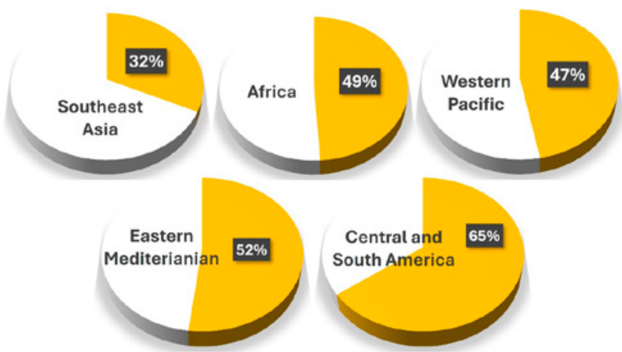

Figure 3. Consumption frequency (at least once daily) of carbonated soft drinks among young adolescents aged 12 to 15 years in low- and middle-income countries (by region) (based on tabulated data published in Yang et al., 2017 [85])

intakes, but also in the early introduction of children and adolescents to alcohol consumption. In addition, non-alcoholic beverages are sweetened with excessive quantities of sugar which make alcohol taste better leading to excessive drinking, especially among adolescents [38]. In Poland, the legal framework for non-alcoholic beverages is established under the Act on Upbringing in Sobriety and Counteracting Alcoholism [87]. According to this legislation, a beverage is classified as alcoholic if it contains ≥ 0.5% ABV. Consequently, beverages containing < 0.5% ABV are legally considered non-alcoholic. This threshold aligns Poland with several other European countries. The Polish definition is particularly relevant for regulatory purposes, including sales restrictions, advertising rules, and consumer protection measures.

LABELING DILEMMA

The definition of the term "non-alcoholic" is not straightforward and varies significantly between jurisdictions. In addition, the level of alcohol in foods is expressed in confusing terms such as: "no", "free", "zero", "low", "light", or "reduced". Many people consider these labels confusing and make it difficult to determine their preferences or avoid unhealthy foods [88] (Figure 4).

Although the consumer assumes that alcohol-free-labeled products are completely free of alcohol, these products do contain a little alcohol either added deliberately or as a leftover after alcoholization [89].

In the UK, drinks that contain less than or equal to 0.05% ABV are considered non-alcoholic, drinks with an alcohol level less than or equal to 0.5% ABV are classified as "dealcoholized", and drinks with alcohol content less than or equal to 1.2% ABV are labeled as low-alcohol content [90]. In Germany, China, USA, and Sweden, however, the term "non-alcoholic" or "alcohol-free" is applied to malt beverages containing less than or equal to 0.5% ABV [91, 92]. In Italy, the term "Birra analcolica" (non-alcoholic beer) refers to drinks containing alcohol with a level of less than or equal to 1.2% ABV [93]. In Finland, this percentage increases again to reach 2.8% ABV [94]. In Japan and Spain, drinks containing less than 1% ABV are considered non-alcoholic [95]. In Türkiye, the term non-alcoholic describes beverages that contain ethanol of less than 0.3% ABV [35]. Figure 5 represents the threshold concentration of ethanol in non-alcoholic beverages in various countries.

As an addition to the definition dilemma highlighted by the European Commission's 2022 report, the labeling of "non-alcoholic" beverages does not necessarily align with existing legal definitions [96]. For example, Regulation (EU) 1169/2011 requires that only beverages containing more than 1.2% ABV must declare their alcohol content on the label. Consequently, beverages with ≤ 1.2% ABV,

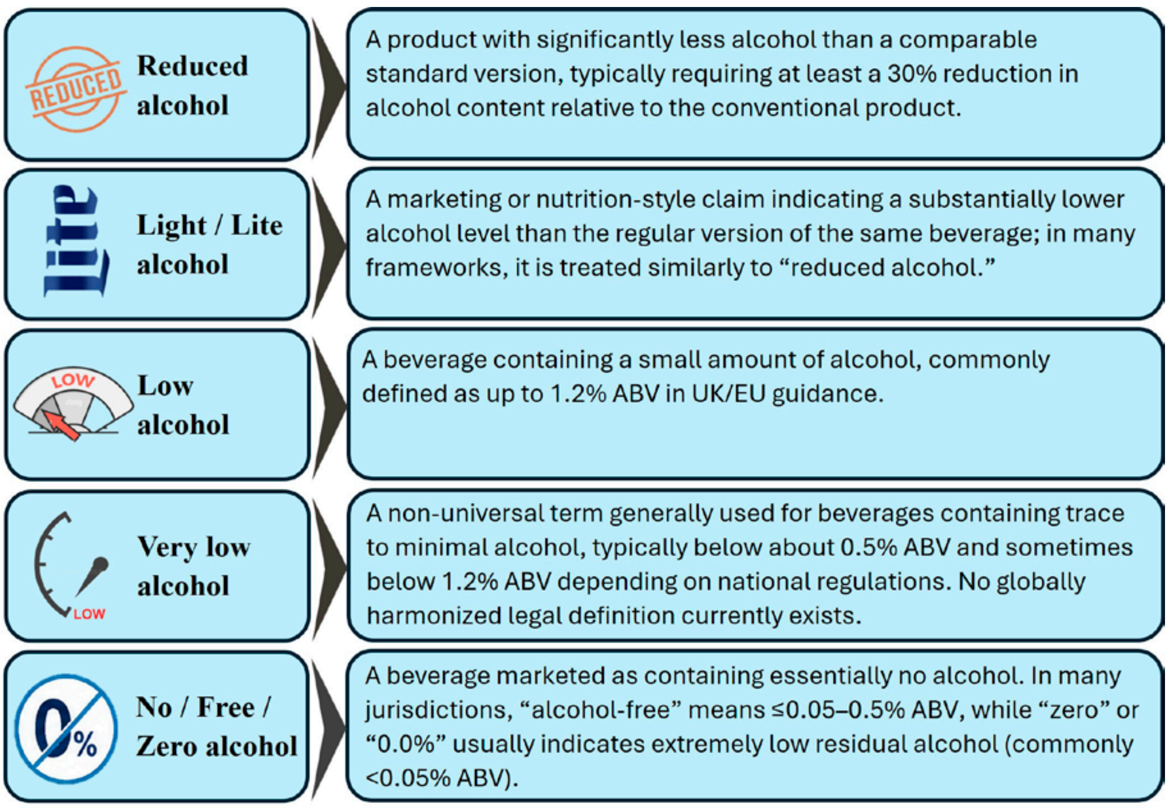

Figure 4. The most popular definitions of common labeling of "no or reduced" alcohol content

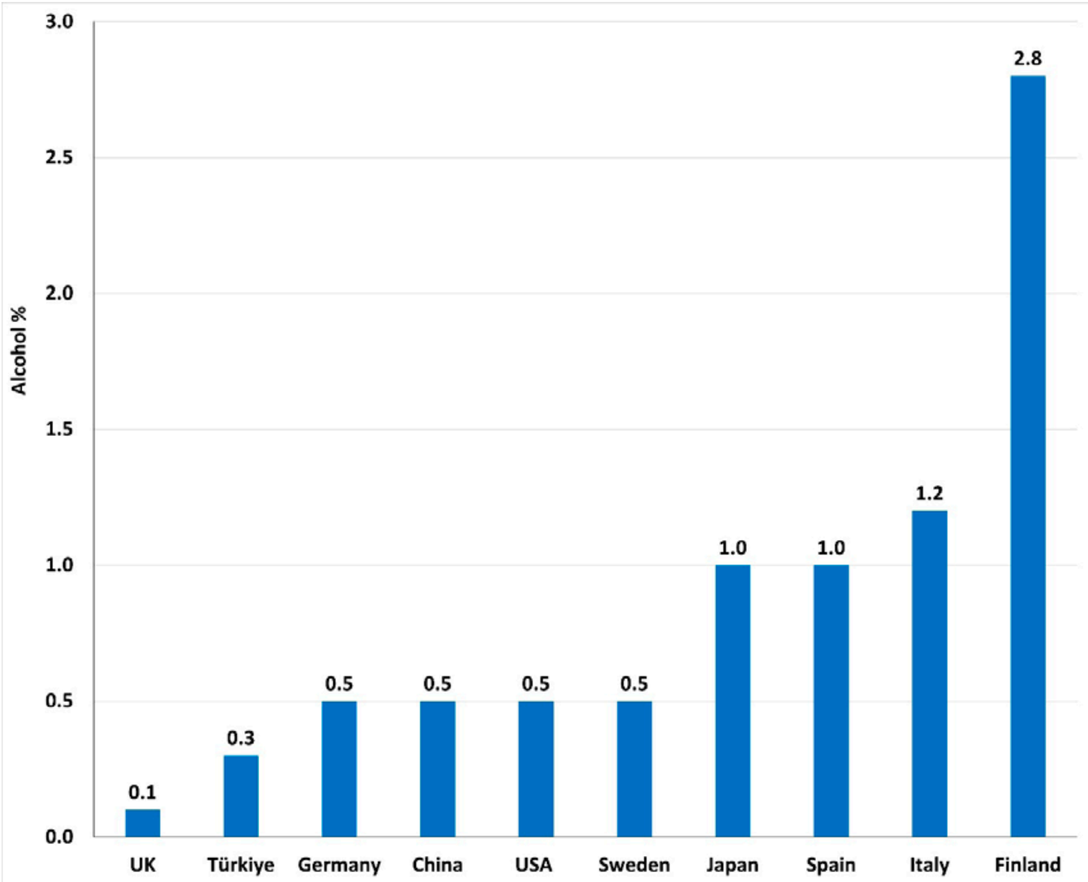

Figure 5. The threshold concentration of ethanol in non-alcoholic beverages in some countries

including many products marketed as "non-alcoholic" or "low-alcohol" – have no mandatory obligation to disclose their alcohol strength. This means a drink labeled "non-alcoholic" could legally contain up to 1.2% ABV without any consumer-facing indication of alcohol, creating a regulatory gap. Moreover, this labeling threshold conflicts with the EU Customs Code, which defines "non-alcoholic beverage" for tariff purposes as containing ≤ 0.5% ABV, further adding to the definitional confusion. In Australia, alcohol content must be declared when greater than 0.5% ABV [97, 98]. The Canadian Food and Drug Regulations mandate declaration of alcohol content when above 1.1% ABV [99]. Although the U.S. Environment Protection Agency (EPA) considers ethanol a "Generally Recognized As Safe" (GRAS) ingredient for use as an antimicrobial agent in pizza crust at levels below 2.0% ABV (21 CFR 184.1293), it does not exempt ethanol from reporting requirements when added to food [100].

Goh et al. [101] found that 6 distinct beverages contained more than 1% ABV ethanol despite being labeled as alcohol-free and that around 29% of 45 different beverages claiming to have no or low alcohol content on the Canadian market had ethanol above indicated levels. However, fruit juices often contain little alcohol because of natural fermentation. A total of 100 non-alcoholic beverages and energy drinks in the Jordanian market labeled "alcohol-free" showed alcohol content ≤ 0.0015 % ABV [102]. Four kinds of fruit juices (apple, cranberry, vitamins and orange) were analyzed and found to contain ethanol below 0.05 % ABV [33, 103]. Figure 6 illustrates the highest concentration of ethanol detected in some food products.

The production of non-alcoholic and alcohol-free beers and beverages usually follows the same procedure used to produce conventional beer followed by the removal of alcohol (dealcoholization). However, the distinction between naturally fermented residues and de-alcoholized residues is vital for specific consumer groups. Non-alcoholic or "alcohol-free" beverages and juices such as Alcopops Selina are becoming increasingly popular all over the world as a way to reduce alcohol consumption and especially in Muslim countries where alcoholic beverages are strictly prohibited. From an Islamic perspective, consumption of foods and beverages containing ethanol at a concentration level of less than 1% ABV is permitted provided that this ethanol has been produced by natural fermentation but not as a result of dealcoholization [104, 105]. Hence, descriptive labeling in these countries is of utmost importance. Furthermore, people who want to avoid or control their

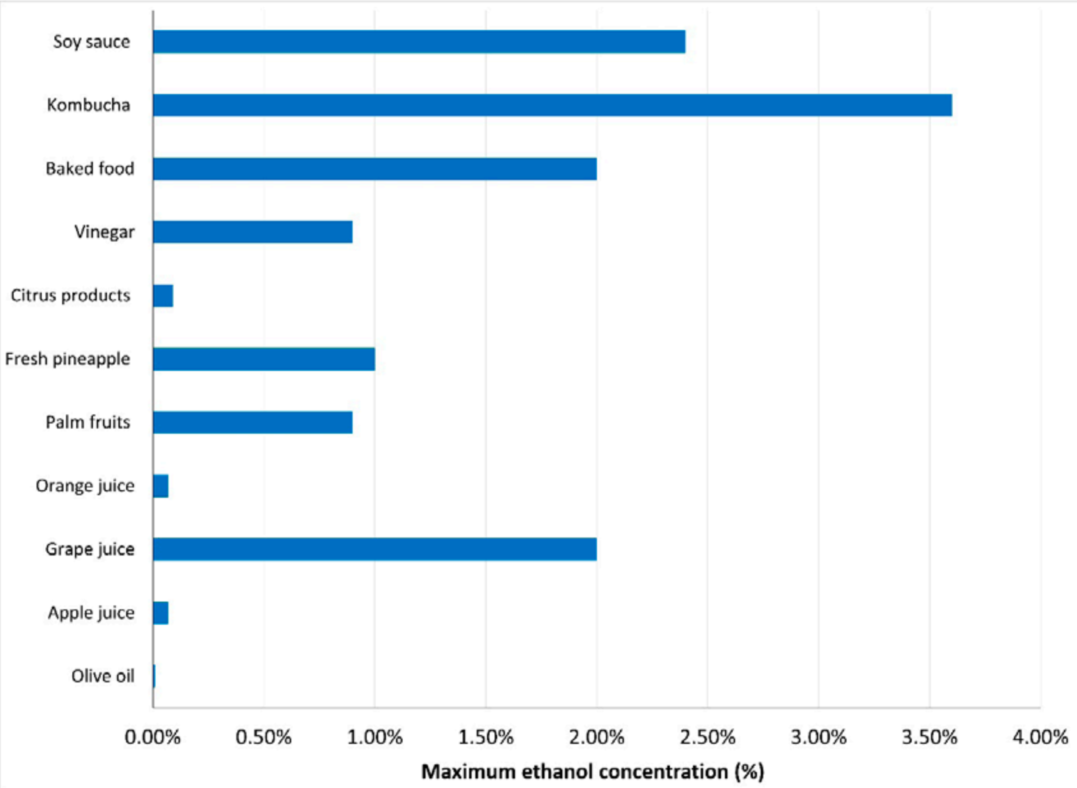

Figure 6. The highest concentration of ethanol detected in some food products (based on Reimann et al., 2023 [11]; Gorgus et al., 2016 [13]; Pourjabbar et al., 2021 [17]; Talebi et al., 2017 [24]; Park et al., 2017 [51])

alcohol consumption need a clear labeling system. This becomes crucial when it comes to children and pregnant women.

CONCLUDING REMARKS

This review demonstrates that ethanol is present in a wide range of foods and beverages, arising from natural fermentation, deliberate addition during manufacturing, and active packaging technologies. Although concentrations are often low, they are not negligible for vulnerable population groups.

The review clearly demonstrates that appropriate nutritional labeling is essential to help assess any health consequences. Marketing strategies across consumer products should be assessed with respect to adverse public health impacts. Available data on ethanol exposure from food remain incomplete and sometimes inconsistent. The available data are either contradictory or limited, and still require a lot of effort. Moreover, factors such as age, gender, genetic polymorphism, morbidity and whether the person drinks alcohol must be considered for a study to be reliable and informative. Thus, further investigation of this important topic is essential to achieve two goals: 1) generating sufficient data to support comprehensive and comparative conclusions; and 2) standardizing research methods to make data comparable.

There is also an urgent need for global harmonization of definitions and labeling terminology from scientific, regulatory, and commercial perspectives.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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