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# ROCZNIKI PAŃSTWOWEGO ZAKŁADU HIGIENY
[ANNALS OF THE NATIONAL INSTITUTE OF HYGIENE]

**Volume 77** **2026** **Number 1**

## EDITORIAL INTRODUCTION

Ladies and Gentlemen,

I would like to present to you issue No. 1/2026 of the journal Roczniki Państwowego Zakładu Higieny (Annals of the National Institute of Hygiene), which opens with an article by S.S. Albaseer et al. describing the presence of small or trace amounts of ethanol in various food products that are commonly considered alcohol-free or labeled as „zero alcohol" or „alcohol-free," along with an assessment of the health risks associated with their consumption, especially in vulnerable groups. In this issue, we also publish a review article by D. Szynal and T. Olszowski on burnout syndrome in nurses. Burnout syndrome is currently a problem for many professional groups, but in medical professions, it can pose a threat to the health and lives of patients. In turn, U. Kacprzak et al., based on literature data from recent years, described the effects of using a ketogenic diet in adults with obesity, together with an assessment of the safety of this type of diet, due to the growing popularity of its use. Excessive table salt consumption is a significant risk factor for cardiovascular disease, among other conditions. E. Rychlik et al. assessed trends in salt consumption in Poland using data from Household Budget Surveys from 2015-2024. The authors found that although a decline in salt consumption in g/person/day is observed, the amounts consumed still significantly exceed the World Health Organization's recommendations. A comparison of adherence to the Mediterranean diet among adolescents from urban and rural areas in Morocco, using the KIDMED questionnaire, was the subject of an evaluation conducted by H. Barouaca and K. Faraj. Obesity and limited physical activity are risk factors for many diseases and health disorders. E. Lyulina et al. assessed the association between the prevalence of obesity and insufficient physical activity in adults and life expectancy at birth, using data from 2000 to 2020 in 172 countries. Another publication in this issue, by L. Ouahmane et al., presents research confirming the *in vitro* antibacterial and antifungal properties of essential oils extracted from the peels of four types of Moroccan citrus fruits. The authors also point to the potential for widespread use of essential oils in biomedicine and industry.

I invite you to read and publish in the journal Roczniki Państwowego Zakładu Higieny.

Kind regards,

Prof. Hanna Mojska, PhD
Editor-in-Chief
Roczniki Państwowego Zakładu Higieny

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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

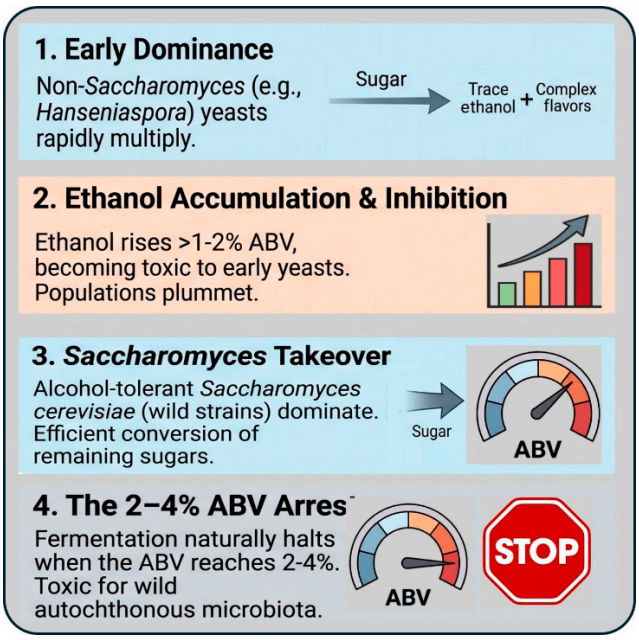


Figure 1. Sequential phases of spontaneous natural fermentation, illustrating the transition from non-*Saccharomyces* dominance to *Saccharomyces cerevisiae* takeover and the eventual 2-4% ABV arrest threshold

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-steady-state

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 $10^{-11}$ cm²/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].

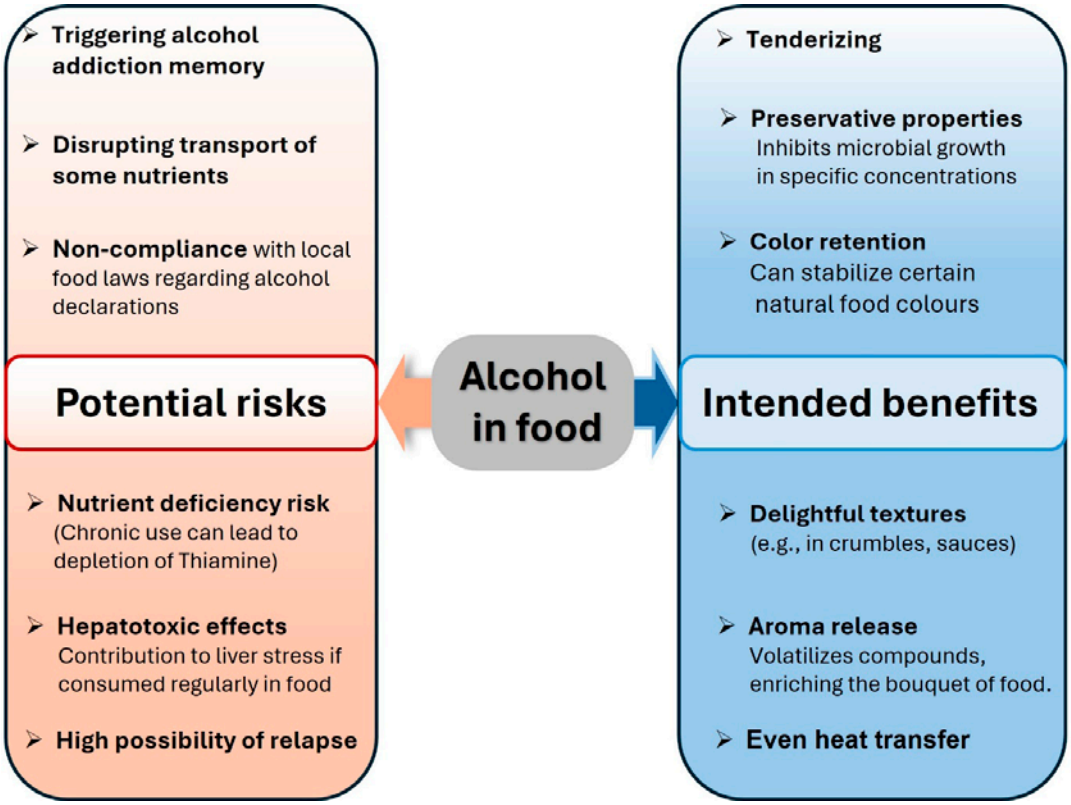


Figure 2. Most frequent negative and positive aspects of mixing alcohol with food (based on Herdiana et al., 2025 [42])

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

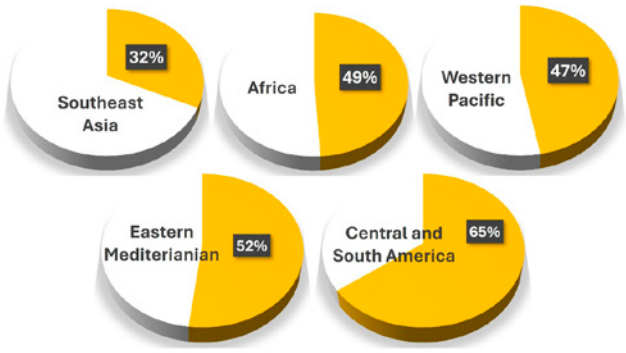


Figure 3. Consumption frequency (at least once daily) of carbonated soft drinks among young adolescents aged 12 to 15 years in low- and middle-income countries (by region) (based on tabulated data published in Yang et al., 2017 [85])

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,

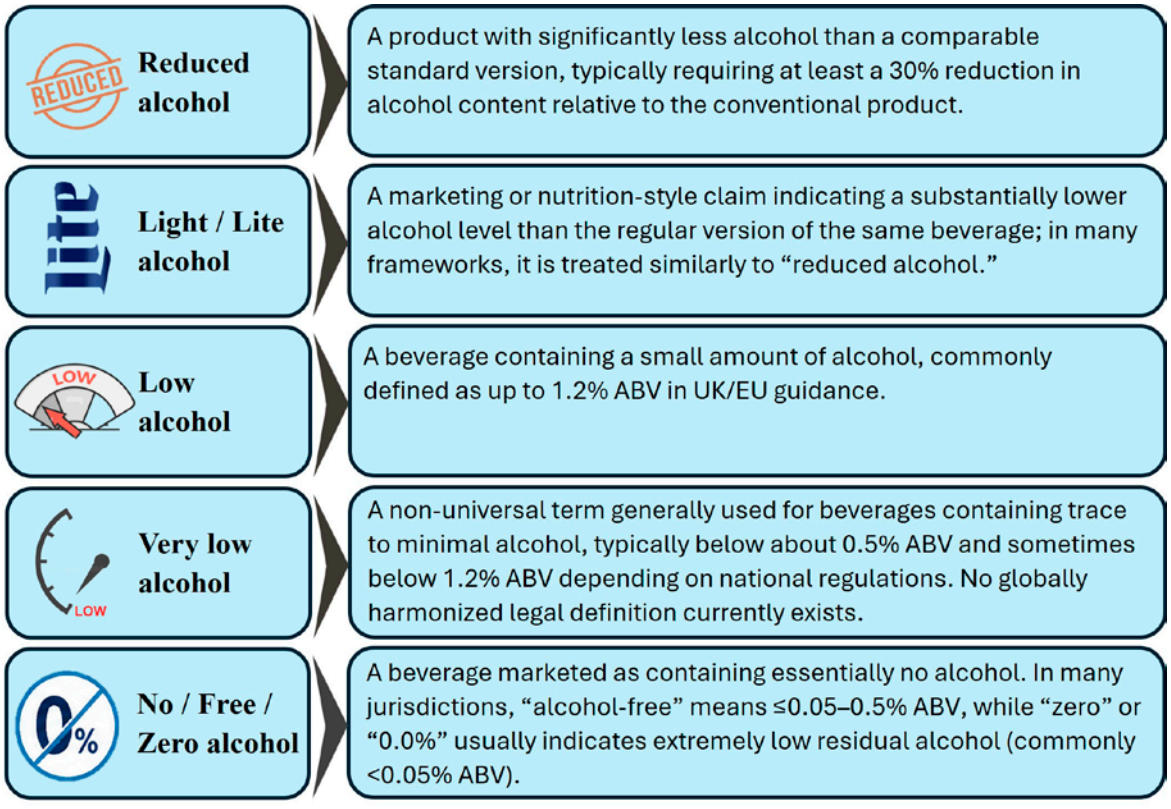


Figure 4. The most popular definitions of common labeling of "no or reduced" alcohol content

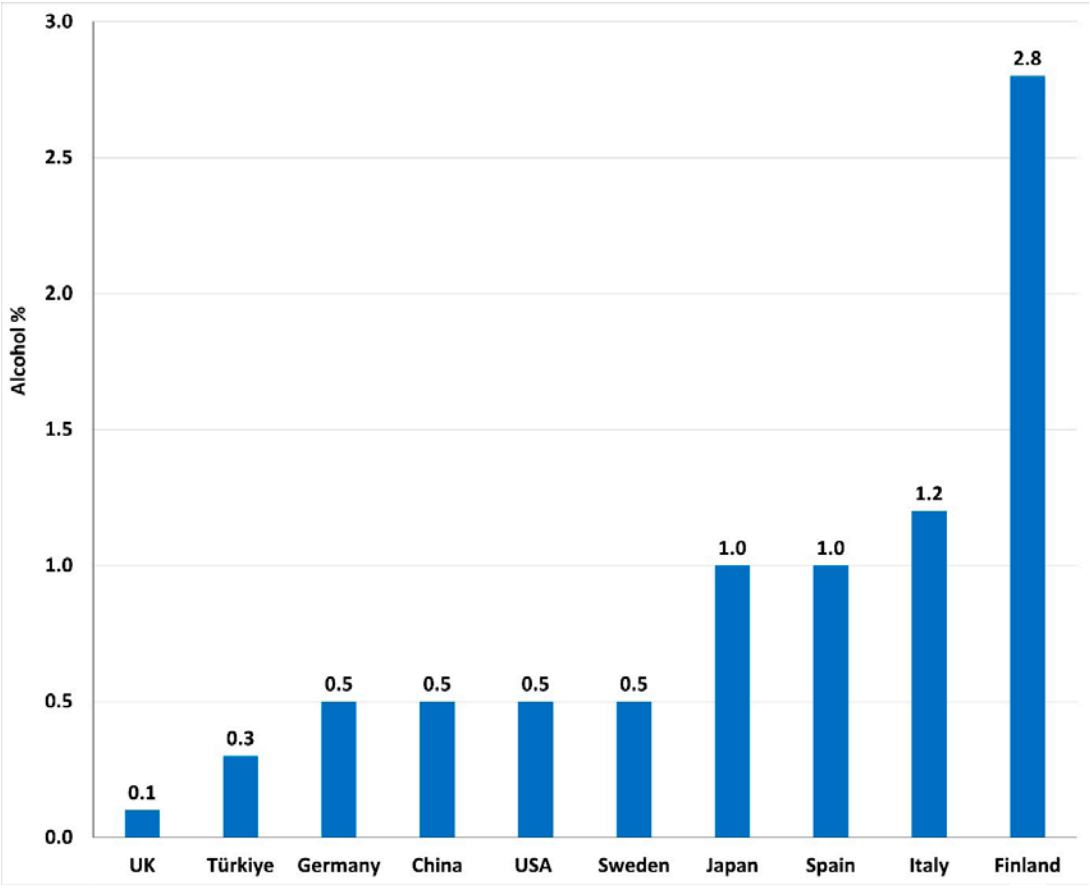


Figure 5. The threshold concentration of ethanol in non-alcoholic beverages in some countries

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

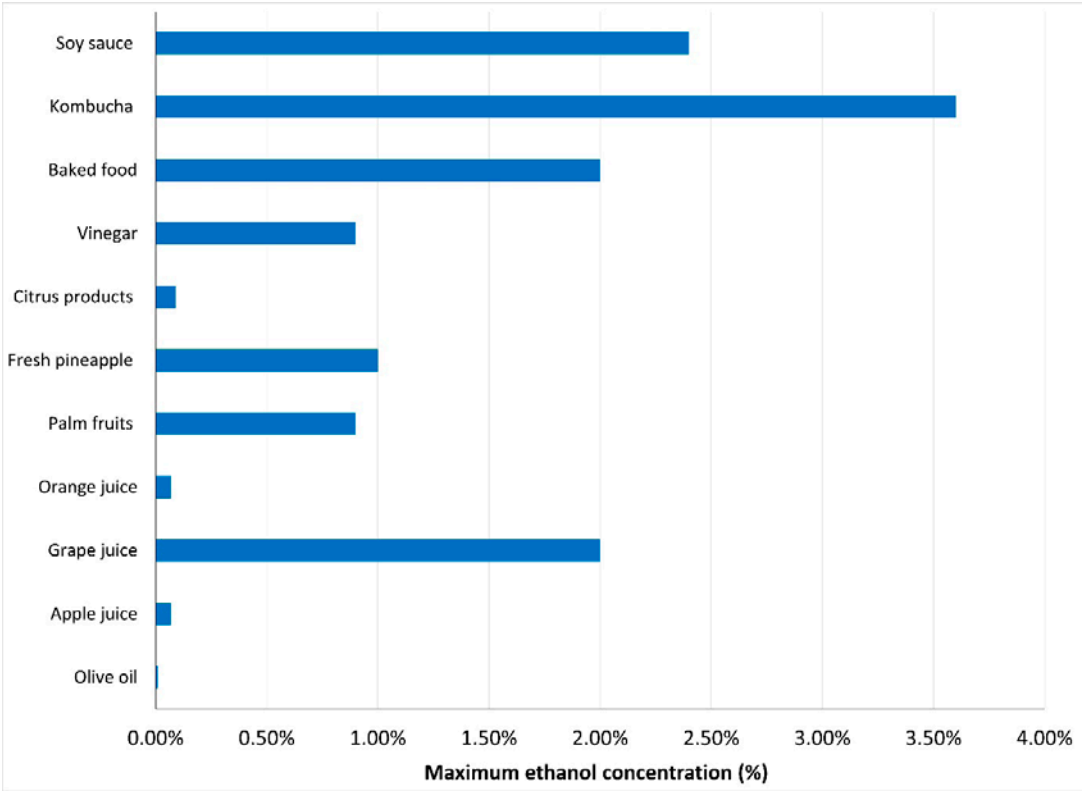


Figure 6. The highest concentration of ethanol detected in some food products (based on Reimann et al., 2023 [11]; Gorgus et al., 2016 [13]; Pourjabbar et al., 2021 [17]; Talebi et al., 2017 [24]; Park et al., 2017 [51])

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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REVIEW ARTICLE

# NURSE BURNOUT AS A PUBLIC HEALTH ISSUE AND ITS IMPACT ON PATIENT CARE QUALITY. A NARRATIVE REVIEW

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## ABSTRACT

Occupational burnout among nurses is a significant public health issue. It affects both nurses' well-being and the quality of patient care. The aim of this narrative review is to provide a comprehensive synthesis of four key aspects of occupational burnout among nurses, namely its prevalence, determinants, consequences for patient care and mental health, and available prevention strategies. Literature was identified through searches of PubMed and Google Scholar. Articles published in English between 2015 and 2026 were reviewed and selected according to predefined inclusion and exclusion criteria. Burnout develops through the interaction of organizational, psychosocial, and individual factors. The most important contributors include work overload, staffing shortages, low autonomy, psychosocial stress, personality traits, and health status. Higher burnout levels are associated with increased medical errors, patient falls, and missed nursing care. Burnout also contributes to lower patient satisfaction and poorer perceived quality of care. Prolonged stress increases the risk of depression, anxiety, sleep disturbances, reduced psychological resilience, and intentions to leave the profession, negatively impacting nurses' quality of life and social functioning. Effective preventive and therapeutic strategies include mindfulness-based programs, cognitive-behavioral therapy, physical exercise, and resilience training. These interventions may be delivered both in person and digitally. Their effectiveness improves in supportive environments with allocated participation time and leadership engagement. Interventions at individual, team, and system levels reduce emotional exhaustion and depersonalization, enhance staff well-being, and improve patient safety. In the context of a global nursing shortage and increased workloads following the COVID-19 pandemic, multi-level strategies to prevent occupational burnout are essential for protecting nurses' mental health and maintaining high-quality healthcare. The review highlights the importance of multi-level preventive interventions to reduce burnout and improve healthcare outcomes.

**Keywords:** *Maslach Burnout Syndrome, nursing workforce, clinical outcomes, psychosocial interventions, occupational stress*

## INTRODUCTION

Nurse burnout constitutes a significant problem in modern healthcare systems and is increasingly recognized as a public health challenge. Nursing work involves high psychological and physical demands. Nurses are responsible for patients' lives and frequently function under conditions of chronic stress and staff shortages. The phenomenon of professional burnout (also referred to as job burnout, burnout syndrome, or occupational burnout) was first described in the 1970s, although it is believed to have existed much earlier. Its lower prevalence at that time did not attract significant attention from researchers. The term was first defined by Herbert Freudenberger in his article "Staff burnout", published in 1974 in the Journal of Social Issues. He described burnout as "a state of extreme exhaustion resulting from excessive demands on the energy and all resources available to an individual" [1]. Burnout is a chronic state of work-related stress. It contributes to decreased engagement, emotional exhaustion, and dissatisfaction with professional responsibilities [2]. According to Christina Maslach, professional burnout is a syndrome characterized by emotional exhaustion, depersonalization, and reduced personal accomplishment. It may occur in individuals working under prolonged occupational stress. Today, this phenomenon is recognized as a significant health and social issue, affecting both individual quality of life and organizational functioning and efficiency [3]. Burnout is a multidimensional process that can manifest across various aspects of individual functioning. According to Christina Maslach's concept, three core components of this phenomenon can be distinguished:

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- Emotional exhaustion – considered the most visible and often the first symptom of burnout. It manifests as a sense of profound mental fatigue, lack of energy to perform professional duties, and difficulty coping with prolonged stress.
- Depersonalization – the next stage, associated with the development of a detached, often cynical attitude toward others, such as colleagues or patients. This may lead to treating them impersonally, which negatively affects interpersonal relationships in the workplace.
- Reduced personal accomplishment – involves a perception of low effectiveness in one's professional activities. The individual experiences decreased job satisfaction, may doubt their competencies, and this, in turn, leads to reduced motivation and work performance [3, 4].

Although the Maslach Burnout Inventory (MBI) and the three-dimensional model of burnout proposed by Christina Maslach remain the most widely used framework in burnout research, other conceptualizations and measurement tools have also been developed and applied in the literature. These include the Copenhagen Burnout Inventory (CBI), which distinguishes between personal, work-related, and client-related burnout, and the Oldenburg Burnout Inventory (OLBI), which conceptualizes burnout in terms of exhaustion and disengagement. The use of different theoretical models and instruments across studies reflects the heterogeneous nature of burnout research and contributes to variability in reported prevalence and outcomes among nurses. These instruments are well established in the burnout literature. This diversity in conceptual frameworks should be considered when interpreting findings across studies included in this review. Consequently, studies included in this review employ different conceptual frameworks and measurement instruments, which should be taken into account when interpreting and comparing reported findings on nurse burnout.

Nurse burnout represents a significant public health concern affecting both nurses' well-being and the quality of healthcare delivery. Chronic occupational stress contributes to emotional exhaustion and reduced work engagement. It may also impair communication and increase the risk of adverse patient outcomes, including medical errors and missed care. Burnout has also been associated with absenteeism, turnover intention, and workforce shortages, highlighting its systemic impact on healthcare organizations and patient safety [5, 6]. Under conditions of chronic occupational stress, nursing staff more frequently experience decreased engagement, which may result in reduced attentiveness, lower quality of communication with patients, and an increased risk of medical errors [7]. Nurse burnout also has an epidemiological dimension – the prevalence of this phenomenon within the nursing workforce is high, as confirmed by studies conducted in multiple countries, indicating its widespread nature among nurses [8]. Consequently, there is increased absenteeism, staff turnover, and withdrawal from the profession, further exacerbating workforce shortages in healthcare systems [9, 10]. From a public health perspective, the impact of burnout on patient safety is particularly important. Research indicates that higher levels of burnout among nurses are associated with more frequent adverse events, such as medication errors, hospital-acquired infections, and lower patient satisfaction with care [11]. Thus, burnout should be regarded as a risk factor for the deterioration of healthcare quality. In response to the growing scale of the problem, the World Health Organization recognized occupational burnout as a work-related phenomenon included in the International Classification of Diseases (ICD-11). This decision emphasized its importance for public health [12]. This highlights the need for preventive and interventional measures at organizational and systemic levels, such as improving working conditions, providing psychological support, and optimizing the workload of healthcare personnel.

The aim of this review article is to provide a comprehensive analysis of nurse burnout as a public health issue. Specifically, this review examines four key aspects: prevalence of nurse burnout, determinants and contributing factors, consequences for patient care and healthcare systems, including patient safety and service quality, and prevention and intervention strategies aimed at reducing burnout among nurses.

## METHODOLOGY OF THE NARRATIVE REVIEW

This narrative literature review was conducted to identify and synthesize current evidence regarding burnout among nurses, its determinants, consequences, and prevention strategies. A literature search was performed in PubMed and Google Scholar. Additional relevant publications were identified through manual screening of reference lists. The search strategy combined keywords and Medical Subject Headings (MeSH) related to the topic, including: "nurse burnout", "occupational burnout", "emotional exhaustion", "depersonalization", "nursing staff", "work-related stress", "mental health", "patient safety", "job satisfaction", and "burnout prevention". Boolean operators (AND, OR) were used to refine the search. The review included publications published between 2009 and 2026 in English or Polish. Original research articles, systematic reviews, and meta-analyses focusing on burnout among nurses were eligible for inclusion. Studies concerning other

healthcare professions without separate analyses for nurses, conference abstracts, editorials, commentaries, and publications lacking full-text availability were excluded. The identified records were screened based on title and abstract, followed by full-text assessment for relevance to the objectives of the review. Particular attention was given to studies examining the prevalence, determinants, consequences, and prevention of burnout among nurses. As a narrative review, this study does not follow formal systematic review procedures such as PRISMA-guided screening or quantitative synthesis.

## NURSE BURNOUT – PREVALENCE AND DETERMINANTS

Nurse burnout is a widespread and increasingly recognized phenomenon within healthcare systems. The previously mentioned symptoms of the syndrome – emotional exhaustion, depersonalization, and reduced personal accomplishment – affect a substantial proportion of healthcare personnel, particularly in high-workload units. Among the three dimensions of burnout, emotional exhaustion and depersonalization are the most frequently discussed in the literature [3, 4, 9].

### Global studies

Several meta-analyses indicate that the prevalence of burnout among nurses ranges from 11% to 56%. This percentage further increased during the COVID-19 pandemic, largely due to healthcare system overload and workforce shortages [13]. Ge et al. [13] conducted a meta-analysis of studies published between 2012 and 2022 and estimated the global prevalence of burnout among nurses at approximately 30%. The prevalence increased over time, particularly in Europe and Africa. A total of 94 studies reporting burnout prevalence among nurses were included in the analysis. The global mean prevalence was 30%. Subgroup analyses showed that specialization, geographic region, and publication year were the main sources of heterogeneity. Meta-regression indicated a gradual increase in prevalence over the past decade, particularly in Europe, Africa, and among nurses working in obstetrics. No significant changes were observed in intensive care units, oncology departments, or emergency units [13].

Getie et al. [14] analyzed 14 systematic reviews and meta-analyses sourced from various databases. The results indicated that the global prevalence of nurse burnout encompasses three main dimensions: emotional exhaustion, depersonalization, and reduced personal accomplishment. The highest levels of emotional exhaustion were reported among nurses working during the COVID-19 pandemic. Oncology nurses exhibited the highest rates of depersonalization, while intensive care unit nurses reported the greatest levels of reduced personal accomplishment.

Similarly, Woo et al. [8] reported that approximately one in ten nurses worldwide experienced burnout symptoms. Collectively, the reviewed studies suggest that the nursing work environment carries a substantial risk of occupational burnout. The observed differences are likely related to variations in healthcare systems, nursing specialties, measurement tools, and working conditions across countries [8, 13, 14].

Global analyses further indicate that burnout prevalence and its manifestations vary across geographical regions and healthcare systems. Higher prevalence has been reported particularly in Europe and Africa, suggesting that differences in workforce availability, organizational support, healthcare system capacity, and broader socioeconomic conditions may influence the risk of burnout among nurses [13, 14]. Studies from the United States and low- and middle-income countries similarly point to the role of organizational constraints, staffing shortages, and socioeconomic factors in contributing to burnout among nursing personnel [13, 14].

### Studies conducted in Poland

Evidence from European countries confirms that burnout remains a major challenge for the nursing workforce. In Poland, Nalepa et al. [15] focused on analyzing the relationship between shift work and burnout among nurses. The study demonstrated a significant association between shift work and the increased risk of burnout. Nurses working in shift systems, especially night and rotating shifts, more frequently experienced emotional

Table 1. Global prevalence of nurse burnout (systematic reviews and meta-analyses)

| Author (year) | Scope | Study type | Main findings |
|---|---|---|---|
| Woo et al. 2020 [8] | Global | Systematic review and meta-analysis | Approximately 11% of nurses worldwide experienced burnout symptoms; prevalence varied across regions and clinical settings. |
| Ge et al. 2023 [13] | Global | Systematic review and meta-analysis | Burnout prevalence ranged from 11% to 56%, with an increasing trend observed over time, particularly in Europe and Africa. |
| Getie et al. 2025 [14] | Global | Umbrella review | Emotional exhaustion was the most prevalent dimension of burnout, especially during the COVID-19 pandemic. |

exhaustion, depersonalization, and reduced personal accomplishment.

A cross-sectional study conducted in Poland showed that employed in hospitals in the Małopolska region showed that 39% of participants experienced a moderate level of emotional exhaustion, more than 70% presented low levels of depersonalization, and 49% reported reduced personal accomplishment [16].

Research conducted by Łopatkiewicz [17] among psychiatric nurses employed in the Mazowieckie region also demonstrated a substantial risk of burnout. According to the study findings, 51% of respondents experienced emotional exhaustion and 46% reported increased fatigue. Furthermore, education level, age, and professional experience influenced both mental health status and burnout intensity.

Similarly, Rutka et al. [18] found that approximately one-third of nurses working in anesthesiology and intensive care settings reported symptoms of burnout. Moreover, a considerable proportion of respondents perceived their professional group as particularly vulnerable to the development of this syndrome. Despite differences in study populations and clinical settings, the reviewed European studies showed consistent findings. Shift work, high workload, and demanding psychosocial working conditions were repeatedly associated with increased burnout risk [15-18].

The studies summarized in Table 2 demonstrate variability in burnout prevalence across European nursing settings, likely reflecting differences in work organization, clinical specialization, and psychosocial working conditions.

The available Polish evidence suggests that burnout is strongly associated with shift work, psychosocial workload, staffing shortages, and increasing healthcare demands. Although individual characteristics such as age, education level, and professional experience may influence burnout severity, organizational factors consistently appear to exert the strongest impact on nurses' well-being [15-18]. This finding highlights the importance of system-level interventions, with improvements in staffing adequacy, working conditions, and managerial support potentially being more effective than interventions focused solely on individual coping strategies.

## FACTORS INFLUENCING OCCUPATIONAL BURNOUT AND PREVENTION STRATEGIES

Overall, burnout appears to result from an interaction between organizational pressures and individual vulnerability rather than being solely an individual psychological problem. Consequently, effective prevention strategies should address both workplace conditions and individual resilience, including workload management, adequate staffing, supportive leadership, and access to psychological support [14, 18]. Burnout develops as a consequence of prolonged exposure to occupational stressors and reflects a combination of organizational and individual risk factors that may reinforce one another. From a public health perspective, understanding these determinants is essential, as nurse burnout affects not only staff well-being but also the quality and safety of patient care.

Organizational factors related to the work environment constitute some of the most important determinants of burnout risk among nurses. These include:

- Work overload and staff shortages – an insufficient number of nurses is associated with higher workloads, chronic physical and emotional stress, and a reduced sense of control over professional tasks [18].
- Low autonomy and limited organizational support – lack of decision-making opportunities, insufficient support from supervisors, team conflicts, and difficult interpersonal relationships have been

Table 2. Nurse burnout in Polish studies

| Author (year) | Country | Study design | Population | Main findings |
|---|---|---|---|---|
| Nalepa et al. 2025 [15] | Poland | Cross-sectional study | Hospital nurses | Shift work was associated with higher levels of emotional exhaustion, depersonalization, and reduced personal accomplishment. |
| Nowacka et al. 2022 [16] | Poland | Cross-sectional study | Hospital nurses | A substantial proportion of nurses experienced emotional exhaustion and reduced personal accomplishment. |
| Łopatkiewicz 2020 [17] | Poland | Cross-sectional study | Psychiatric nurses | Burnout symptoms and fatigue were common among psychiatric nurses and were influenced by demographic and professional factors. |
| Rutka et al. 2024 [18] | Poland | Cross-sectional study | ICU and anaesthesiology nurses | Approximately one-third of nurses reported burnout symptoms and perceived their professional group as highly vulnerable to burnout. |

associated with higher levels of burnout among nurses [18, 19].
- Poor work organization – excessive bureaucracy, unclear job responsibilities, shift work, and inadequate logistical or equipment resources are associated with higher levels of occupational stress among nurses [20].

Psychosocial work conditions – factors such as the nurse-to-patient ratio, on-call duties beyond standard hours, and heightened psychosocial demands are associated with an increased risk of burnout [21].

The consistency of these findings across multiple studies suggests that organizational conditions are important and potentially modifiable determinants of burnout. Therefore, interventions targeting workplace organization may contribute more substantially to burnout reduction than interventions focusing exclusively on individual-level factors [18-21]. Excessive workload has been associated with reduced attention, more frequent medical errors, and lower patient satisfaction. These findings suggest a relationship between organizational factors and healthcare quality [18, 21].

Alongside organizational factors, individual predispositions also influence nurses' susceptibility to burnout:
- Psychological resilience and stress coping strategies – individuals with lower resilience or maladaptive coping strategies are more prone to emotional exhaustion and decreased work motivation [22].
- Personality traits and psychophysical health – mental health disorders, chronic fatigue, health problems, and inadequate recovery after work increase the risk of burnout [23].
- Sociodemographic factors – age, work experience, place of residence, and education level may modify burnout risk, although these relationships often depend on other environmental and individual conditions [23].

However, evidence regarding the influence of individual characteristics remains less consistent than findings related to organizational factors. This suggests that personal attributes may modify burnout risk but are unlikely to constitute its primary cause in the absence of adverse working conditions [22, 23].

In addition, nursing work involves several profession-specific stressors that make this professional group particularly vulnerable to burnout:
- Constant patient contact and emotional burden – have been linked to emotional exhaustion and empathy fatigue among nurses [19, 24].
- Shift work and irregular life rhythms – are associated with circadian rhythm disruption, poorer sleep quality, increased psychophysical strain, and a higher risk of burnout [20].
- High responsibility for patients – the need for constant vigilance and rapid decision-making under time pressure has been associated with chronic occupational stress [25].

## IMPACT OF BURNOUT ON PATIENT CARE QUALITY

Patient safety is a fundamental principle in the provision of healthcare services, which all healthcare personnel should adhere to [26]. A systematic review encompassing 20 studies confirmed the existence of a relationship between nurse burnout and the quality and safety of healthcare, although a quantitative synthesis of the data to determine the strength of this association was not performed [27]. According to recent research, the proportion of nurses experiencing burnout is higher than in other healthcare professional groups [28, 29]. Several studies have demonstrated that nurse burnout is significantly associated with poorer patient safety and healthcare quality outcomes.

Higher burnout levels have been consistently associated with adverse patient safety and care quality outcomes, including increased medication errors, patient falls, hospital-acquired infections, missed nursing care, and lower patient satisfaction. Burnout has also been linked to poorer self-assessed quality of care among nurses, although evidence does not consistently show an association with standardized mortality rates [6].

Several studies further support the relationship between burnout and patient safety-related outcomes. Ryu et al. [30] demonstrated that burnout among shift-working nurses was negatively associated with patient safety-related outcomes, while coping skills partially mediated this relationship, suggesting that strengthening coping mechanisms may mitigate some of the negative effects of occupational stress. Similarly, Zabin et al. [31] reported a significant association between occupational stress, patient safety culture, and patient safety outcomes, although heterogeneity in study designs and working conditions limited direct comparability.

Beyond direct patient safety outcomes, burnout has also been associated with psychosocial and interpersonal factors relevant to clinical practice. Zhou's [32] review indicated a consistent negative correlation between empathy and nurse burnout, although the strength of this relationship may depend on clinical context and measurement tools. Longitudinal evidence by Dong et al. [33] further confirmed a bidirectional relationship between burnout and empathy, particularly in relation to depersonalization and reduced personal accomplishment, suggesting that persistent burnout is associated with lower empathy levels over time.

Table 3. Association between nurse burnout and patient care quality outcomes

| Author (year) | Scope | Study design | Main outcomes assessed | Key findings |
|---|---|---|---|---|
| Li et al. 2024 [6] | International | Systematic review | Patient safety and quality of care | Higher burnout was associated with more frequent adverse events, missed care, and lower patient satisfaction. |
| Ryu et al. 2021 [30] | South Korea | Cross-sectional study | Patient safety-related outcomes | Burnout was negatively associated with patient safety outcomes, while coping skills partially reduced this effect. |
| Zabin et al. 2023 [31] | International | Systematic review | Patient safety culture and outcomes | Occupational stress and burnout were associated with poorer patient safety culture and outcomes. |
| Dong et al. 2025 [33] | China | Longitudinal study | Empathy and quality of care | Persistent burnout was associated with lower empathy and poorer interpersonal functioning over time. |
| Mazur et al. 2023 [34] (Selected aspects of patient communication and occupational burnout among nurses working during the COVID-19 pandemic) | Poland | Cross-sectional study | Communication and care quality | Higher burnout levels were associated with poorer communication and reduced care quality indicators. |

Communication quality has also been identified as an important correlate of burnout. A nationwide Polish study conducted during the COVID-19 pandemic found that higher burnout levels were associated with poorer communication skills, particularly in relation to psychological distance and emotional deterioration. Notably, communication deficits were most strongly linked to specific burnout dimensions, highlighting the role of interpersonal functioning in occupational well-being [34].

## BURNOUT AND MENTAL HEALTH OF HEALTHCARE PERSONNEL

Mental health in the workplace is one of the key factors determining job satisfaction and, consequently, affects employee retention and organizational efficiency [35]. Poor mental health limits an individual's ability to lead an active and fulfilling life. It often coexists with disorders such as depression, anxiety, and chronic feelings of threat [36]. This issue is particularly significant in the healthcare sector, where employees are exposed to high psychological and physical demands. Nurses, as frontline personnel, operate in conditions of constant patient contact and rapidly changing, often stressful clinical situations, which further intensify occupational burdens [37]. Increasing occupational stress among nurses is associated with lower job satisfaction, poorer perceived work quality, and a greater intention to leave the profession, contributing to the ongoing global nursing workforce crisis [38, 39].

In a study by Buivydienė et al. [40], a high level of depression was noted in 2.4% of respondents, while stress affected 1.4%. Lack of social and organizational support has also been associated with increased burnout, poorer mental health outcomes, and higher turnover intention among nurses [41]. Similarly, high burnout levels among nurses have been associated with job dissatisfaction and increased intention to change employment [42]. Negative mental health experiences among nursing staff have been associated with poorer quality of patient care and a higher likelihood of clinical errors [43]. Merkuri et al. [44] noted that burnout is associated with poorer physical and emotional health among nurses, as well as less favorable organizational outcomes.

Today, the quality of nursing care is crucial, serving as a key determinant of patient safety and recovery. Its level is influenced by various environmental factors, including hospital noise [45]. A significant portion of nurses serve as frontline personnel, maintaining direct contact with patients; thus, their actions and decisions are closely related to patient health and safety outcomes, highlighting the importance of civil responsibility in clinical diagnostics [46]. Liang et al. [47] identified 176 articles. High burnout levels were strongly associated with an increased risk of mental health problems. Burnout was linked to a more than sevenfold increase in depression risk and a more than fourfold increase in anxiety and

stress. It was also associated with substantially lower psychological resilience. Moreover, severe burnout was associated with nearly a fourfold higher risk of intending to change jobs compared to remaining in the current position, which in turn was related to the quality of care provided. In 2020, burnout prevalence among nurses in Brazil was reported at 14.3%, with symptoms including irritability, insomnia, anxiety, and social withdrawal, which were associated with reduced work performance and increased interpersonal conflicts [49, 50].

The studies summarized in Table 4 consistently demonstrate that nurse burnout is strongly associated with adverse mental health outcomes, including depression, anxiety, reduced resilience, sleep disturbances, and increased turnover intention.

Nursing is characterized by consistently high occupational demands, which may contribute to cumulative work-related strain and increased vulnerability to stress-related outcomes [48]. Burnout has been associated with reduced quality of patient care, increased risk of clinical errors, higher absenteeism, lower job satisfaction, and interpersonal difficulties in both professional and personal contexts [48]. In addition, evidence indicates that burnout negatively affects nurses' quality of life across physical, emotional, and social domains. Higher levels of burnout have also been linked to poorer sleep quality, including insomnia and reduced sleep duration [48, 51]. Overall, these findings suggest that burnout exerts a multidimensional impact on both professional functioning and personal well-being of nurses.

## PREVENTION AND COUNTERACTING BURNOUT

Jiménez-García et al. [52] analyzed a wide range of psychosocial, behavioral, and organizational interventions aimed at reducing burnout among nurses. The reviewed evidence demonstrated that appropriately planned and structured interventions can significantly decrease burnout levels, particularly emotional exhaustion and depersonalization. Programs based on mindfulness and positive psychology, including digital formats, produced especially effective and long-lasting results. Interventions such as yoga, physical exercise, and cognitive-behavioral therapy also reduced stress levels, although these effects were often short-term.

The effectiveness of organizational and team-based interventions depended largely on workplace conditions. Supportive leadership, allocated participation time, and program continuity were

Table 4. Association between nurse burnout and mental health outcomes

| Author (year) | Scope | Study design | Mental health outcomes assessed | Key findings |
|---|---|---|---|---|
| Liang et al. 2025 [47] | Global | Systematic review and meta-analysis | Depression, anxiety, stress, resilience, turnover intention | Burnout was strongly associated with poorer mental health, lower resilience, and increased intention to leave the profession. |
| Buivydienė et al. 2025 [40] | Lithuania | Cross-sectional study | Depression and stress | Burnout was associated with adverse mental health indicators, including symptoms of depression and stress. |
| Merkuri et al. 2025 [44] | Europe | Review | Physical and emotional health | Burnout was linked to poorer physical and emotional health as well as unfavorable organizational outcomes. |
| Ambani et al. 2020 [42] (The nursing practice environment and nurse job outcomes: a path analysis of survey data) | Not specified | Cross-sectional study | Job satisfaction and turnover intention | Higher burnout levels were associated with lower job satisfaction and greater intention to leave the profession. |
| Vidotti 2018 et al. [51] (Burnout syndrome and shift work among nursing staff) | International | Observational studies | Sleep quality and insomnia | Burnout was consistently associated with poor sleep quality, insomnia, and reduced sleep duration. |

identified as particularly important factors contributing to intervention success [52]. Similarly, a scoping umbrella review by Sampedro et al. [53] showed that nurse-focused interventions, especially coping skills training, mindfulness-based interventions, and relaxation techniques, significantly reduced emotional exhaustion and depersonalization These dimensions are closely associated with employment stability, quality of care, and patient safety.

The systematic review by Sharin et al. [54] highlighted the important role of psychoeducational interventions in mitigating burnout among nurses. Both single and combined interventions, particularly those based on mindfulness (MBI) and cognitive-behavioral therapy (CBT), were found to effectively reduce burnout levels. However, the long-term sustainability of these effects remains uncertain and requires further longitudinal research. The authors also emphasized the advantages and limitations of different delivery formats. In-person interventions allow for more individualized support, whereas digital and hybrid solutions improve accessibility and flexibility.

Additional evidence suggests that burnout prevention strategies may also improve broader organizational and patient-related outcomes. Cohen et al. [55] reported that workplace interventions contributed to improved well-being, increased engagement and psychological resilience, and reduced burnout among healthcare workers. However, some studies were limited by methodological constraints, including the absence of control groups and insufficient follow-up monitoring. Results reported by Li et al. [6] further suggest that system-level interventions aimed at reducing nurse burnout may improve patient care outcomes. Likewise, Lee et al. [56] demonstrated in a systematic review and meta-analysis that both in-person and online group interventions may reduce overall burnout levels, emotional exhaustion, and depersonalization among nurses.

## INTERVENTIONS FOR PREVENTION AND REDUCTION OF NURSE BURNOUT

The evidence suggests that organizational determinants exert a stronger and more consistent influence on burnout development than individual factors, underscoring the need for system-level preventive strategies. Although individual-focused interventions such as mindfulness-based and cognitive-behavioral approaches may reduce emotional exhaustion and depersonalization, their long-term effectiveness appears limited without supportive organizational conditions.

The studies summarized in Table 5 indicate that both individual- and organizational-level interventions may effectively reduce nurse burnout, particularly emotional exhaustion and depersonalization. However, variability in intervention type and study methodology limits conclusions regarding long-term effectiveness.

System-level and team-based interventions appear to be more effective when implemented in supportive organizational environments characterized by strong

Table 5. Interventions for prevention and reduction of nurse burnout

| Author (year) | Scope | Study design | Type of intervention | Key findings |
|---|---|---|---|---|
| Jiménez-García et al. 2026 [52] | International | Systematic review | Mindfulness-based, behavioral, and organizational interventions | Interventions significantly reduced emotional exhaustion and depersonalization, with the strongest effects observed for mindfulness-based approaches. |
| Sampedro et al. 2026 [53] | International | Umbrella review | Coping skills training, mindfulness, relaxation techniques | Interventions consistently improved coping capacity and reduced burnout dimensions. |
| Sharin et al. 2025 [54] | International | Systematic review | Psychoeducational and cognitive-behavioral interventions | Both in-person and digital interventions were effective in reducing burnout, although long-term effects remain uncertain. |
| Cohen et al. 2023 [55] | International | Systematic review | Workplace and organizational interventions | Organizational interventions improved well-being, resilience, and work engagement while reducing burnout. |
| Li et al. 2024 [6] | International | Systematic review | System-level healthcare interventions | Reductions in burnout were associated with improvements in patient care outcomes. |
| Lee et al. 2023 [56] | International | Systematic review and meta-analysis | Group-based interventions | Structured in-person and online interventions significantly reduced burnout and emotional exhaustion. |

leadership and protected time for participation. However, the current evidence base remains limited in terms of long-term follow-up, highlighting the need for future research focusing on the sustainability of intervention effects and the identification of mechanisms underlying lasting behavioral and organizational change. Future research should also explore strategies to enhance psychological resilience among nurses and to adapt intervention programs to evolving healthcare work conditions, including increased digitalization and hybrid care models following the COVID-19 pandemic. Overall, evidence supports the implementation of multi-level prevention strategies integrating organizational and individual approaches to improve nurses' well-being, strengthen workforce retention, and enhance overall healthcare quality.

## LIMITATIONS

The findings presented in this review should be interpreted in light of several limitations of the available literature. First, the majority of studies examining burnout among nurses are observational and cross-sectional in design, which limits the ability to establish causal relationships between identified risk factors and burnout outcomes. Consequently, although associations between working conditions and burnout are consistently reported, causality cannot be definitively inferred.

Second, most studies rely on self-reported questionnaires, including the Maslach Burnout Inventory and similar survey instruments. Self-reported measures may be affected by recall bias, response bias, and social desirability bias, potentially influencing the accuracy of reported burnout levels.

Third, considerable heterogeneity exists across studies regarding sample characteristics, healthcare settings, countries, and measurement tools, making direct comparisons difficult. Differences in organizational structures, staffing models, and healthcare systems may limit the generalizability of the findings.

Despite these limitations, the reviewed literature consistently demonstrates that burnout among nurses represents a significant occupational and public health concern, warranting further longitudinal and intervention-based research.

This narrative review has several limitations. First, as a narrative review, it does not follow the rigorous methodology of a systematic review, which may increase the risk of selection bias despite the use of predefined search terms and eligibility criteria. Second, the included studies were heterogeneous with respect to study design, healthcare settings, populations, and instruments used to assess burnout, limiting direct comparison of findings. Third, most of the available evidence was derived from cross-sectional studies, which restricts the ability to establish causal relationships between burnout, its determinants, and patient care outcomes. Finally, publication bias cannot be excluded, as studies reporting significant associations may be more likely to be published than studies with null or inconclusive findings.

## CONCLUSIONS

Occupational burnout among nurses is a multifactorial and work-related phenomenon driven primarily by organizational and psychosocial conditions, including workload, staffing shortages, shift work, and limited managerial support. This narrative review synthesizes current evidence indicating that burnout represents a systemic occupational risk embedded within healthcare environments rather than an individual psychological problem.

Across the included literature, nurse burnout is consistently associated with a wide range of adverse outcomes. At the individual level, it is linked to poorer mental health, including increased symptoms of depression, anxiety, stress, reduced psychological resilience, sleep disturbances, lower job satisfaction, and higher turnover intention. At the organizational level, it contributes to reduced workforce stability and impaired healthcare system functioning.

Importantly, burnout is also consistently associated with reduced patient care quality, including increased risk of clinical errors, reduced patient safety, and lower patient satisfaction. These findings highlight its dual impact on both healthcare workers and system-level outcomes.

Overall, effective prevention and management of nurse burnout require integrated, multi-level strategies combining improvements in workplace organization with interventions supporting individual resilience. The current evidence base is largely cross-sectional, limiting causal inference and emphasizing the need for longitudinal and intervention-based research to strengthen future recommendations.

**Conflict of interest**
*The authors declare no conflict of interest.*

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REVIEW ARTICLE

# KETOGENIC DIET IN ADULT OBESITY: SAFETY, LIMITATIONS, AND EVIDENCE FROM VARIOUS CLINICAL APPLICATIONS

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## ABSTRACT

The aim of this study was to present the current state of knowledge regarding the use of the ketogenic diet in the treatment of obesity in adults, with particular emphasis on its safety, indications, and contraindications, and to relate these findings to its established use in drug-resistant epilepsy and other clinical conditions. Despite growing interest in its clinical application, the effectiveness and safety of this intervention remain a matter of debate. A narrative review of the literature available in PubMed and Google Scholar from 2021 to 2024 was conducted using the keywords "ketogenic diet", "obesity", "epilepsy", "type 2 diabetes", "cardiovascular diseases", "PCOS", "neurological diseases", and "psychiatric disorders", as well as their combinations with AND/OR operators. Meta-analyses, randomized controlled trials, systematic reviews, and selected clinical trials evaluating the effectiveness and safety of the ketogenic diet were included in the analysis. The ketogenic diet demonstrates effectiveness in short-term weight loss and improvement of selected metabolic parameters in patients with obesity. However, its long-term effects remain equivocal and do not appear to offer significant advantages over other dietary strategies. The diet is associated with a risk of adverse effects and requires appropriate clinical monitoring. While it is a recognized and effective therapeutic option for drug-resistant epilepsy, its use in other conditions has not been established as a standard therapeutic approach. The ketogenic diet may be considered as part of obesity treatment in carefully selected patients, provided that potential benefits and risks are individually assessed. Further high-quality studies are needed to determine its long-term effectiveness and safety.

**Keywords:** *ketogenic diet, adult obesity, safety, limitations, evidence from various clinical applications*

## INTRODUCTION

Obesity is a lifestyle disease that poses one of the most serious challenges to modern medicine. Its prevalence is increasing in many countries around the world [1, 2]. This disease is associated with an increased risk of numerous complications, including cardiovascular disease, type 2 diabetes, and certain cancers, which translates into a significant burden on healthcare systems [2]. The basic recommendation for people with obesity in the doctor's office is lifestyle changes, primarily related to dietary modifications and increased physical activity [2].

One nutritional model that has gained significant popularity in recent years is the ketogenic diet [1]. It is characterized by a significant reduction in carbohydrate intake while simultaneously increasing fat consumption, leading to the induction of ketosis. Not every low-carbohydrate diet is a ketogenic diet. Nutritional ketosis is achieved only when carbohydrate intake is sufficiently restricted, whereas less restrictive low-carbohydrate dietary patterns may provide metabolic benefits without inducing ketosis. Therefore, distinguishing between these dietary models is essential when interpreting clinical evidence. The mechanism of action of ketosis is associated with, among other things, changes in energy metabolism, reduced insulin levels, and an impact on appetite regulation. Numerous studies have shown that the ketogenic diet can lead to significant weight loss in the short term, but its long-term effectiveness and safety remain controversial [2].

Despite the growing popularity of the ketogenic diet in the treatment of obesity, significant doubts remain

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regarding its impact on lipid profiles, kidney function, the risk of nutritional deficiencies, and the long-term maintenance of therapeutic effects. At the same time, this diet is well-established in the treatment of drug-resistant epilepsy, where its effectiveness has been confirmed in numerous clinical trials, making it an interesting example of a nutritional intervention with documented therapeutic effects [3, 4]. In recent years, there has also been growing interest in the potential use of the ketogenic diet in other conditions, including metabolic, neurological, and cancer diseases. However, for most of these indications, available data remain limited and require further research [2, 5].

The aim of this paper is to present the current state of knowledge on the use of the ketogenic diet in the treatment of obesity in adults, with particular emphasis on indications, contraindications and safety of its use in clinical practice, as well as to relate these data to its role in the treatment of drug-resistant epilepsy, cancer and other disease states in which the ketogenic diet is considered as a therapy or its component.

## MATERIALS AND METHODS

This work is a narrative review of the literature. The analysis was based on scientific publications available in the PubMed and Google Scholar databases, published primarily between 2021 and 2024. The following keywords were used in the search: "ketogenic diet," "obesity," "weight loss," "epilepsy," "type 2 diabetes," "cardiovascular diseases," "PCOS," "neurological diseases," and "psychiatric disorders." Meta-analyses, systematic reviews, randomized controlled trials, and selected clinical trials on the efficacy, safety, and clinical applications of the ketogenic diet were included in the analysis. Publications that did not meet the criteria for thematic relevance, publications with limited data availability, and articles duplicating previously analyzed results were excluded. After a preliminary review of titles and abstracts, publications that most closely matched the topic of the study were selected, with particular emphasis on studies concerning the treatment

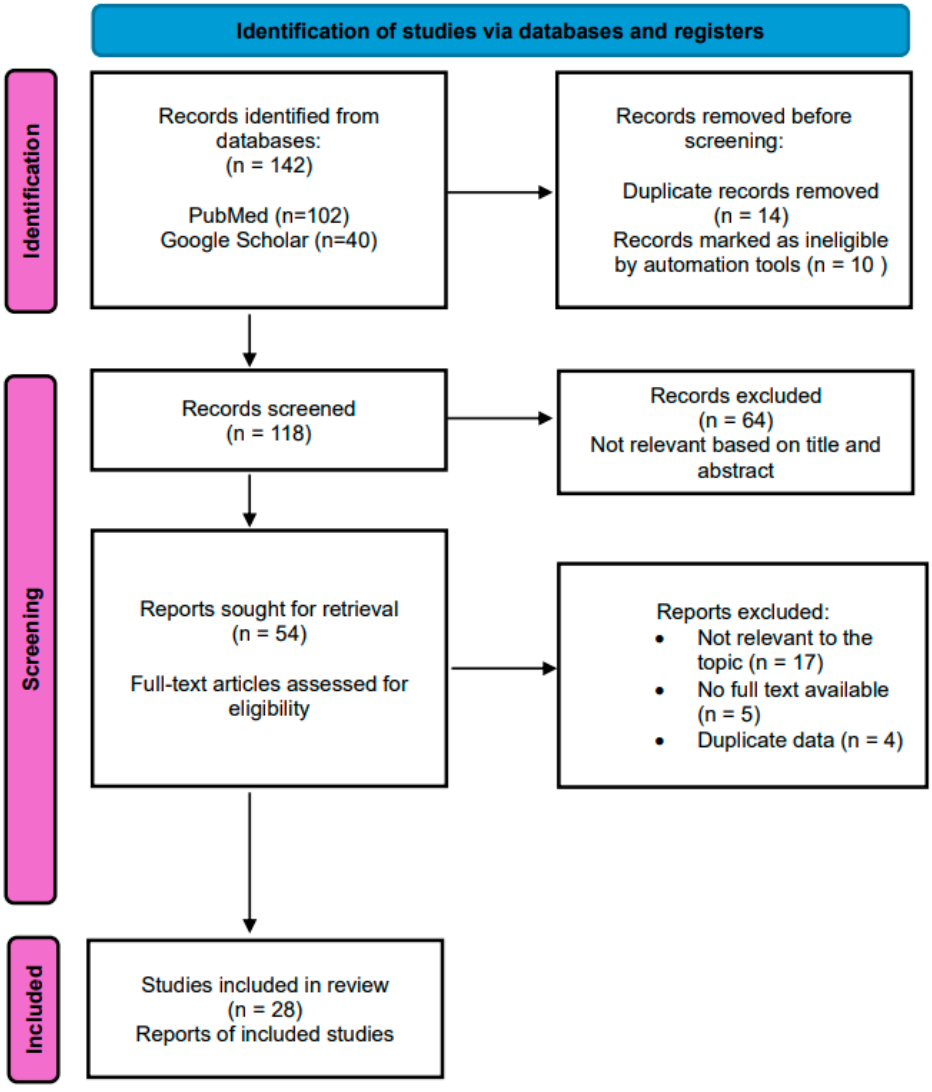


Figure 1. Flow diagram of study selection based on the PRISMA framework

of obesity in adults. The publication selection process is presented schematically in Figure 1, based on the PRISMA framework.

## DESCRIPTION OF THE STATE OF KNOWLEDGE

### Mechanism of action of the ketogenic diet

The premise of the ketogenic diet is to achieve ketosis, a metabolic state in which ketone bodies, formed in the liver from fatty acids, become the body's primary energy source. To achieve this state, carbohydrate intake must be significantly reduced while simultaneously increasing fat consumption, whereas protein intake should be adjusted to individual requirements rather than deliberately increased. The classic ketogenic diet is based on a 4:1 lipid to nonlipid weight ratio, meaning 80% of energy comes from fat, 15% from protein, and 5% from carbohydrates. However, these ratios are sometimes adjusted to 3:1 or 2:1 to tailor the diet to the individual patient [3, 6-8].

In the human body, conditions of limited glucose availability result in decreased insulin levels and increased glucagon secretion, which promotes increased lipolysis in adipose tissue. The released fatty acids are transported to the liver, where they are converted through β-oxidation into ketone bodies, such as β-hydroxybutyrate, acetoacetate, and acetone [1, 2, 6, 7, 9]. These compounds constitute an alternative energy source for many tissues, including the central nervous system [5, 8, 9].

Appetite regulation is a significant mechanism responsible for weight loss during a ketogenic diet. It has been shown that ketosis can reduce the feeling of hunger by affecting the satiety centers in the hypothalamus and modulating appetite-regulating hormones such as ghrelin and leptin [6]. Furthermore, increased protein and fat consumption may promote prolonged satiety after a meal [1, 6]. An additional factor in weight loss may also be increased metabolic energy expenditure associated with gluconeogenesis [1, 6].

A ketogenic diet also affects the functioning of the nervous system, as ketone bodies are an efficient energy source for neurons and exhibit neuroprotective effects, including by reducing oxidative stress, modulating neurotransmission, and influencing mitochondrial function [3, 7, 8, 10]. These properties form the basis for using a ketogenic nutritional model in the treatment of drug-resistant epilepsy, which has led to a reduction in the frequency of seizures in some patients [3].

Due to its multifaceted effects on cellular metabolism, oxidative stress, and mitochondrial function, the ketogenic diet is also being studied in the context of other conditions, including neurodegenerative, metabolic, and cancer diseases [3, 5, 7-10]. These mechanisms may potentially play a therapeutic role, but their clinical significance in most of these conditions has not yet been clearly confirmed.

### The ketogenic diet in the treatment of obesity

Due to its growing popularity in recent years, the ketogenic diet is one of the most frequently analyzed nutritional models in the treatment of obesity in adults. Numerous randomized controlled trials and meta-analyses have been published assessing its effectiveness in weight loss and its impact on metabolic parameters.

Clinical studies suggest that the ketogenic diet results in significant weight loss, often greater than that of low-fat diets. A meta-analysis demonstrated that very-low-carbohydrate ketogenic diets were associated with an additional mean weight loss of 0.91 kg compared with low-fat dietary interventions [6, 11]. These findings are particularly favorable in the short term (up to 6 months), and the mechanism of this effect is multifactorial and includes both decreased appetite associated with ketosis and hormonal and metabolic changes favoring the use of adipose tissue as the primary energy source [1, 6, 11, 12].

However, the long-term effectiveness of the ketogenic diet is less clear and beneficial. Some studies indicate that after 12 months, the differences in weight loss between the ketogenic diet and other nutritional strategies diminish or disappear. The reasons are attributed, among others, to increased water loss in the initial stages of this dietary pattern and the difficulty of maintaining a restrictive diet long-term [1, 13].

The effectiveness of a ketogenic diet is assessed not only based on weight loss but also on its impact on cardiovascular risk factors. It has been shown that ketosis can lead to improved glycemic control, reduced triglyceride levels, and increased HDL cholesterol levels [1, 6, 10, 11, 13]. On the other hand, some studies report an ambiguous or even negative effect on LDL cholesterol levels, raising questions about the long-term safety of this diet [1, 10]. The advantage of the ketogenic diet over other dietary patterns in generating muscle mass growth has also been considered, which would also be a positive indicator of the positive impact of ketosis on individuals with obesity. However, the study results did not reveal significant differences between groups using different diets [14].

A significant limitation of the ketogenic diet's effectiveness is its dependence on patients' adherence to dietary recommendations. The limited variety of products may lead to long-term non-adherence to the diet. This dietary model is characterized by a high degree of restriction; a single deviation from the diet

may result in a state of ketosis and, consequently, a lack of interventional effectiveness [1, 3].

In summary, the ketogenic diet can be an effective treatment for obesity in adult patients, but its effects are most noticeable in the short term, and in the long term, it has no observed advantage over other dietary strategies. It is necessary to individualize recommendations, consider potential benefits and risks, and assess the likelihood of adherence to the diet before implementing this form of therapy [6].

**Ketogenic diet in the treatment of drug-resistant epilepsy**

One of the first and best-described applications of the ketogenic diet in the scientific literature is the treatment of drug-resistant epilepsy. Unlike the treatment of obesity, where scientific data is ambiguous and sometimes contradictory, the effectiveness of the ketogenic diet in reducing the frequency of seizures has been confirmed by numerous clinical studies [4, 5, 15].

Drug-resistant epilepsy is characterized by a failure to achieve seizure control despite the use of at least two appropriately selected antiepileptic drugs [3, 4]. In this group of patients, the ketogenic diet is an important therapeutic option, used as a standalone treatment or as part of a combined therapy [3, 5]. Studies have shown that in some patients, the diet leads to a reduction in seizure frequency by over 50%, and in some cases even to their complete cessation [3, 5].

The effectiveness of the ketogenic diet in epilepsy is mediated by a number of complex biochemical and neurophysiological processes. The mechanism of action of this nutritional model is not yet fully understood, but it is hypothesized that ketone bodies, such as β-hydroxybutyrate, may stabilize neuronal cell membranes, modulate neurotransmission, and increase gamma-aminobutyric acid synthesis, leading to reduced neuronal excitability. Furthermore, ketosis may reduce oxidative stress and positively impact mitochondrial function, which may also play a role in antiepileptic effects [3, 5, 6, 8].

Unlike obesity treatment, the use of a ketogenic diet as a treatment for drug-resistant epilepsy requires close supervision by a team of specialists, including a physician and a clinical dietitian, as well as careful monitoring of the patient's condition, metabolic parameters, and potential adverse effects [5, 8]. Long-term use of the ketogenic diet may result in side effects such as gastrointestinal disturbances, hyperlipidemia, or kidney stones. However, the balance of benefits and risks in this group of patients often favors its use, sometimes in a modified form to ensure patient adherence [3, 5, 8].

Comparing the use of the ketogenic diet in the treatment of obesity and drug-resistant epilepsy highlights significant differences in the reliability of scientific evidence and clinical approach. In the case of epilepsy, the diet is a recognized therapeutic method with documented effectiveness, while in the treatment of obesity, its role remains supportive and requires further research, particularly in the context of long-term safety and durability of effects.

In summary, the ketogenic diet is an effective and recognized treatment method for drug-resistant epilepsy, the use of which is based on a reliable scientific basis. The different nature of the evidence for obesity and epilepsy emphasizes the need for cautious interpretation of research results and individualized therapeutic decisions in the treatment of obesity.

**The ketogenic diet in the treatment of other diseases**

Besides its use in the treatment of obesity and drug-resistant epilepsy, the ketogenic diet is being studied in many other conditions. In most of these cases, the observed therapeutic effects may be partially related to weight loss and improved metabolic parameters, making it difficult to clearly assess the direct impact of the ketogenic diet. As a therapeutic element, its use is being considered in the treatment of cancer, cardiovascular diseases, type 2 diabetes, polycystic ovary syndrome, and certain neurological and psychiatric conditions, among others.

In the case of cancer, it has been suggested that limiting glucose availability may affect cancer cell metabolism, slowing tumor growth [6, 12, 16]. Some studies also indicate the potential sensitization of some cancer cells to chemotherapy or radiotherapy when using a ketogenic diet [6, 12, 16, 17]. Clinical trial results to date are limited and do not allow for clear recommendations, but it appears that the ketogenic diet may be a potential candidate for adjuvant cancer therapy [6, 12, 18]. However, due to their restrictive nature and the frequent presence of cancer cachexia, ketogenic diets may increase the risk of malnutrition and should only be implemented under close medical and nutritional supervision.

In type 2 diabetes, the ketogenic diet has been shown to have beneficial effects on glycemic control, improved insulin sensitivity, and weight loss. However, its long-term safety remains controversial, primarily due to its adverse effects on LDL levels and the observed increased risk of hypoglycemia and ketoacidosis. For these reason ketogenic diets are not routinely recommended for patients with type 1 diabetes and their use is limited to highly selected clinical situations, such as patients with concomitant drug-resistant epilepsy, under specialist supervision [1, 6, 11, 19]. Some studies have shown that despite improved patient outcomes in the short term, there is no significant difference in long-term weight loss, glycemic control, or insulin sensitivity [1, 20].

Furthermore, a randomized controlled trial from 2024 showed that a 10-day ketogenic diet did not improve glucose tolerance, insulin sensitivity, plasma lipid profile, or blood pressure in obese patients with type 2 diabetes unless accompanied by weight loss [21]. Current American Diabetes Association (ADA) and Polish Diabetes Association (PDA) recommendations support individualized low-carbohydrate dietary patterns for selected adults with type 2 diabetes but do not specifically recommend ketogenic diets over less restrictive low-carbohydrate interventions [22, 23].

In cardiovascular diseases, both potential metabolic benefits and adverse effects on LDL cholesterol levels are observed, and consequently, on the risk of developing atherosclerosis and its associated complications [1]. The ketogenic diet may affect the cardiovascular system at various levels. Its anti-inflammatory effects, the positive effect of ketone bodies on the vascular endothelium, lowering triglyceride levels, increasing HDL levels, and potential weight loss may have a cardioprotective effect [24]. On the other hand, some studies report that the ketogenic diet leads to cardiomyocyte apoptosis and cardiac fibrosis, which may suggest its harmful effects [6].

The literature also indicates the potential impact of the ketogenic diet on the hormonal system, which, combined with its positive effect on certain metabolic parameters, may be used in the short-term treatment of polycystic ovary syndrome (PCOS) [6, 25]. Due to the proven effectiveness of other nutritional models in this condition, it is particularly important that the person prescribing dietary intervention is a specialist who will select an individualized treatment, assess contraindications, and assess the risk of adverse effects [25].

In neurology, the ketogenic diet is being studied in conditions such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis, citing its pleiotropic effects on the body and neuroprotective nature [5, 6, 8, 26]. Available scientific data indicates the potential benefits of using a ketogenic diet in neurological diseases, but the limited number of studies prevents clear confirmation of the therapeutic effects of this nutritional model [5, 6]. The exceptions with confirmed therapeutic effects are the previously described drug-resistant epilepsy and drug-resistant migraine. Current clinical recommendations indicate that ketogenic dietary therapies may reduce the frequency and severity of migraine attacks and can be considered in selected patients with chronic or drug-resistant migraine [15, 27].

In psychiatry, the ketogenic diet is also beginning to be studied; its potential impact on mood disorders and cognitive functioning may contribute to the treatment of conditions such as depression and schizophrenia [6, 28]. A 2024 study demonstrated increased life satisfaction, improved overall functioning, and improved sleep quality in patients with schizophrenia and bipolar disorder who received a ketogenic diet in combination with pharmacotherapy [28]. However, it should be emphasized that for most of these indications, the available data are preliminary, and the use of a ketogenic diet requires further research, particularly with large cohorts and longer durations, and cautious interpretation of results.

There are also isolated reports of the use of a ketogenic diet in the treatment of lipoedema, but the scientific data in this area is very limited and does not allow for the formulation of clear conclusions [29].

In summary, despite growing interest in the use of the ketogenic diet in various disease entities, its effectiveness has only been unequivocally confirmed in selected indications. In most cases, the available data are preliminary, emphasizing the need for further research and a cautious approach to its use in clinical practice.

**Indications and contraindications**

The basis for qualifying a patient for a ketogenic diet should be an individual clinical assessment, taking into account the potential benefits and risks associated with its implementation and the patient's likelihood of compliance. This dietary model is not a universal method for treating obesity, but it is one of the possible dietary interventions in appropriately selected patients.

The main applications of the ketogenic diet are drug-resistant epilepsy and obesity in adult patients with co-occurring metabolic disorders such as insulin resistance or type 2 diabetes [30]. This nutritional model has been shown to improve glycemic control and weight loss, making it a potentially beneficial therapeutic option in patients with obesity [30]. Furthermore, the ketogenic diet may be considered in patients who fail to achieve clinically significant results with other dietary models.

However, there are contraindications to the ketogenic diet. The most important include kidney disease, liver disease, lipid metabolism disorders, concomitant propofol therapy, which increases the risk of propofol infusion syndrome, and congenital metabolic diseases that impair the utilization of fatty acids as an energy source [3, 12]. Furthermore, special caution should be exercised in patients with cardiovascular disease, nutritional disorders, malnourished individuals, and those with poor ability to adhere to restrictive dietary recommendations [3]. Pregnancy and breastfeeding are additional contraindications due to the lack of sufficient safety data.

In clinical practice, proper patient qualification and monitoring of the treatment course are crucial. Before

initiating a ketogenic diet, it is recommended to assess the patient's general condition, including laboratory tests such as lipid profile, renal and liver function, and carbohydrate metabolism. Regular monitoring of metabolic parameters and assessment of treatment tolerance are necessary during the diet [30].

**Safety**

Introducing a ketogenic diet is associated with the risk of adverse effects, which are most often short-term, but some may also be long-term, especially during chronic use. The earliest observed early adverse effects are a series of symptoms collectively referred to as "keto flu," which include weakness, headaches, dizziness, nausea, and impaired concentration [3, 5, 8]. These are usually transient and subside within a few days to weeks, and their occurrence is associated with the body's adaptation to using ketone bodies as its primary energy source [5, 6]. During the initial period of the diet, special attention should be paid to disturbances in water and electrolyte metabolism, including increased sodium and potassium loss, which requires appropriate monitoring [3, 6, 8].

The literature highlights the potential adverse effects of the ketogenic diet on lipid profiles, particularly increased LDL cholesterol in some patients, which could potentially be a long-term side effect of this dietary model. At the same time, beneficial changes in triglyceride and HDL cholesterol levels are observed, suggesting a complex and individually variable effect of this diet on cardiovascular risk [8, 18, 31, 32].

Adoption of a ketogenic diet may also be associated with the development of kidney stones and a high burden on the kidneys due to increased protein intake and metabolic changes [5, 6, 8]. Individuals with pre-existing kidney disease are particularly susceptible to this adverse effect, and in their case, special caution or even complete elimination of this dietary model is recommended. Moreover, prolonged ketogenic diets may accelerate the progression of renal insufficiency in susceptible individuals, highlighting the need for careful patient selection and renal function monitoring.

Another important safety aspect of the ketogenic diet is the possible occurrence of nutritional deficiencies, including those in the B vitamin group, vitamin C, minerals, and dietary fiber, resulting from the limited consumption of grain products, fruits, and some vegetables [8]. Supplementation of these dietary components is important, especially with long-term adherence to the diet, as their deficiency can result in constipation, osteopenia, or even osteoporosis, which can develop not only due to deficiencies but also due to acid-base disturbances [15].

In summary, the ketogenic diet can be used in selected patients with obesity, but requires appropriate qualification, monitoring of metabolic parameters,

Table 1. Application of the ketogenic diet in selected medical conditions

| Medical condition | Effectiveness | Level of evidence | Main benefits | Limitations/risks |
|---|---|---|---|---|
| Obesity | moderate | moderate | weight loss | low adherence, lack of long-term studies |
| Drug-resistant epilepsy | high | high | reduction in seizure frequency | low adherence |
| Type 2 diabetes | moderate | moderate | improved glycemic control, weight loss | risk of hypoglycemia, unclear long-term effects |
| Cardiovascular diseases | uncertain | low/moderate | decreased triglycerides (TAG), increased HDL | increased LDL |
| Cancer | uncertain | low | enhanced response to primary cancer treatment | limited number of studies |
| PCOS | moderate | low/moderate | improvement in metabolic and hormonal parameters | lack of long-term studies |
| Neurodegenerative diseases | uncertain | low | neuroprotective effects | limited number of studies |
| Psychiatric disorders | uncertain | low | improved well-being and cognitive function | limited number of studies |
| Lipedema | uncertain | low | reduction in symptom severity | limited number of studies |

TAG – triglycerides; HDL – high-density lipoproteins; LDL – low-density lipoproteins.

individualization of recommendations and special caution in people with comorbidities. A summary of current applications of the ketogenic diet in selected disease entities is presented in Table 1.

## DISCUSSION

The ketogenic diet is currently one of the most popular nutritional models, and its effectiveness and therapeutic potential are being studied in numerous disease entities. However, the level of scientific evidence regarding its effectiveness and safety varies significantly depending on the clinical indication. A review of the scientific literature indicates that in the treatment of obesity, this diet may be effective in short-term weight loss and improving selected metabolic parameters, but its long-term advantages over other dietary strategies remain inconclusive [1, 11].

One of the main limitations of the available studies is the relatively short follow-up period and the significant heterogeneity of the analyzed populations. Data on the long-term effects of the ketogenic diet are lacking, which is particularly important in the context of the chronic nature of obesity. Furthermore, the restrictive nature of the diet makes it difficult for patients to maintain it, especially with long-term use, which reduces its actual effectiveness in clinical practice [1].

The impact of the ketogenic diet on cardiovascular risk is also controversial. Although beneficial changes in triglyceride and HDL cholesterol levels are observed, a simultaneous potential increase in LDL cholesterol levels in some patients requires cautious interpretation and individualized treatment recommendations [1, 20]. This indicates the need to monitor metabolic parameters during the diet and consider the patient's risk profile.

Among the ambiguous data on obesity treatment, the use of the ketogenic diet in the treatment of drug-resistant epilepsy stands out, as its effectiveness has been confirmed in clinical trials and is reflected in recommendations from scientific societies [3]. This difference emphasizes that the ketogenic diet should not be considered a universal therapeutic tool, but rather an intervention with varying clinical value depending on the disease entity.

In recent years, there has been growing interest in the potential use of the ketogenic diet in other conditions, such as cancer, metabolic, neurological, and psychiatric disorders. However, in most of these cases, the available data are preliminary, and their interpretation is limited by the small number of clinical trials and the lack of standardized interventions. Therefore, the use of a ketogenic diet for these indications should be considered experimental [6, 12].

From a clinical perspective, individualizing the approach to each patient is crucial. A ketogenic diet can be an effective tool supporting the treatment of obesity in selected patients, but its implementation should be preceded by an assessment of the potential benefits and risks and should take into account the patient's preferences and the possibility of long-term compliance. This also requires appropriate monitoring and interdisciplinary collaboration between a diabetologist, dietitian, and family physician.

## CONCLUSION

The ketogenic diet can be an effective method for short-term weight loss in adult patients with obesity and lead to improvements in selected metabolic parameters. The long-term effectiveness of the ketogenic diet in the treatment of obesity remains ambiguous, and its advantages over other dietary models have not been clearly confirmed. Its use is associated with the risk of adverse effects, therefore, it requires appropriate patient qualification and monitoring of metabolic parameters during use. The ketogenic diet has proven use in the treatment of drug-resistant epilepsy, where its effectiveness has been confirmed in clinical trials and recommendations from scientific societies. However, in most other conditions, such as cancer, metabolic, neurological, and psychiatric diseases, the use of this dietary model remains in the research phase and is not currently standard of care. Implementation of the ketogenic diet should be considered taking into account the patient's clinical condition, potential benefits and risks, and the likelihood of patient compliance. Further studies, particularly long-term studies, are necessary to clearly assess safety and effectiveness in the treatment of obesity and other chronic diseases.

**Conflict of interest**
*The authors declare no conflict of interest.*

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ORIGINAL ARTICLE

# ANTIBACTERIAL AND ANTIFUNGAL EFFICACY OF CITRUS PEEL ESSENTIAL OILS FROM FOUR MOROCCAN CITRUS VARIETIES

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## ABSTRACT

**Background.** Infections brought on by bacteria and fungi pose a serious risk to public healthcare worldwide. The emergence of virulent and resistant microbes has weakened the effectiveness of several antimicrobial therapies. As a result, natural compounds are becoming more and more popular as substitute antibacterial agents. Citrus peels and other by-products are known to contain essential oils with potential biological benefits.

**Objective.** The current study examines the antimicrobial characteristics of four Moroccan citrus peel essential oils *in vitro.*

**Material and Methods.** Citrus peels were hydrodistilled to extract the essential oils. Antimicrobial properties were assessed by applying the agar disk-diffusion technique. Minimum inhibitory concentration (MIC) and minimum bactericidal or fungicidal concentration (MBC/MFC) were ascertained by the broth microdilution method.

**Results.** The extraction yield of citrus peels ranged from 0.4% to 1.0%. All essential oils have demonstrated antimicrobial activity. *Citrus clementina* was the most effective against *Salmonella* Typhimurium sp. (33.33 ± 2.08 mm), while the essential oil of *Citrus sinensis* demonstrated the strongest antibacterial activity against *Bacillus* sp. (24.50 ± 0.71 mm), *Staphylococcus aureus* (21.00 ± 2.65 mm), *Enterococcus faecalis* (19.00 ± 1.00 mm), and *Pseudomonas fluorescens* (26.00 ± 0.00 mm). For fungal strains, *Citrus sinensis* peel essential oil showed the strongest antifungal efficacy against *Cryptococcus neoformans* (34.33 ± 0.52 mm) and *Candida albicans* (39.67 ± 1.63 mm). *Citrus sinensis* and *Citrus clementina* peel essential oils exhibited mostly bactericidal and fungicidal effects against the majority of tested strains.

**Conclusions.** Moroccan citrus peel essential oils exhibited strong antimicrobial properties, highlighting their potential as natural substances and supporting their valorization in biomedicine and industrial applications.

**Keywords:** *citrus peel, essential oils, antibacterial activity, antifungal activity, natural products, public health*

## INTRODUCTION

Bacterial and fungal infectious diseases constitute a serious public health problem worldwide [1]. Bacterial infections cause around 12.5% of all deaths worldwide, whereas fungal infections afflict about 150 million people each year and cause about 1.7 million deaths [2, 3]. Additionally, it has been shown that a number of harmful microbes have become resistant to standard antibiotic treatments [4]. Consequently, plant-based treatments are becoming more and more well-liked as organic suppliers of antibacterial qualities. The *Rutaceae* family includes *Citrus* species [5], which rank among the most cultivated and widely consumed crops [6-8]. Of the 140 million tons of citrus produced annually worldwide [9], around 18% is used for industrial processing, like juice production [8]. Pulp, seeds, and peels are among the substantial amounts of by-products produced by this extensive use [8]. Citrus peels, which comprise between 50 and 60 percent of raw fruits, are the most common residue [10]. Because these byproducts are frequently underutilized, their accumulation raises environmental issues [11].

Nonetheless, essential oils, phenolic acids, carotenoids, and flavonoids are among the natural and active compounds that can be found in citrus

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fruit peels [12-14]. More than 400 chemicals make up citrus essential oils (CEOs), which are complex combinations mostly consisting of monoterpenes, flavonoids, sesquiterpenes, coumarins, and oxygenated derivatives [14, 15]. Limonene, a cyclic monoterpene (C10H16) [16], is typically the most prevalent of these compounds [17]. CEOs' chemical makeup, especially that of d-limonene and flavonoids, is linked to many of the biological properties, notably antifungal, antioxidant, antibacterial, and anti-inflammatory activities [18-20].

However, notwithstanding the increasing amount of research on citrus essential oils, a gap remains in comparative information on the antimicrobial effects, particularly about the high value of these by-products for medical purposes. This work aims to clarify the antibacterial and antifungal effects of citrus peel essential oils from four Moroccan varieties and to encourage the value-adding of citrus peel by-products as a natural and environmentally friendly substitute with potential uses in the food and health sectors by showcasing their bioactive potential.

## MATERIALS AND METHODS

### Materials

*Biological material*

The collected plant material selected for the present work consisted of the peels of citrus fruits from four varieties: *Citrus limon* (lemon), *Citrus clementina* (clementine), *Citrus sinensis* (orange), and *Citrus aurantium* (bitter orange). The fruits were purchased from a local market in Taroudant City, Morocco. Only mature, healthy fruits free from visible defects were selected. The plant material was botanically identified by the research team of the Laboratory of Natural Substances and Environment at Ibn Zohr University.

*Microorganisms*

For this study, eight bacterial and two fungal strains were chosen. The bacterial panel included four Gram-positive (*Bacillus* sp. CIP104717, *Staphylococcus aureus* ATCC25923, *Listeria monocytogenes* ATCC19144, and *Enterococcus faecalis* ATCC19433) and four Gram-negative (*Pseudomonas* sp., *Pseudomonas fluorescens* CAN 228-1, *Escherichia coli* CIP54127, and *Salmonella* Typhimurium ATCC14028). *Candida albicans* CIP88465 and *Cryptococcus neoformans* ATCC11576 were the fungal strains used to assess antifungal activity. Reference strains were obtained from recognized collections, including the American Type Culture Collection (ATCC) and the Pasteur Institute's collection (CIP). However, *Pseudomonas* sp., and *Pseudomonas fluorescens* CAN 228-1 were obtained from the laboratory microbial collection and were previously identified using standard microbiological methods. Yeast strains were cultivated on Sabouraud dextrose agar (SDA), while bacterial strains were cultivated on Luria-Bertani (LB) agar.

### Methods

*Essential oils extraction*

Fresh citrus peels served for essential oils extraction. The fruits were thoroughly washed with distilled water to remove impurities. The peels were carefully separated and cut into small pieces. A Clevenger-type apparatus was used for 3 h of hydrodistillation. A total of 600 g of fresh peels was used for each essential oil. The essential oils were dehydrated using anhydrous sodium sulfate [2]. The following equation was employed to measure the yields of extracted citrus peel essential oils:

$$\text{Oil yield (\%)} = \frac{\text{Volume of the extracted essential oil (mL)}}{\text{Fres peelh weight (g)}} \times 100$$

Based on the available scientific data, it can be concluded that, unlike hydrodistillation/steam distillation methods for extracting essential oils, cold pressing may imply a high risk of transferring lipophilic fungicides into the oils. For these reasons, the observed antimicrobial and antifungal activity of essential oils obtained by hydrodistillation is mainly due to their natural properties.

*Antibacterial and antifungal activities*

The antibacterial potential was evaluated using the disk-diffusion assay [21]. Yeast Morphology Agar (YMA) (Difco, USA) was used for antifungal experiments, and Mueller-Hinton Agar (MHA) (Difco, USA) was used to measure antibacterial activity. Suspensions of bacteria and yeast were prepared from 24-hour cultures. The sampled colonies were transferred to 9 mL of API NaCl 0.85% medium (bioMérieux, France) and adjusted to $10^6$ CFU/mL for bacteria and $10^4$ CFU/mL for yeasts. Sterile paper discs (6 mm) impregnated with 15 µL of citrus peel essential oils were aseptically placed on the surface of agar after the standardized inocula were dispersed onto the relevant agar media. A pre-diffusion step was carried out at 4°C for 2 h to facilitate uniform diffusion of the essential oils into the agar before microbial growth. The plates were incubated for 24 h at 37°C for bacteria and 48 h at 28°C for yeasts. For antifungal assays, fluconazole and econazole (30 µg/disc) were the positive controls, while chloramphenicol, penicillin, and gentamicin (30 µg/disc) served as antibacterial controls. Antifungal and antibacterial activities were expressed as the mean diameter of the

zone of inhibition (ZI) (mm), and all experiments were conducted in triplicate (Table 1).

*Minimum inhibitory concentration (MIC)*

The minimum inhibitory concentration (MIC) values of citrus peel essential oils were quantified using the broth microdilution technique, which is performed in sterile 96-well microplates according to Chebaibi et al. [22]. Two-fold serial dilutions of each essential oil were dissolved in dimethyl sulfoxide (DMSO) (Sigma-Aldrich, USA) at concentrations between 25 and 0.097 mg/mL. Each well contained culture medium (Sabouraud dextrose broth for yeasts and Mueller-Hinton broth (Difco, USA) for bacteria), essential oil solution, and a standardized microbial inoculum ($10^8$ CFU/mL and $10^6$ CFU/mL for yeast and bacteria, respectively). Negative control wells were composed of DMSO and culture medium, whereas wells designed for growth control contained medium and inoculum without essential oil. All assays were performed in triplicate. Microplates were incubated at 37°C for 24 h for bacteria and 48 h for yeasts. Following incubation, 0.04% resazurin solution was added, followed by an additional 2-hour incubation. The MIC is defined as the lowest essential oil concentration that does not cause a color shift, signifying the inhibition of microbial growth.

*Minimum fungicidal and bactericidal concentration (MFC and MBC)*

The MFC and MBC were identified as described by Chebaibi et al. [22]. After MIC determination, aliquots (10 µL) from wells showing no visible microbial growth were subcultured onto Mueller-Hinton agar for bacteria and Sabouraud dextrose agar for yeasts. The incubation was carried out at 28°C for 48 h for yeasts and at 37°C for 24 h for bacteria. The MFC and MBC were defined as the lowest concentration of essential oil at which no microbial growth was observed on agar plates. All assays were performed in triplicate.

*Statistical analysis*

All experiments are expressed in triplicate, and results are expressed as mean ± standard deviation (SD). Statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate differences between the tested citrus peel essential oils. A p-value $< 0.05$ was considered statistically significant.

## RESULTS

**The yield of fresh citrus peel studied**

The citrus fruits of the four studied varieties (*Citrus sinensis*, *Citrus limon*, *Citrus clementina*, and *Citrus aurantium)* were collected between November 2023 and January 2024. Hydrodistillation was utilized to extract essential oils from fresh peels. The yield of essential oils varied among the studied varieties, ranging from 0.4% to 1.0%. *Citrus clementina* had the lowest output (0.4%), followed by *Citrus sinensis* (0.6%) and *Citrus limon* (0.8%), whereas *Citrus aurantium* peel essential oil exhibited the highest yield (1.0%). In addition, the physical properties of the extracted citrus peel essential oils, such as colour, viscosity, and scent, varied noticeably.

**Antimicrobial activity assay**

*Antibacterial activity*

Eight bacterial strains, including four Gram-positive and four Gram-negative bacteria, were used to test the four citrus peel essential oils' (CPEOs') *in vitro* antibacterial activity (Table 1). The *Citrus* species and the bacterial strain under examination both affected the antibacterial activity. *Citrus limon* showed the lowest antibacterial activity among the essential oils, whereas *Citrus sinensis* was characterized by the highest activity against most bacterial strains. All the evaluated essential oils showed minimal sensitivity to *Listeria monocytogenes*. Several bacterial strains, including *Pseudomonas* sp., *Pseudomonas fluorescens*, *Escherichia coli*, *Bacillus* sp., *Staphylococcus aureus*, and *Enterococcus faecalis,* were highly susceptible to *Citrus sinensis* and *Citrus clementina* peel essential oils. *Citrus aurantium* essential oil showed a modest level of antibacterial activity, with the strongest inhibitory impact on *Pseudomonas* sp. Conversely, the only bacterial strain that was susceptible to the essential oil found in *Citrus limon* peel was *Escherichia coli*. Significant differences were observed between the tested citrus peel essential oils against *Escherichia coli* ($p < 0.05$).

*Antifungal activity*

Applying the agar disk-diffusion technique, the *in vitro* antifungal activity of the four citrus peel essential oils (CPEOs*)* was assessed against two pathogenic yeasts, *Candida albicans* CIP88465 and *Cryptococcus neoformans* ATCC11576. The inhibition zone diameters obtained are presented in Table 2. Overall, *Citrus sinensis*, *Citrus clementina*, and *Citrus aurantium* essential oils exhibited stronger antifungal activity than *Citrus limon*. Among the tested oils, the essential oil of *Citrus sinensis* demonstrated the strongest antifungal activity against both fungal strains. In general, *Candida albicans* was more sensitive to the tested CPEOs than *Cryptococcus neoformans*, as indicated by the larger inhibition zone diameters observed across all essential oils. Statistical analysis using one-way ANOVA revealed highly significant differences between the tested groups against *Candida albicans* ($p < 0.001$).

Table 1. *In vitro* antibacterial activity of citrus peel essential oils (CPEOs) and reference antibiotics against the tested bacterial strains

| CPEOs | | *Citrus limon* | | | *Citrus clementina* | | | *Citrus sinensis* | | | *Citrus aurantium* | | | Antibiotic (ZI ± SD, mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tested bacteria | | Inhibition zone[a] (mm) | Min | Max | Inhibition zone[a] (mm) | Min | Max | Inhibition zone[a] (mm) | Min | Max | Inhibition zone[a] (mm) | Min | Max | Pen | Chlor | Genta |
| Gram-positive bacteria | *Bacillus* sp. CIP104717 | ND | ND | ND | 14.50 ± 0.71 | 14.00 | 15.00 | 24.50 ± 0.71 | 24.00 | 25.00 | ND | ND | ND | 22.33 ± 0.44 | ND | ND |
| | *Staphylococcus aureus* ATCC25923 | 10.00 ± 0.00 | 10.00 | 10.00 | 13.00 ± 1.41 | 12.00 | 14.00 | 21.00 ± 2.65 | 19.00 | 24.00 | 11.50 ± 0.71 | 11.00 | 12.00 | 20.00 ± 0.67 | ND | ND |
| | *Listeria monocytogenes* ATCC19144 | 9.67 ± 1.15 | 9.00 | 11.00 | 8.00 ± 1.00 | 7.00 | 9.00 | 9.00 ± 1.00 | 8.00 | 10.00 | 7.33 ± 0.58 | 7.00 | 8.00 | ND | 28.00 ± 0.67 | ND |
| | *Enterococcus faecalis* ATCC19433 | 6.00 ± 1.00 | 5.00 | 7.00 | 17.00 ± 1.00 | 16.00 | 18.00 | 19.00 ± 1.00 | 18.00 | 20.00 | 5.33 ± 1.53 | 4.00 | 7.00 | ND | 15.16 ± 0.22 | ND |
| Gram-negative bacteria | *Escherichia coli* CIP54127 | 12.00 ± 1.41 | 11.00 | 13.00 | 18.00 ± 6.24 | 13.00 | 25.00 | 25.33 ± 1.53 | 24.00 | 27.00 | 11.00 ± 0.00 | 11.00 | 11.00 | ND | ND | 32.66 ± 0.44 |
| | *Pseudomonas* sp. | ND | ND | ND | 23.33 ± 3.21 | 21.00 | 27.00 | 33.33 ± 2.08 | 31.00 | 35.00 | 15.50 ± 0.71 | 15.00 | 16.00 | ND | ND | 42.33 ± 0.46 |
| | *Pseudomonas fluorescens* CAN 228-1 | ND | ND | ND | 19.00 ± 1.41 | 18.00 | 20.00 | 26.00 ± 0.00 | 26.00 | 26.00 | 11.50 ± 0 .71 | 11.00 | 12.00 | ND | ND | 44.00 ± 0.68 |
| | *Salmonella* Typhimurium ATCC14028 | 4.33 ± 0.58 | 4.00 | 5.00 | 14.00 ± 1.00 | 13.00 | 15.00 | 16.00 ± 1.00 | 15.00 | 17.00 | 4.33 ± 0.58 | 4.00 | 5.00 | ND | ND | 26.16 ± 0.55 |

[a] – Data are presented as mean ± standard deviation (n = 3); ND – not determined; Pen – penicillin; Chlor – chloramphenicol; Genta – gentamicin. The measurement scale was as follows: no inhibition: < 9 mm; moderate inhibition: 9-12 mm; strong inhibition: 13-15 mm; very strong inhibition: > 15 mm.

Table 2. *In vitro* antifungal activity of citrus peel essential oils (CPEOs) and reference antifungal agents against the tested fungal strains

| | *Candida albicans* CIP88465 | | | *Cryptococcus neoformans* ATCC11576 | | |
|---|---|---|---|---|---|---|
| CPEOs | Inhibition zone (mm)[a] | Minimum | Maximum | Inhibition zone (mm)[a] | Minimum | Maximum |
| *Citrus limon* | 13.33 ± 0.52 | 13.00 | 14.00 | 10.33 ± 0.82 | 9.00 | 11.00 |
| *Citrus clementin*a | 27.17 ± 2.04 | 23.00 | 28.00 | 27.33 ± 1.03 | 26.00 | 28.00 |
| *Citrus sinensi*s | 39.67 ± 1.63 | 37.00 | 42.00 | 34.33 ± 0.52 | 34.00 | 35.00 |
| *Citrus aurantiu*m | 28.50 ± 1.05 | 27.00 | 30.00 | 26.17 ± 1.60 | 23.00 | 27.00 |
| Fluconazole | 24.83 ± 2.40 | 20.00 | 26.00 | 25.17 ± 2.56 | 20.00 | 27.00 |
| Econazole | 40.33 ± 2.88 | 38.00 | 44.00 | 38.67 ± 0.52 | 38.00 | 39.00 |

[a] – Data are presented as mean ± standard deviation (n = 3).

**Minimum inhibitory concentration (MIC), minimum fungicidal concentration (MFC), and minimum bactericidal concentration (MBC)**

The minimum inhibitory concentration (MIC), fungicidal (MFC), and bactericidal (MBC) concentrations of citrus peel essential oils were determined, and MFC/MIC or MBC/MIC ratios were used to evaluate fungicidal and bactericidal effects (Tables 3 and 4). An MFC/MIC ≤ 4 or MBC/MIC indicates a fungicidal or bactericidal activity, whereas a ratio > 4 demonstrates a fungistatic or bacteriostatic effect [22].

For Gram-positive bacteria, MIC results varied between 3.12 and 25 mg/mL. *Citrus sinensis* and *Citrus clementina* peel essential oils exhibited bactericidal activity against most tested strains, whereas *Citrus aurantium* did not show bactericidal activity within the tested concentration range. *Enterococcus faecalis* was the most resistant strain, showing elevated MBC/MIC ratios. For Gram-negative bacteria, *Citrus sinensis*

Table 3. *In vitro* MIC, MBC, and MBC/MIC values of the selected citrus peel essential oils against tested bacterial strains

| | CPEOs | *Citrus clementina* | | | *Citrus sinensis* | | | *Citrus aurantium* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | MIC (mg/mL) | MBC (mg/mL) | MBC/ MIC | MIC (mg/mL) | MBC (mg/mL) | MBC/ MIC | MIC (mg/mL) | MBC (mg/mL) | MBC/ MIC |
| Gram- positive bacteria | *Bacillus* sp. CIP104718 | 6.25 | 25.00 | 4.00 | 3.12 | 12.50 | 4.00 | ND | ND | ND |
| | *Staphylococcus aureus* ATCC25923 | 12.50 | 25.00 | 2.00 | 12.50 | 25.00 | 2.00 | 25.00 | > 25 | > 1 |
| | *Enterococcus faecalis* ATCC19434 | 3.12 | 25.00 | 8.1 | 0.78 | 12.50 | 16.02 | ND | ND | ND |
| Gram-negative bacteria | *Escherichia coli* CIP54128 | 12.50 | 12.50 | 1.00 | 6.25 | 12.50 | 2.00 | 25.00 | > 25 | > 1 |
| | *Pseudomonas* sp. | 12.50 | 25.00 | 2.00 | 6.25 | 25.00 | 4.00 | ND | ND | ND |
| | *Pseudomonas fluorescens* CAN 228-1 | 6.25 | 25.00 | 4.00 | 6.25 | 25.00 | 4.00 | ND | ND | ND |
| | *Salmonella* Typhimurium ATCC14028 | ND | ND | ND | ND | ND | ND | ND | ND | ND |

ND – not determined

Table 4. Minimum Inhibitory Concentration (MIC) and Minimum Fungicidal Concentration (MFC) of the tested citrus peels essential oils (CPEOs) against the selected fungal strains

| CPEOs | *Candida albicans* CIP88465 | | | *Cryptococcus neoformans* ATCC11576 | | |
|---|---|---|---|---|---|---|
| | MIC (mg/mL) | MFC (mg/mL) | MFC/MIC | MIC (mg/mL) | MFC (mg/mL) | MFC/MIC |
| *Citrus limon* | 25.00 | 25.00 | 1.00 | 3.12 | 25.00 | 8.01 |
| *Citrus clementina* | 3.12 | 6.25 | 2.00 | 1.56 | 12.50 | 8.01 |
| *Citrus sinensis* | 3.12 | 6.25 | 2.00 | 6.25 | 6.25 | 1.00 |
| *Citrus aurantium* | 25.00 | 25.00 | 1.00 | 3.12 | 12.50 | 4.01 |
| Fluconazole | 0.25 | 0.25 | 1.00 | 0.25 | 0.25 | 1.00 |
| Econazole | 0.06 | 0.12 | 1.93 | 0.06 | 0.12 | 1.93 |

and *Citrus clementina* peel demonstrated bactericidal activity against most strains, while *Citrus aurantium* exhibited a bacteriostatic effect against *Escherichia coli*.

Regarding fungal strains, all tested essential oils exhibited a fungicidal effect against *Candida albicans.* In contrast, against *Cryptococcus neoformans*, *Citrus limon*, *Citrus clementina,* and *Citrus aurantium* exhibited fungistatic effects*,* whereas *Citrus sinensis* showed a fungicidal effect.

## DISCUSSION

Four Moroccan citrus peel essential oils were tested for antimicrobial effectiveness against two yeast species and eight bacterial strains. Although minor differences were noted, the citrus peel essential oil yields found in this study are largely in line with those found in earlier studies. *Citrus limon* essential oil production (0.8%) was similar to what Abdu et al. [23] reported. On the other hand, *Citrus clementina* yielded a little smaller amount than Boudries et al. [21]. The yield of *Citrus aurantium* peel essential oil was greater than what Boukhennoufa et al. [15] had reported. In a similar vein, *Citrus sinensis* peel essential oil output was higher than that of Naveed et al. [24]. The harvesting period, soil properties, climate, water availability, plant genotype, and extraction technique are some of the variables that may be responsible for the well-documented variations in essential oil yields [21, 22, 25]. This study's *in vitro* antibacterial activity is in line with results on citrus peel essential oils that have already been reported. *Citrus sinensis*'s broad-spectrum antibacterial effectiveness against *Staphylococcus aureus* and *Escherichia coli* has been confirmed by numerous studies [26-28]. Previous studies have also documented the sensitivity of *Enterococcus faecalis* to *Citrus sinensis*, which supports the findings of this work [26]. *Citrus limon* peel essential oil has also been shown in a number of studies to demonstrate a mild antibacterial effect against *E. coli*, *S. aureus* and *Listeria monocytogenes*, which is similar to the activity found in our study [27, 29, 30]. In line with the study's findings of a moderate inhibitory impact, the essential oil of *Citrus clementina* has also been demonstrated to possess an inhibitory effect against *E. coli* and *S. aureus* [21]. Strong antibacterial action against *S. aureus* has also been demonstrated for *Citrus aurantium* peel essential oil, particularly when diluted in dimethyl sulfoxide (DMSO) [31]. Citrus peel essential oils' antibacterial activity and mode of action are influenced by their chemical composition [21]. The mechanism of action, which is frequently connected to the permeability of the bacterial cell wall and membrane, explains the reduced susceptibility observed in *Enterococcus faecalis* [32]. The *in vitro* antifungal effectiveness of the current study is consistent with previous investigations that described *Candida albicans*' vulnerability to citrus essential oils. Numerous studies have demonstrated the strong antifungal effect of *Citrus sinensis* essential oil against *Candida albicans*, exhibiting an inhibition zone (ZI) between 29 and 55 mm [26, 33]. The inhibitory zone identified in this study, which is within this range, validates the essential oil's antifungal properties. Similar to the current investigation, Boudries et al. [21] found a pronounced antifungal effect of *Citrus clementina* peel essential oil against *C. albicans* (ZI = 27.63 mm). The mild antifungal activity seen in this investigation is comparable to what was reported by Abdu et al. [23] for *Citrus limon* against the same yeast (ZI = 18 mm). Furthermore, Nidhi et al. [34] showed that *Candida albicans* was sensitive to the essential oil of *Citrus aurantium* peel, which confirmed the antifungal effect found in this study.

There is a significant dearth of published information about citrus peel essential oils' antifungal activity against *Cryptococcus neoformans*, in contrast to the many studies that have examined their

effectiveness against *Candida albicans*. An important contribution that emphasises the uniqueness and added value of this work is the robust antifungal activity that was found in the current investigation against this opportunistic pathogenic yeast. *Citrus sinensis* and *Citrus clementina* essential oils‑showed superior bactericidal and fungicidal activity against most of the tested bacteria, as evidenced by the calculation of MIC, MBC, and MFC values. Both the action of the primary ingredients, like monoterpenes, and potential synergistic interactions between the major and small components of the essential oils may be responsible for these effects [21].

## CONCLUSION

The present study demonstrated that the four Moroccan citrus peel essential oils represent a valuable source of antibacterial and antifungal agents. *Citrus sinensis* and *Citrus clementina* exhibited the strongest antimicrobial activity, showing predominantly bactericidal and fungicidal effects against most of the tested strains, whereas *Citrus limon* and *Citrus aurantium* displayed moderate antimicrobial activity. Importantly, this research offers fresh perspectives on the effectiveness of citrus peel essential oils as antifungals against *Cryptococcus neoformans,* an opportunistic pathogen that has been rarely investigated, which constitutes a key originality of this work. Notably, *Citrus sinensis* peel essential oil exhibited a fungicidal effect against this yeast. Overall, these results demonstrate the antimicrobial properties of citrus peel by-products as natural antimicrobial agents and support their potential as alternatives to conventional treatments such as commonly used antibiotics (e.g., chloramphenicol, penicillin, and gentamicin) and antifungal agents (e.g., fluconazole, econazole). They may also serve as promising resources for developing new pharmaceutical agents for global health applications. Additionally, the antibacterial activity of Moroccan citrus essential oils appears to be comparable to that observed in citrus oils from other regions of the world. Nonetheless, variations in the chemical composition of the essential oils, geographical origin, and climatic conditions may account for small differences in activity.

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**Conflict of interest**

*No conflict of interest is declared by the authors.*

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ORIGINAL ARTICLE

# MEDITERRANEAN DIET ADHERENCE AND RURAL-URBAN DISPARITY AMONG MOROCCAN ADOLESCENTS: A NATIONALLY REPRESENTATIVE CROSS-SECTIONAL STUDY

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## ABSTRACT

**Background.** Mediterranean diet adherence (MDA) is declining globally, yet comprehensive national data on Moroccan adolescent dietary patterns remain scarce.

**Objective.** The present study aimed to assess MDA and analyze urban-rural disparities among Moroccan adolescents.

**Material and Methods.** This cross-sectional national study recruited 3600 adolescents aged 10-18 years (2160 urban and 1440 rural) across Morocco's 12 administrative regions. The Mediterranean Diet Quality Index for children and adolescents (KIDMED) was used to assess MDA; a structured questionnaire was additionally administered to collect sociodemographic and anthropometric data. The nutritional status was assessed using body mass index-for-age z-scores according to World Health Organization (WHO) standards. Multiple logistic regression identified factors associated with poor adherence. *Chi*-square tests were conducted to examine differences in Mediterranean diet dietary behaviour classes by location and sex.

**Results.** Mean KIDMED score was 4.55 ± 3.51. Poor adherence (≤ 3) was found in 38.66%, medium adherence (4-7) in 38.80%, and optimal adherence (≥ 8) in 22.50%. Urban adolescents showed significantly higher adherence than rural counterparts (5.36 ± 3.54 vs. 3.33 ± 3.08; $p < 0.001$). Rural residence was associated with a 3.12-fold higher odds of poor adherence (adjusted OR = 3.12, 95% CI: 2.69-3.62; $p < 0.001$). Urban-rural disparities were more pronounced among females (2.24 points) than males (1.67 points). Fish consumption demonstrated the largest geographical disparity (41.30% vs. 27.40%; $p < 0.001$).

**Conclusions.** The present study reveals a critical urban-rural inequality in MDA: optimal adherence was achieved by only 22.50% of adolescents nationally, and was more than three times lower in rural (9.65%) than urban (31.10%) settings. Rural residence was the strongest independent determinant of poor adherence. These findings call for geographically targeted, school-based policies integrating both nutritional education and structural improvements in food access infrastructure, particularly in rural Morocco.

**Keywords:** *Mediterranean diet, KIDMED, dietary patterns, adolescents, urban-rural disparities, national study, Morocco*

## INTRODUCTION

The nutrition transition is considered one of the most important public health challenges of the 21st century at the global level [1]. The rapid socioeconomic transformations and urbanization fundamentally alter traditional dietary patterns in developing countries, characterized by the coexistence of undernutrition with increasing prevalence of obesity and chronic disease associated with dietary patterns [2]. This epidemiological transition is particularly evident among adolescent populations who progressively adopt westernized dietary patterns rich in ultra-processed foods. Adolescence represents a sensitive period during which dietary patterns are consolidated and exert lasting influences on long-term health trajectory, making this population particularly vulnerable to suboptimal dietary habits. Paradoxically, Mediterranean countries are currently experiencing a worrying shift away from traditional eating habits, particularly among younger generations [3]. It is known that the Mediterranean diet (MD), defined by

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CIHEAM/FAO [3] and recognized by UNESCO as an Intangible Cultural Heritage of Humanity since 2013 [4], is characterized by moderate dairy consumption, low red meat intake and high consumption of fruits, vegetables, legumes, nuts, olive oil, and fish. Despite that the MD can achieve all nutritional requirements, it presents multidimensional benefits documented by previous studies, including maintaining optimal body weight [5], increased longevity [6], and protective effects against cardiovascular diseases [7, 8], diabetes [9, 10], obesity [11, 12], metabolic syndrome [13], certain cancers, and cognitive impairment [14].

A significant geographic heterogeneity in the level of MDA has been demonstrated, with overall adherence estimated at 21.00% and optimal adherence varying between 7.00% and 30.00% [15, 16]. Geographical and socio-economic factors appear to influence these trends, with significant disparities between urban and rural areas as observed in Spain [17] and other Mediterranean regions. Rural environments tend to maintain traditional food patterns but may face restrictions that limit access to a diverse diet, while urban populations generally have access to greater food diversity, including processed foods, which may paradoxically undermine nutritional quality [17, 18].

Morocco has a rich culinary heritage deeply rooted in Mediterranean principles, situated at the crossroads of Mediterranean and African cultures. Yet MDA patterns among Moroccan adolescents remain insufficiently characterized at the national level. The majority of research on MDA has focused on European Mediterranean populations, leaving a significant knowledge gap with regard to North African countries. Existing Moroccan studies on MD have been geographically fragmented to specific regions such as the Drâa-Tafilalet region [19], the Rif Mountains [20], or the city of Casablanca [21]. To the best of authors' knowledge, no study has yet assessed MDA patterns among Moroccan adolescents using a nationally representative sample, significantly limiting the generalizability of current findings and impeding evidence-based national nutrition policy. Understanding urban-rural disparities carries considerable public health relevance, as these differences directly inform the design of targeted interventions and policy frameworks. Urbanization may generate divergent dietary trajectories between urban and rural contexts, warranting particular attention in countries undergoing rapid nutritional transition [17, 21]. In this context, the present study aimed to evaluate the prevalence of MDA at the national level among Moroccan adolescents aged 10 to 18 years, using the validated Mediterranean Diet Quality Index for children and adolescents (KIDMED). The primary objective was to estimate the overall prevalence of adherence and to characterize urban-rural divergence. Secondary objectives included analyzing consumption patterns of specific MD components and exploring variation by age and sex.

## METHODS

### Study design and participants

This is a nationally representative cross-sectional study conducted from 20 September 2022 to 10 June 2023 among 3600 adolescents aged 10 to 18 years (urban and rural) across Morocco's 12 administrative regions. The age range of 10-18 years was selected in accordance with the World Health Organization's definition of adolescence (10-19 years). The lower limit of 10 years corresponds to the earliest age of enrolment in Moroccan secondary education (middle school); the upper limit of 18 years aligns with the legal age of majority in Morocco and the upper age of the secondary school system (high school), ensuring ecological validity within a school-based sampling design. The sampling frame included public and private secondary schools (middle school and high school) as listed in the official registry provided by the Ministry of National Education. Schools were stratified by: administrative region (n = 12), settlement type (urban: > 10,000 inhabitants; rural: ≤ 10,000 inhabitants), and ownership (public vs. private). The 12 administrative regions were: Tanger-Tétouan-Al Hoceima, Oriental, Fès-Meknès, Rabat-Salé-Kénitra, Béni Mellal-Khénifra, Casablanca-Settat, Marrakech-Safi, Drâa-Tafilalet, Souss-Massa, Guelmim-Oued Noun, Laâyoune-Sakia El Hamra, and Dakhla-Oued Ed-Dahab.

A systematic sampling approach was used within each region: two urban schools (one public, one private) and one rural school (public, given negligible coverage of private institutions in rural settings) were selected, totaling 36 schools nationwide. Within each school, three classes were randomly selected from available grade levels to ensure age diversity. Eligible participants were adolescents aged 10-18 years present on the survey day with parental consent. Exclusion criteria: chronic medical conditions requiring therapeutic diets (diabetes, coeliac disease, food allergies); clinically diagnosed eating disorders; and inability to complete questionnaires independently due to cognitive impairment. The recruitment process and final sample composition are presented in Figure 1.

### Sample size justification

The sample size was calculated using standard methods for prevalence estimation in cluster-sampled populations. Based on published estimates, the prevalence of MDA among Moroccan school-age children is 39.98% [19] with a 95.00% confidence level and desired precision of ± 2.40%. To account for clustered sampling, a design effect (DEFF) of 1.80,

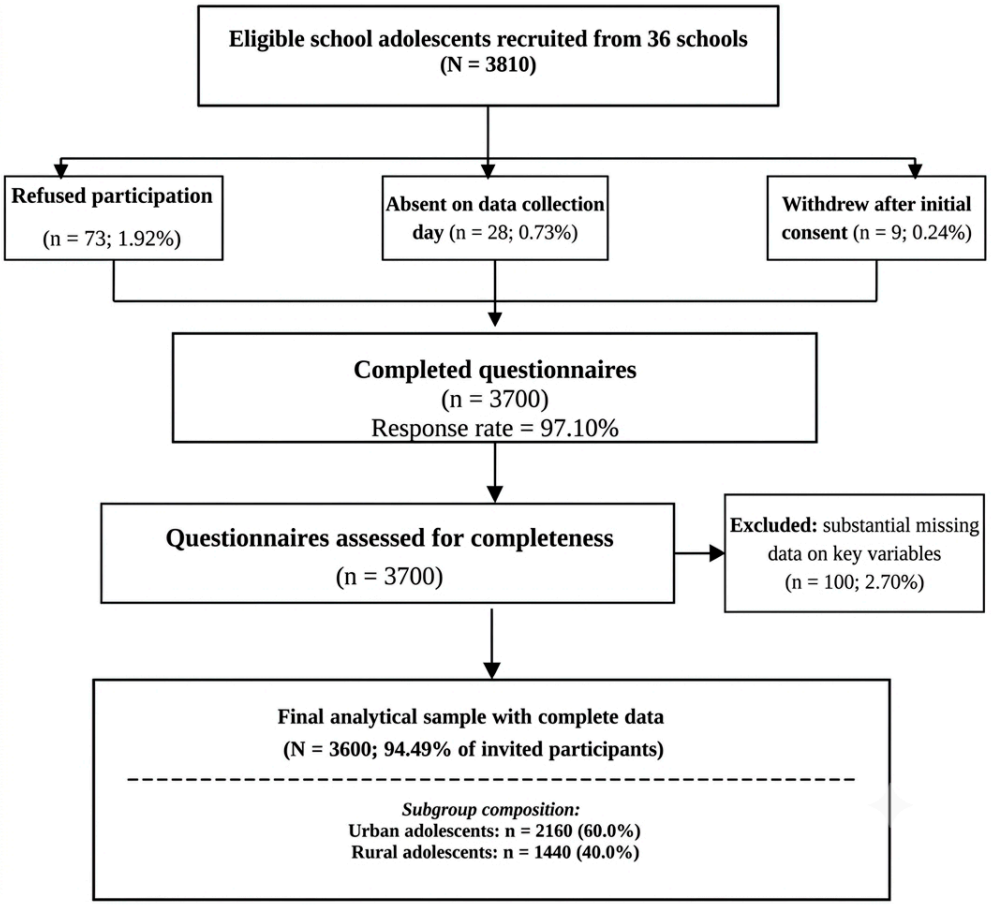


Figure 1. Flow diagram of participant recruitment and final analytical sample

was applied corresponding to an estimated intra-cluster correlation coefficient (ICC) of approximately 0.05, consistent with published ICC values for dietary behaviour outcomes in school-based surveys [22]. Using the formula:

$$N = Z^2pq/d^2 \times DEFF/(1 - r)$$

where Z = 1.96, p = 0.3998, q = 0.6002, r = non-response rate, d = 0.024: basic sample size $n_0$ = 1600; adjusted for DEFF: $n_1$ = 2880; adjusted for 19.00% non-response: N final = 3556. The final sample of 3600 exceeded this minimum, providing adequate statistical power for planned subgroup analyses.

**Anthropometric parameters**

All anthropometric measures were taken following WHO standardized protocols for adolescent populations [23]. Weight was measured to the nearest 0.1 kg (SECA 803, Germany), with participants barefoot and wearing light indoor clothing. Height was measured to the nearest 0.1 cm (SECA 213, Germany) in the Frankfurt horizontal plane [24]. Each measurement was performed twice, with the mean value recorded. Nutritional status was assessed using age- and sex-specific BMI z-scores derived with WHO AnthroPlus software (version 1.0.4), based on the WHO 2007 growth reference standards [25, 26]. Four categories were defined: underweight (BMI z-score < −2SD), normal weight (−2SD ≤ BMI z-score ≤ +1SD), overweight (+1SD < BMI z-score ≤ +2SD), and obesity (BMI z-score > +2SD) [27].

**Mediterranean diet adherence assessment**

To assess the MDA, the present study used the validated KIDMED index questionnaire, developed by Serra-Majem et al. (2004) [28]. The KIDMED index is composed of a 16-item questionnaire) assigning positive scores (+1) to beneficial Mediterranean behaviours and negative scores (−1) to detrimental habits, yielding total scores ranging from −4 to +12, with higher scores indicating greater adherence. Previous studies have extensively validated the KIDMED and confirmed its reliability and applicability across diverse populations, including non-European settings [29-31], providing the basis for its adoption in the present study.

To meet the objective, the KIDMED questionnaire was translated into the Arabic language following cross-cultural adaptation procedures [32, 33]. To the best of the authors' knowledge, no formally published psychometric validation study of the KIDMED index conducted specifically among Moroccan adolescents exists in the peer-reviewed literature. Accordingly, a pilot study was conducted to assess comprehension,

internal consistency, face validity, and feasibility, with the recruitment of 51 Moroccan adolescents aged 12 to 18 years (mean = 16.84 ± 1.58 years), including 33 females (64.70%) and 18 males (35.30%). The results revealed high acceptability, as all items were understood without ambiguity by at least 94.00% of participants, and the mean completion time was 13.20 minutes (range: 10-18 minutes). The internal consistency of the KIDMED questionnaire was evaluated using Cronbach's alpha coefficient, yielding $\alpha = 0.75$ (95% CI: 0.65-0.85), indicating acceptable internal consistency ($\alpha \geq 0.70$). Minor linguistic adjustments were made based on pilot feedback to enhance clarity while maintaining semantic equivalence with the original instrument.

These items are categorized into two groups:

Positive items (+1 point each):

- Takes a fruit or fruit juice every day;
- Has a second fruit every day;
- Has fresh or cooked vegetables regularly once a day;
- Has fresh or cooked vegetables more than once a day;
- Consumes fish regularly (at least 2-3 times per week);
- Likes pulses and eats them more than once a week;
- Consumes pasta or rice almost every day (5+ times per week);
- Has cereals or grains for breakfast;
- Consumes nuts regularly (at least 2-3 times per week);
- Uses olive oil at home;
- Has a dairy product for breakfast;
- Takes two yoghurts and/or cheese (40 g) daily.

Negative items (−1 point each):

- Goes more than once a week to a fast-food restaurant;
- Skips breakfast;
- Has commercially baked goods or pastries for breakfast;
- Takes sweets and candy several times every day.

KIDMED scores were categorised as ≤ 3 (poor adherence), 4-7 (medium adherence), and ≥ 8 (optimal adherence) [26].

**Data collection procedures**

The training session was delivered online through Google Meet and led by two registered dietitians. Life and Earth Sciences teachers attended a full-day workshop on KIDMED administration and standardized anthropometric measurement procedures. The structured electronic Arabic-version questionnaires (Google Forms) comprised three main components (demographic, anthropometric, and KIDMED) administered in fixed sequence. After a structured briefing session, participants completed the questionnaire independently within a standardized 15-minute timeframe, followed by systematic response verification to minimize missing data. Anthropometric data were entered directly into Google Forms, eliminating transcription errors. Demographic variables assessed included participant's age, sex, educational level, family composition, and household location (urban/rural).

**Statistical analysis**

Statistical analyses were performed using R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria). Continuous variables were expressed as means ± standard deviations (SD). Normality was assessed using the Kolmogorov-Smirnov (K-S) test: all continuous variables (KIDMED score, age, BMI z-score, family size) showed significant K-S results (all $p < 0.05$), reflecting minor departures from normality; however, given the large sample (N = 3600), the central limit theorem supports the robustness of parametric comparisons (independent t-test) for group-level inference. Age and BMI z-score were used exclusively as categorical variables in regression analyses. Group comparisons for continuous variables were performed using the independent t-test; categorical variables were expressed as absolute frequencies and percentages (standardized to 2 decimal places) and compared using Pearson's *Chi*-square test.

To examine urban-rural disparities across demographic subgroups, separate analyses were performed by sex (females vs. males) and age group (≤ 16 years vs. > 16 years) using independent t-tests. Multiple logistic regression analysis identified independent factors associated with poor MDA (KIDMED score ≤ 3). Variables included in the model were rural residence, age group (≤ 16 vs. > 16 years), educational level (middle school vs. high school), sex, large family size (≥ 7 members), and WHO nutritional status (underweight, overweight, and obesity, each vs. normal weight as reference), entered simultaneously as dummy variables in a single multivariable model, with all N = 3600 participants included in all estimates (no exclusions for any BMI z-score comparison). Crude (unadjusted) odds ratio (ORs) were estimated from separate univariable logistic regression models for each predictor individually; adjusted ORs were estimated from a single multivariable model including all variables simultaneously, allowing quantification of confounding and magnitude of change after adjustment. Model fit was assessed using Nagelkerke $R^2$ and the Hosmer-Lemeshow goodness-of-fit test. Individual KIDMED components were compared by *Chi*-square tests (Tables 3 and 4). Effect sizes were calculated using Cohen's d for mean differences and Cramér's V for categorical associations. All statistical tests were two-tailed. For sociodemographic variables

with three or more categories (family size: 3 groups; nutritional status: 4 groups), pairwise post-hoc comparisons of MDA category distributions were conducted using *Chi*-square tests with Bonferroni correction (adjusted significance level: $\alpha = 0.05/k$, where k denotes the number of pairwise comparisons: $k = 3$ for family size, $k = 6$ for nutritional status). For the mean KIDMED score, pairwise Welch's t-tests with Bonferroni correction were applied to the same groups. Post-hoc superscript letters (a, b) in Table 2 denote statistically distinct subgroups after correction; groups sharing the same letter are not significantly different. Statistical significance was set at $p < 0.05$ for all primary analyses.

The age cut-off of ≤ 16 vs. > 16 years was selected because age 16 represents a developmental threshold in the Moroccan educational system, corresponding to the transition from middle school (collège) to high school (lycée), consistent with the dichotomization used in comparable Mediterranean adolescent studies [34]. The family size threshold of ≥ 7 members was selected based on the distribution of the study data (19.39% of participants; see Table 1) and is supported by national data on household food insecurity in Morocco indicating that larger Moroccan households face disproportionately higher food access constraints [35], while ensuring adequate cell sizes for logistic regression.

**Ethical approval**

Written informed consent was obtained from parents of all participating adolescents before data collection. Participation was voluntary, confidential, and participants could withdraw at any time. No incentives were provided. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki as revised in 2024 [36]. The study protocol was approved by the Bioethical Commission (No. Adol-H-83/2022).

## RESULTS

**Study participants**

The overall mean age was 16.81 years, with urban participants significantly older than rural counterparts ($p < 0.001$) (Table 1). Urban-rural differences were significant across all demographic and anthropometric characteristics (all $p < 0.001$), as detailed in Table 1.

Table 1. Characteristics of study participants (N = 3600) and comparison between urban and rural adolescents

| Characteristic | Urban (n = 2160) | Rural (n = 1440) | Total (N = 3600) | p-value |
|---|---|---|---|---|
| Demographics | | | | |
| Age, mean ± SD (years) | 17.09 ± 1.39 | 16.39 ± 1.92 | 16.81 ± 1.66 | < 0.001 |
| Age groups, n (%) | | | | |
| ≤ 16 years | 953 (44.12%) | 789 (54.79%) | 1742 (48.39%) | < 0.001 |
| > 16 years | 1207 (55.88%) | 651 (45.21%) | 1858 (51.61%) | |
| Sex, n (%) | | | | |
| Female | 1361 (63.01%) | 744 (51.67%) | 2105 (58.47%) | < 0.001 |
| Male | 799 (36.99%) | 696 (48.33%) | 1495 (41.53%) | < 0.001 |
| Educational level, n (%) | | | | |
| Middle school | 281 (13.01%) | 409 (28.40%) | 690 (19.17%) | < 0.001 |
| High school | 1879 (86.99%) | 1031 (71.60%) | 2910 (80.83%) | |
| Anthropometric data | | | | |
| BMI z-score, mean ± SD | 0.51 ± 0.98 | 0.42 ± 0.95 | 0.48 ± 0.97 | 0.021 |
| Nutritional status, n (%) | | | | |
| Underweight | 43 (1.99%) | 14 (0.97%) | 57 (1.58%) | 0.041 |
| Normal weight | 1648 (76.30%) | 1129 (78.40%) | 2777 (77.14%) | |
| Overweight | 427 (19.77%) | 278 (19.31%) | 705 (19.58%) | |
| Obesity | 42 (1.94%) | 19 (1.32%) | 61 (1.69%) | |
| Family characteristics | | | | |
| Family size, mean ± SD | 5.75 ± 1.58 | 6.16 ± 1.74 | 5.92 ± 1.66 | < 0.001 |
| Family size categories, n (%) | | | | |
| 2-3 members | 85 (3.94%) | 40 (2.78%) | 125 (3.47%) | < 0.001 |
| 4-6 members | 1697 (78.56%) | 1080 (75.00%) | 2777 (77.14%) | |
| ≥ 7 members | 378 (17.50%) | 320 (22.22%) | 698 (19.39%) | |

SD – standard deviation; BMI z-score derived using WHO AnthroPlus v1.0.4 (WHO 2007 growth reference); Statistical tests: independent t-tests for continuous variables; Pearson *Chi*-square ($\chi^2$) for categorical variables.

**Mediterranean diet adherence**

The MDA categories differed significantly by geographical location, educational level, and age group (all $p < 0.001$), with urban adolescents, high school students, and older adolescents (> 16 years) showing better adherence, respectively (Table 2). We have found no significant sex-based differences were observed ($p = 0.44$). The post-hoc pairwise comparisons revealed a significant gradient in adherence across family size categories: large families (≥ 7 members) showed significantly poorer adherence compared with both smaller family groups (all $P_{Bonf} \leq 0.004$), while no significant difference was found between small and medium-sized families ($P_{Bonf} = 0.745$). In addition,

Table 2. KIDMED scores and adherence categories by sociodemographic and anthropometric variables

| Variable | n | KIDMED Mean ± SD | Poor ≤ 3 n (%) | Medium 4-7 n (%) | Optimal ≥ 8 n (%) | p overall | P Bonferroni |
|---|---|---|---|---|---|---|---|
| Overall | 3600 | 4.55 ± 3.51 | 1392 (38.66%) | 1398 (38.83%) | 810 (22.50%) | - | - |
| Geographical location | | | | | | | |
| Urban area | 2160 | 5.36 ± 3.54 | 651 (30.13%) | 838 (38.79%) | 671 (31.06%) | < 0.001 | - |
| Rural area | 1440 | 3.33 ± 3.08 | 741 (51.45%) | 560 (38.88%) | 139 (9.65%) | | - |
| Sex | | | | | | | |
| Female | 2105 | 4.61 ± 3.49 | 792 (37.62%) | 832 (39.52%) | 481 (22.85%) | 0.442 | - |
| Male | 1495 | 4.46 ± 3.52 | 600 (40.13%) | 566 (37.85%) | 329 (22.00%) | | |
| Educational level | | | | | | | |
| Middle school | 690 | 3.89 ± 3.21 | 312 (45.21%) | 267 (38.69%) | 111 (16.08%) | < 0.001 | - |
| High school | 2910 | 4.73 ± 3.58 | 1080 (37.11%) | 1131 (38.86%) | 699 (24.02%) | | |
| Age group | | | | | | | |
| ≤ 16 years | 1742 | 4.27 ± 3.40 | 733 (42.08%) | 684 (39.26%) | 325 (18.66%) | < 0.001 | - |
| > 16 years | 1858 | 4.74 ± 3.60 | 659 (35.46%) | 714 (38.42%) | 485 (26.10%) | | |
| Family size | | | | | | | |
| 2-3 members[a] | 125 | 5.21 ± 3.67[a] | 38 (30.40%)[a] | 52 (41.60%)[a] | 35 (28.00%)[a] | < 0.001* | vs. 4-6: p = 0.745 vs. ≥ 7: p = 0.004 |
| 4-6 members[a] | 2777 | 4.60 ± 3.52[a] | 1043 (37.60%)[a] | 1072 (38.60%)[a] | 662 (23.80%)[a] | | vs. ≥ 7: p < 0.001 |
| ≥ 7 members[b] | 698 | 4.31 ± 3.46[b] | 311 (44.60%)[b] | 274 (39.30%)[b] | 113 (16.20%)[b] | | Reference |
| Nutritional status | | | | | | | |
| Underweight | 57 | 4.21 ± 3.28 | 24 (42.10%) | 22 (38.60%) | 11 (19.30%) | 0.973* | vs. NW: p = 1.000 vs. OW: p = 1.000 vs. Ob: p = 1.000 |
| Normal weight | 2777 | 4.57 ± 3.50 | 1071 (38.60%) | 1077 (38.80%) | 629 (22.70%) | | vs. OW: p = 1.000 vs. Ob: p = 1.000 |
| Overweight | 705 | 4.57 ± 3.55 | 271 (38.40%) | 275 (39.00%) | 159 (22.60%) | | vs. Ob: p = 1.000 |
| Obesity | 61 | 4.41 ± 3.58 | 26 (42.60%) | 24 (39.30%) | 11 (18.00%) | | Reference |

SD – standard deviation; Statistical tests: independent t-tests for continuous variables (KIDMED score); Pearson *Chi*-square ($\chi^2$) for adherence category distributions; * Corrected overall p-values: family size $\chi^2 = 25.92$ (df = 4, $p < 0.001$); nutritional status $\chi^2 = 1.28$ (df = 6, $p = 0.973$); Bonferroni post-hoc correction, Family size (k = 3 pairs, adjusted $\alpha = 0.0167$): 2-3 vs. 4-6 members: $\chi^2 = 2.785$, $p = 0.745$ (ns); 2-3 vs. ≥ 7 members: $\chi^2 = 13.381$, $p = 0.004$; 4-6 vs. ≥ 7 members: $\chi^2 = 21.706$, $p < 0.001$; KIDMED mean Welch t-test (Bonferroni, k = 3): 2-3 vs. 4-6: $p = 0.213$; 2-3 vs. ≥ 7: $t = 2.547$, $p = 0.035$; 4-6 vs. ≥ 7: $p = 0.146$; Nutritional status (k = 6 pairs, adjusted $\alpha = 0.0083$): UW vs. NW: $p = 1.000$; UW vs. OW: $p = 1.000$; UW vs. Ob: $p = 1.000$; NW vs. OW: $p = 1.000$; NW vs. Ob: $p = 1.000$; OW vs. Ob: $p = 1.000$ (all ns); [a], [b]: groups sharing the same letter are not significantly different after Bonferroni correction; Abbreviations: UW – underweight; NW – normal weight; OW – overweight; Ob – obesity.

no significant differences in MDA distribution were observed across nutritional status categories after Bonferroni correction (all $P_{Bonf} > 0.05$). Detailed results are presented in Table 2.

**Individual KIDMED components by geographical location**

The urban-rural disparities were significant across all positive Mediterranean diet behaviours (all $p < 0.05$), while no significant geographical differences emerged for any negative behaviour (all $p > 0.05$) (Table 3). Moreover, among positive behaviours, fish consumption showed the largest urban-rural gap, followed by olive oil usage, breakfast cereals, and daily fruit intake.

**Sex-specific patterns in individual KIDMED components**

The sex-based differences in individual KIDMED components were no significant for most dietary behaviours, except for pasta/rice consumption, nut consumption, fast-food frequency, yoghurt/cheese intake, and sweets consumption (Table 4). The olive oil usage at home showed the highest adoption rate overall, while daily yoghurt/cheese intake showed the lowest.

**Urban-rural differences by age and sex**

Substantial urban-rural differences in MDA were observed across all demographic subgroups, with all comparisons reaching statistical significance ($p < 0.001$) (Table 5). The urban-rural mean difference was more pronounced among females (2.24 points) than among males (1.67 points; $d = 0.49$). Combined stratification identified rural females aged ≤ 16 years as the most vulnerable subgroup, with the lowest mean KIDMED score (2.89) and the largest urban-rural difference (2.34 points; 95% CI: 1.90-2.78). All effect sizes ranged from medium to large (Cohen's d: 0.49-0.75), confirming substantial public health significance.

**Factors associated with poor Mediterranean diet adherence**

Multiple logistic regression identified rural residence as the strongest independent factor associated with poor MDA ($p < 0.001$) (Table 6), representing more than three-fold higher odds among rural compared to urban adolescents after controlling for all other variables. Notably, the adjusted OR (3.12) was substantially higher than the crude OR (2.46), indicating the presence of negative confounding. Younger age (≤ 16 years) was the second strongest

Table 3. Individual KIDMED components by geographical location

| KIDMED component | Urban (n = 2160) n (%) | Rural (n = 1440) n (%) | Total (N = 3600) n (%) | p-value* |
|---|---|---|---|---|
| Positive behaviours (% adopting behaviour) | | | | |
| Takes a fruit or fruit juice every day | 834 (38.61%) | 421 (29.23%) | 1255 (34.86%) | < 0.001 |
| Has a second fruit every day | 869 (40.23%) | 476 (33.05%) | 1345 (37.36%) | < 0.001 |
| Has fresh/cooked vegetables once a day | 985 (45.60%) | 530 (36.80%) | 1515 (42.08%) | < 0.001 |
| Has fresh/cooked vegetables > once a day | 956 (44.26%) | 523 (36.32%) | 1479 (41.08%) | < 0.001 |
| Consumes fish regularly (≥ 2-3 times/ week) | 892 (41.29%) | 395 (27.43%) | 1287 (35.75%) | < 0.001 |
| Likes pulses and eats them > 1/week | 1354 (62.68%) | 791 (54.93%) | 2145 (59.58%) | < 0.001 |
| Consumes pasta or rice ≥ 5 times/week | 1012 (46.85%) | 545 (37.84%) | 1557 (43.25%) | < 0.001 |
| Has cereals/grains for breakfast | 1698 (78.61%) | 984 (68.33%) | 2682 (74.50%) | < 0.001 |
| Consumes nuts regularly (≥ 2-3 times/ week) | 1378 (63.79%) | 865 (60.07%) | 2243 (62.30%) | 0.029 |
| Uses olive oil at home | 1934 (89.53%) | 1145 (79.51%) | 3079 (85.52%) | < 0.001 |
| Has a dairy product for breakfast | 1054 (48.79%) | 587 (40.76%) | 1641 (45.58%) | < 0.001 |
| Takes 2 yoghurts and/or cheese (40 g) daily | 512 (23.70%) | 254 (17.63%) | 766 (21.27%) | < 0.001 |
| Negative behaviours (% engaging in behaviour) | | | | |
| Goes > 1/week to a fast-food restaurant | 482 (22.31%) | 353 (24.51%) | 835 (23.19%) | 0.152 |
| Skips breakfast | 675 (31.25%) | 472 (32.77%) | 1147 (31.86%) | 0.347 |
| Has commercially baked goods for breakfast | 426 (19.72%) | 298 (20.69%) | 724 (20.11%) | 0.494 |
| Takes sweets and candy several times/day | 488 (22.59%) | 354 (24.58%) | 842 (23.38%) | 0.208 |

* $\chi^2$: *Chi*-square tests.

Table 4. Individual KIDMED components by sex

| KIDMED component | Female (n = 2105) n (%) | Male (n = 1495) n (%) | p-value* |
|---|---|---|---|
| Positive behaviours (% adopting behaviour) | | | |
| Takes a fruit or fruit juice every day | 743 (35.29%) | 512 (34.24%) | 0.512 |
| Has a second fruit every day | 796 (37.81%) | 549 (36.72%) | 0.504 |
| Has fresh/cooked vegetables once a day | 894 (42.47%) | 621 (41.53%) | 0.584 |
| Has fresh/cooked vegetables > once a day | 881 (41.85%) | 598 (40.00%) | 0.274 |
| Consumes fish regularly (≥ 2-3 times/week) | 751 (35.70%) | 536 (35.90%) | 0.916 |
| Likes pulses and eats them > 1/week | 1247 (59.23%) | 898 (60.06%) | 0.618 |
| Consumes pasta or rice ≥ 5 times/week | 832 (39.52%) | 725 (48.49%) | < 0.001 |
| Has cereals/grains for breakfast | 1574 (74.77%) | 1108 (74.08%) | 0.662 |
| Consumes nuts regularly (≥ 2-3 times/week) | 1247 (59.23%) | 996 (66.62%) | < 0.001 |
| Uses olive oil at home | 1787 (84.89%) | 1292 (86.42%) | 0.238 |
| Has a dairy product for breakfast | 965 (45.84%) | 676 (45.22%) | 0.717 |
| Takes 2 yoghurts and/or cheese (40 g) daily | 410 (19.48%) | 356 (23.81%) | 0.003 |
| Negative behaviours (% engaging in behaviour) | | | |
| Goes > 1/week to a fast-food restaurant | 372 (17.67%) | 463 (30.97%) | < 0.001 |
| Skips breakfast | 657 (31.21%) | 490 (32.78%) | 0.365 |
| Has commercially baked goods for breakfast | 408 (19.38%) | 316 (21.14%) | 0.237 |
| Takes sweets and candy several times/day | 445 (21.14%) | 397 (26.56%) | < 0.001 |

* $\chi^2$: *Chi*-square tests.

Table 5. Urban-rural KIDMED score differences by age and sex

| Subgroup | Urban KIDMED mean (SD) | Rural KIDMED mean (SD) | Mean difference (95% CI) | Cohen's d | p-value* |
|---|---|---|---|---|---|
| By sex | | | | | |
| Urban n: (Female = 1361, Male =799); Rural n: (Female = 744, Male = 696) | | | | | |
| Female (n = 2105) | 5.48 ± 3.52 | 3.24 ± 3.01 | 2.24 (1.95-2.53) | 0.71 | < 0.001 |
| Male (n = 1495) | 5.19 ± 3.57 | 3.52 ± 3.18 | 1.67 (1.37-1.97) | 0.49 | < 0.001 |
| By age group | | | | | |
| Urban n: (≤ 16 years = 953, > 16 years = 1207); Rural n: (≤ 16 years = 789, > 16 years = 651) | | | | | |
| ≤ 16 yrs (n = 1742) | 5.12 ± 3.41 | 3.08 ± 2.95 | 2.04 (1.67-2.41) | 0.64 | < 0.001 |
| > 16 yrs (n = 1858) | 5.56 ± 3.64 | 3.52 ± 3.18 | 2.04 (1.74-2.34) | 0.60 | < 0.001 |
| Combined stratification (exploratory) | | | | | |
| Urban n: (F ≤ 16 yrs = 660, F > 16 yrs = 701); (M ≤ 16 yrs = 385, M > 16 yrs = 414); Rural n: (F ≤ 16 yrs = 361, F > 16 yrs = 383): (M ≤ 16 yrs = 336, M > 16 yrs = 360) | | | | | |
| Female ≤ 16 yrs (n = 1021) | 5.23 ± 3.46 | 2.89 ± 2.84 | 2.34 (1.90-2.78) | 0.75 | < 0.001 |
| Female > 16 yrs (n = 1084) | 5.71 ± 3.56 | 3.54 ± 3.12 | 2.17 (1.74-2.60) | 0.65 | < 0.001 |
| Male ≤ 16 yrs (n = 721) | 4.95 ± 3.34 | 3.32 ± 3.08 | 1.63 (1.08-2.18) | 0.51 | < 0.001 |
| Male > 16 yrs (n = 774) | 5.38 ± 3.75 | 3.49 ± 3.27 | 1.89 (1.46-2.32) | 0.53 | < 0.001 |

Comparisons: independent t-tests; SD – standard deviation; CI – confidence interval; n: Urban and Rural n added explicitly per subgroup; yrs – years; F – Female; M – Male.

factor ($p < 0.001$), followed by middle school education ($p = 0.014$) and large family size (≥ 7 members; $p = 0.042$). Male sex ($p = 0.42$) and all nutritional status categories showed no independent association with poor adherence after adjustment. The model explained 18.70% of variance in poor adherence (Nagelkerke $R^2 = 0.187$). Model fit was confirmed by the Hosmer-Lemeshow test ($p = 0.39$).

## DISCUSSION

This first nationally representative cross-sectional study of 3600 Moroccan adolescents reveals substantial deviation from Mediterranean dietary patterns, with pronounced geographical disparities warranting public health attention. The present findings demonstrate that 38.66% of participants exhibited poor adherence, with a mean KIDMED score of 4.55, indicating that 77.50% of Moroccan adolescents did not achieve optimal MDA. Notably, rural adolescents showed significantly lower adherence (KIDMED score = 3.33) compared to their urban counterparts (5.36). In addition, the present study showed that rural residence emerged as the strongest independent factor associated with poor adherence. Moreover, when compared with previous research conducted in different Moroccan regions, the present study revealed an important variation. The study of El Mokhtari et al. [20] reported a higher

Table 6. Multiple logistic regression analysis for poor MDA (KIDMED ≤ 3)

| Variable | n | Crude OR (95% CI) | p | Adjusted OR (95% CI) | p |
|---|---|---|---|---|---|
| Geographical location | | | | | |
| Urban residence (reference) | 2160 | 1.00 (reference) | - | 1.00 (reference) | - |
| Rural residence | 1440 | 2.46 (2.14-2.82) | < 0.001 | 3.12 (2.69-3.62) | < 0.001 |
| Age group | | | | | |
| > 16 years (reference, n = 1858) | | | | | |
| > 16 years (reference) | 1858 | 1.00 (reference) | - | 1.00 (reference) | - |
| ≤ 16 years | 1742 | 1.14 (0.98-1.32) | ≥ 0.05 | 1.15 (1.08-1.22) | < 0.001 |
| Educational level | | | | | |
| High school (reference, n = 2910) | | | | | |
| High school (reference) | 2910 | 1.00 (reference) | - | 1.00 (reference) | - |
| Middle school | 690 | 1.05 (0.88-1.24) | ≥ 0.05 | 1.28 (1.05-1.56) | 0.014 |
| Sex | | | | | |
| Female (reference, n = 2105) | | | | | |
| Female (reference) | 2105 | 1.00 (reference) | - | 1.00 (reference) | - |
| Male | 1495 | 1.11 (0.97-1.27) | ≥ 0.05 | 1.06 (0.92-1.22) | 0.418 |
| Family size | | | | | |
| < 7 members (reference, n = 2902) | | | | | |
| < 7 members (reference) | 2902 | 1.00 (reference) | - | 1.00 (reference) | - |
| Large family size (≥ 7 members) | 698 | 1.03 (0.89-1.20) | ≥ 0.05 | 1.19 (1.01-1.41) | 0.042 |
| Nutritional status (BMI z-score) | | | | | |
| Normal weight (reference, n = 2777), all N = 3600 in single model | | | | | |
| Normal weight (reference) | 2777 | 1.00 (reference) | - | 1.00 (reference) | - |
| Underweight | 57 | 0.60 (0.33-1.07) | ≥ 0.05 | 1.05 (0.86-1.29) | 0.637 |
| Overweight | 705 | 0.88 (0.74-1.04) | ≥ 0.05 | 0.92 (0.74-1.15) | 0.467 |
| Obesity | 61 | 1.15 (0.68-1.95) | ≥ 0.05 | 1.08 (0.62-1.89) | 0.787 |

Crude (unadjusted) ORs estimated from separate univariable logistic regression models; adjusted ORs estimated from a single multivariable model including all variables simultaneously; BMI z-score categories modelled as dummy variables within a single multivariable model; normal weight (n = 2777) as reference; all N = 3600 participants included in all estimates; OR – odds ratio; CI – confidence interval. The adjusted OR was controlled for the following confounding variables: geographical location (urban/rural), age group (≤ 16 vs. > 16 years), educational level (middle school vs. high school), sex (female vs. male), family size (< 7 vs. ≥ 7 members), and nutritional status (underweight, overweight, and obesity vs. normal weight).

mean KIDMED score among adolescents from the northern Rif region, where 72.80% achieved medium adherence and 14.90% with optimal adherence, contrasting markedly with the national distribution of 38.83% medium and 22.50% optimal. However, the Rif study had a relatively small sample (n = 302), limiting generalizability. A recent study in school-age adolescents in the Atlantic coastal region revealed lower optimal adherence of 7.70% [37], while a higher rate of optimal adherence (39.90%) was reported in the Tafilalet Oasis [19], which included a younger age group (9-13 years), making direct comparison difficult. The prevalence of optimal adherence of 22.50% in the present sample is comparable to that reported in other Mediterranean populations, including Turkish adolescents (22.90%) [38], Italian schoolchildren from Taranto (24.80%) [39], Greek adolescents (21.00%) [40], and Spanish schoolchildren (27.40%) [41].

This convergence across countries points to persistent and shared difficulties in sustaining traditional Mediterranean dietary patterns among younger populations. The poor adherence rate observed in the present sample situates Morocco within the intermediate-to-high range of a broad spectrum of poor adherence prevalences documented across Mediterranean adolescent populations. Recent country-specific data confirm the marked geographical heterogeneity of this phenomenon. In Greece, a large school-based cross-sectional study conducted in Attica (n = 2088 adolescents aged 12-18 years) reported poor adherence in 32.90% of participants, with optimal adherence reaching only 9.10% [40], a substantially worse profile than reported by earlier Greek estimates [41]. In Turkey, a recent cluster-sampled study in Izmir (n = 2693 school-aged children, 2022-2023) identified poor adherence in 16.60% in northern regions to 18.80% in southern localities have been documented [39, 42], while the pooled estimate across Italian studies approximates 30.80% [43]. In Cyprus, a prevalence of 37.00% poor adherence has been reported among primary schoolchildren [44]. Within this distribution, Morocco is positioned alongside Cyprus and broadly consistent with southern, European and Eastern Mediterranean context, while exceeding the more recent figures observed in Turkey and Italy. Taken together, these cross-national data confirm that suboptimal MDA among adolescents is not confined to non-Mediterranean settings but represents a shared public health challenge across the Mediterranean basin itself, driven by the progressive convergence of dietary behaviours toward Western patterns regardless of geographical proximity to the diet's region of origin [15, 40, 43].

The present investigation revealed no significant sex differences in the distribution of overall MDA categories, consistent with findings from southern Spain [17] and the general absence of a consistent sex-related pattern in systematic reviews [30, 31]. A sex difference analysis conducted among adults with obesity [45] and a systematic review during the COVID-19 pandemic [46] suggested contextual sex-related differences; however, their generalizability to healthy non-obese adolescents outside a pandemic context is uncertain. The stratified analyses suggested that urban-rural disparities might be more pronounced among females (2.24-point difference) than males (1.67 points), with young rural females showing the lowest KIDMED scores (2.89). These patterns are plausible but were not tested through a formal interaction term in the regression model, representing a hypothesis for future investigation. Younger age (≤ 16 years) was independently associated with significantly higher odds of poor adherence compared to older adolescents (> 16 years), suggesting that dietary adherence tends to improve as adolescents progress toward late adolescence. This pattern is consistent with findings of Patiño-Alonso et al. [47] in a Spanish cross-sectional study, who reported higher MDA among older participants. Previous studies [30, 48] also showed that older age is associated with higher adherence in adolescents. The present study also revealed that middle school education level and large family size (≥ 7 members) were independently associated with poor adherence. The educational effect may reflect the increased awareness of healthy feeding habits associated with longer schooling, driven by early interventions and habit-based programs [49]. Moreover, the post-hoc pairwise analysis further revealed a significant gradient in MDA across family size categories, with adolescents from large family size (≥ 7 members) displaying significantly higher rates of poor adherence and lower optimal adherence compared with smaller family units, independently confirmed after Bonferroni correction. This finding is consistent with the resource dilution hypothesis, whereby increases in family size reduce per-capita food expenditure and dietary diversity [50]. In the Moroccan context, large family size is structurally linked to rural residence and lower socioeconomic status [35]. These findings underscore that family size composition represents a modifiable socioeconomic risk factor that should be integrated into targeted nutritional interventions for Moroccan adolescents. Conversely, no significant differences in MDA were observed across nutritional status categories after Bonferroni correction, indicating that BMI z-score does not independently determine dietary quality in this population. This dissociation between weight status and dietary adherence aligns with evidence from Spanish [34] and Italian [36] adolescent cohorts, and highlights the importance of addressing upstream socioeconomic and environmental determinants

of dietary quality rather than relying exclusively on anthropometric proxies in public health programming.

The present data showed that urban-rural differences were observed exclusively in positive MD components (cereals, legumes, olive oil, fish, vegetables and fruits), with no significant differences in negative dietary behaviours between geographical areas. This finding suggests that disparities may be explained primarily by differential access to key MD foods rather than by differences in awareness of unhealthy dietary practices. Given Morocco's extensive Atlantic and Mediterranean coastline and longstanding fishing tradition, the marked urban-rural gap in regular fish consumption (41.30% vs. 27.43%) is particularly notable, and may be more plausibly explained by limitations in cold-chain logistics and distribution infrastructure than by differences in food preferences. These patterns suggest that familiarity with health-detrimental eating habits is geographically uniform, whereas access to nutritious Mediterranean diet components may represent a primary structural barrier in rural areas. This interpretation aligns with the double burden of malnutrition framework, whereby industrialized ultra-processed foods tend to penetrate both urban and rural markets rapidly and uniformly, while access to fresh and nutrient-dense foods remains structured by infrastructure, market access, and purchasing power. Nevertheless, this study did not include direct measures of the food environment, proximity to markets, household food security, or nutritional knowledge. Consequently, the proposed access-related explanation remains hypothetical and should be examined in future studies incorporating validated food-environment indicators.

The major strengths of this study include being the first nationally representative assessment of MDA among Moroccan adolescents, with a large sample size (N = 3600), multi-stage stratified sampling across 12 regions, and the use of a validated and culturally adapted KIDMED instrument. Limitations include: the cross-sectional design precluding causal inference; omission of physical activity (a recognized correlate of healthy dietary behaviours varying between urban and rural contexts), contributing to the modest explanatory power of the model (Nagelkerke $R^2 = 18.70\%$); absence of direct socioeconomic indicators (parental income, household food expenditure); and the pilot phase not formally pre-testing comprehension among adolescents aged 10-11 years (pilot phase included only ages 12-18 years).

## CONCLUSIONS

This first nationally representative assessment of MDA among Moroccan adolescents reveals a concerning and significant departure from traditional dietary patterns. The study demonstrates a critical public health inequality: optimal adherence was achieved by only 22.50% of adolescents nationally, but the urban-rural divide is particularly alarming, with optimal adherence being more than three times higher in urban (31.10%) than in rural (9.65%) settings. Rural residence independently conferred more than a threefold greater odds of poor adherence, even after adjustment for sociodemographic and anthropometric covariates. The specific finding that geographic disparities were exclusive to positive dietary components, while unhealthy dietary behaviours were uniformly prevalent, points to structural food access barriers rather than differential nutritional awareness as the primary driver of rural disadvantage. These findings call urgently for geographically differentiated public health policies that integrate cold-chain infrastructure improvements, rural food distribution networks, and school-based nutritional programmes. Future research should incorporate socioeconomic indicators, physical activity data, and validated food-environment measures to further characterize the determinants of dietary inequality in this population.

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**Conflict of interest**

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ORIGINAL ARTICLE

# SALT CONSUMPTION IN HOUSEHOLDS IN POLAND

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## ABSTRACT

**Background.** The main source of sodium in the diet is table salt, as well as sodium from processed food. Sodium is also naturally contained in food, but in small amounts. According to WHO the average daily sodium intake for adults worldwide is 4,278 mg (WHO recommends no more than 2,000 mg).

**Objective.** The aim of this study was to assess the consumption of table salt, sodium intake and its dietary sources in Poland between 2015 and 2024.

**Material and Methods.** The assessment of table salt consumption and sodium intake was based on the Household Budget Survey from 2015 to 2024. The salt amount was calculated into sodium based on the data from National Tables of the Composition and Nutritive Value of Foods (2020).

**Results.** There was observed the decreasing of salt consumption in Poland between 2015 and 2024. In 2024, the mean table salt consumption was 4.9 g/(person·day), which was 1 g lower than in 2015. The total daily salt intake was 8.3 g/person in 2024, which was 1.6 g lower than in 2015. The mean total sodium intake from all food sources was 3,887 mg/(person·day) in 2015, however, this value decreased to 3,270 mg in 2024. Compared to the WHO recommendation (no more than 5 g) it was observed that the total salt (table salt and salt from other sources) intake exceeded this amount in each year. The most important source of sodium besides table salt were cereals.

**Conclusions.** In Poland the WHO limits for total salt and sodium intake are still being exceeded. However, the amount of salt consumed during the analysed 10 years appears to be decreasing. As excessive salt intake has an adverse effect on health, efforts to reduce it must be intensified, particularly through the reformulation of food products and consumer education – specifically regarding the reduction of ultra-processed food consumption.

**Keywords:** *diet, sodium, salt, consumption, Household Budget Survey*

## INTRODUCTION

Table salt is the main source of sodium in the human diet. According to the WHO [1], the average daily sodium intake for adults in the world is 4,278 mg (nearly 11 g of salt per day). This is more than twice the World Health Organization's recommended intake for adults, which is less than 2,000 mg of sodium per day (less than 5 g of salt per day, or about one teaspoon) [1, 2]. The main health effect associated with a high-sodium diet is elevated blood pressure, which increases the risk of cardiovascular disease, stomach cancer, obesity, osteoporosis, and kidney disease [2].

Many epidemiological studies indicate that long-term consumption of excessive amounts of sodium, primarily from salt, is associated with an increased risk of morbidity and mortality from cardiovascular diseases, including hypertension [3-7]. A meta-analysis by Wang et al. [8] showed that people with high sodium intake were 19% more likely to develop cardiovascular disease than those with low intake. This risk increased by up to 6% for every 1 g increase in sodium intake. Another analysis by Ma et al. [9] found that an increase in sodium excretion of 1000 mg per day was associated with a 18% increase in the risk of cardiovascular disease. Reducing sodium intake has been shown to effectively reduce the risk of ischaemic heart disease and stroke [3, 7].

High sodium intake increases the risk of stomach cancer by causing gastric mucosal inflammation and promoting the colonisation of *Helicobacter pylori*, as well as the penetration of carcinogenic compounds [10, 11]. Consuming more than 5 g of salt per day significantly increases the risk of developing this cancer [12]. Furthermore, an increased risk of stomach cancer has been observed in individuals who consume salt-preserved foods, such as pickled vegetables.

Excessive sodium intake may also contribute to obesity. It leads to disturbances in fat metabolism. It can also cause inflammation in the body [13]. Furthermore,

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added salt promotes greater food consumption, thereby increasing energy intake [14]. In the United Kingdom, it has been estimated that increasing salt intake by 1 g per day increases the risk of obesity by 28% in children and 26% in adults [15]. An American study also showed that increasing sodium intake by 1 g per day was associated with a 15% increase in the risk of obesity and a 24% increase in the risk of central obesity [16].

Some studies indicate that a diet high in sodium may promote the development of osteoporosis. This leads to increased calcium excretion in the urine and a negative calcium balance in the body [17, 18]. A national study conducted in Korea between 2008 and 2011 revealed that postmenopausal women consuming ≥ 2000 mg of sodium daily were at a higher risk of developing osteoporosis [19].

Furthermore, high salt consumption contributes to the development of chronic kidney disease (CKD), independently of its effects on blood pressure [20]. Therefore, reducing salt consumption may be beneficial in preventing impaired kidney function and the development of CKD. Furthermore, excessive sodium intake may promote the formation of kidney stones by increasing calcium excretion in urine [21, 22].

According to the Global Burden of Disease Study 2023, 1.7 million deaths worldwide were attributed to excessive sodium intake [23]. Reducing the amount of sodium in people's diets is one of the most cost-effective ways to improve health and reduce the burden of non-communicable diseases. The WHO estimates that for every 1 USD invested in intensifying efforts to reduce sodium intake, a return of at least 12 USD will be achieved [1].

The WHO has estimated changes in sodium intake in the coming years. Based on trends from 2010 to 2019, sodium intake will decrease minimally; in 2030, it may reach 4,163 mg globally and 3,430 mg in the European region [2]. It will decrease by 147 and 15 mg respectively compared to 2019. The WHO believes that the effect would be significantly greater if all countries accelerate the process of adopting policies that ensure at least two mandatory interventions and the implementation of best practices. Modelling that effect it is estimated that average sodium intake by 2030 will decrease more significantly – by 1,010 mg (23.4%) globally and by 870 mg (25.3%) in the European Region.

Reducing salt intake requires a number of initiatives. They include education at the population level and promoting healthy eating habits, interventions in specific settings, e.g., schools, hospitals, food reformulation to reduce salt content, improving consumer information, including through appropriate food labelling [2, 24].

The average salt intake of the population in the WHO European Region is above the WHO recommended level, with fifty-two out of fifty-three Member States exceeding this level, and most of the studies included likely underestimating these values [25]. According to Kwong et al. [25] the average table salt intake among adults in Europe (excluding Russia) was ranged from 6.05 g/(person · day) in Albania to 13.37 g/(person · day) in Czechia.

Systematic data on salt consumption is provided by, among others, the Household Budget Survey (HBS). This survey plays an important role in analysing the standard of living of the population, including available income, expenditure, food consumption, and housing and equipment. This information is combined with data on the different demographic, social, and economic characteristics of households and their members. The survey covers a randomly selected sample of all households, with the exception of those living in institutional households (e.g. retirement homes) [26, 27].

The HBS is a primary source of information on, among other things, the consumption level of basic food products. This survey is based on a representative method, which allows the results to be generalised to the entire household population in the country. This makes it possible to monitor long-term trends in the consumption of various food products in Poland and to make comparisons [26].

The survey is conducted using a monthly rotation system, meaning that different households participate each month. Each participating household keeps a special diary for a month in which they record their income, expenditure and the quantities of food purchased, obtained for free or produced through individual farming, gardening or business activities. Food consumption is assessed based on purchases and items received from other sources. Household Budget Survey results provide information on average per capita consumption of individual food items, including table salt [26].

The aim of the study was to assess table salt consumption in the Polish population between 2015 and 2024, as well as sodium intake and its dietary sources.

## MATERIALS AND METHODS

The assessment of salt consumption and sodium intake was based on the Household Budget Survey conducted by Statistics Poland throughout the country from 2015 to 2024. In 2024, 28,350 households were surveyed, with 68,240 people living in them [26]. These values were lower than in 2015, when 37,148 households comprising 101,076 individuals were surveyed [28]. The smaller sample size in 2024 was

due to the decision taken in 2020 to gradually reduce the size of the Household Budget Survey sample [26].

The study analysed table salt consumption and sodium intake. Sodium intake was calculated based on its content in consumed products and table salt. For food products, the natural sodium content of the food and the sodium added during industrial processing were considered. Data on food consumption, including table salt, were converted into sodium amounts based on the National Tables of the Composition and Nutritive Value of Food (2020), developed at the Institute of Food and Nutrition [29].

The salt intake from the other food than table salt was calculated based on sodium intake analyses. A conversion factor recommended by WHO [2] was used to convert sodium to salt: amount of salt = 2.5 × amount of sodium.

Table salt and sodium intake was presented for members of the entire household group, including: employees, farmers, the self-employed, retirees and pensioners across the frame time 2015-2024. In addition, analyses focusing on administrative divisions and population numbers were carried out, referring to the year 2024.

## RESULTS

According to the results of the Household Budget Survey conducted by Statistics Poland in 2024, the mean daily table salt consumption per one member of a household was 4.9 g (Figure 1). In comparison to the previous year it was the same but a decrease in table salt consumption of 1 g was observed compared to 2015. The amount of the daily total salt intake in 2024 was 8.3 g/person and was 1.6 g lower than in 2015. This decrease was due to both a reduction in the consumption of table salt and salt contained in food products. In comparison to the WHO limit which is 5 g salt/(person · day), it was observed that in each case this amount was exceeded by total salt intake.

The similar observation were made in the respect of sodium intake (Figure 2). The mean total sodium intake from the all food sources in 2015 was 3887 mg/(person · day) in the average household. In the following years, there was a general downward trend in sodium intake, which in 2024 was almost 16% lower than in 2015. The largest decline occurred between 2015 and 2019, after which sodium intake fluctuated, reaching its lowest level in 2023. The amount of sodium intake of the table salt origin in 2015 was 2,299 mg/(person · day) but after 9 years this amount was almost 17% lower. It is worthy to notice that the sodium intake from the table salt was the same in 2023 and 2024. In all years, total sodium intake exceeded the WHO recommendation of no more than 2000 mg. In 2024, it was 163.5% of the maximum amount.

The food group as sources of sodium in diets of the members of total group of households studied in 2015 and 2024 were presented in the Table 1. Most sodium was obtained from table salt – 59.1% and 58.6% respectively in 2015 and 2024. Among food products, cereals provided the most sodium however there were observed differences in the percentage values between

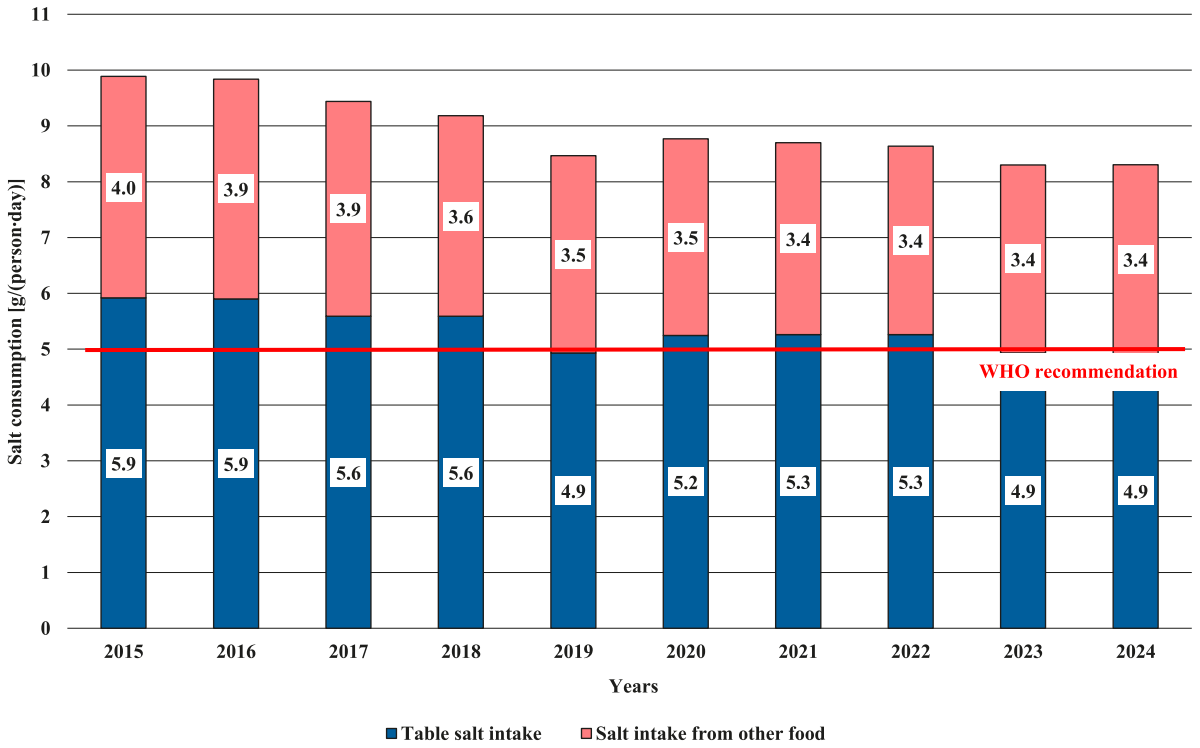


Figure 1. Consumption of table salt and salt from other food products in households in Poland in 2015-2024

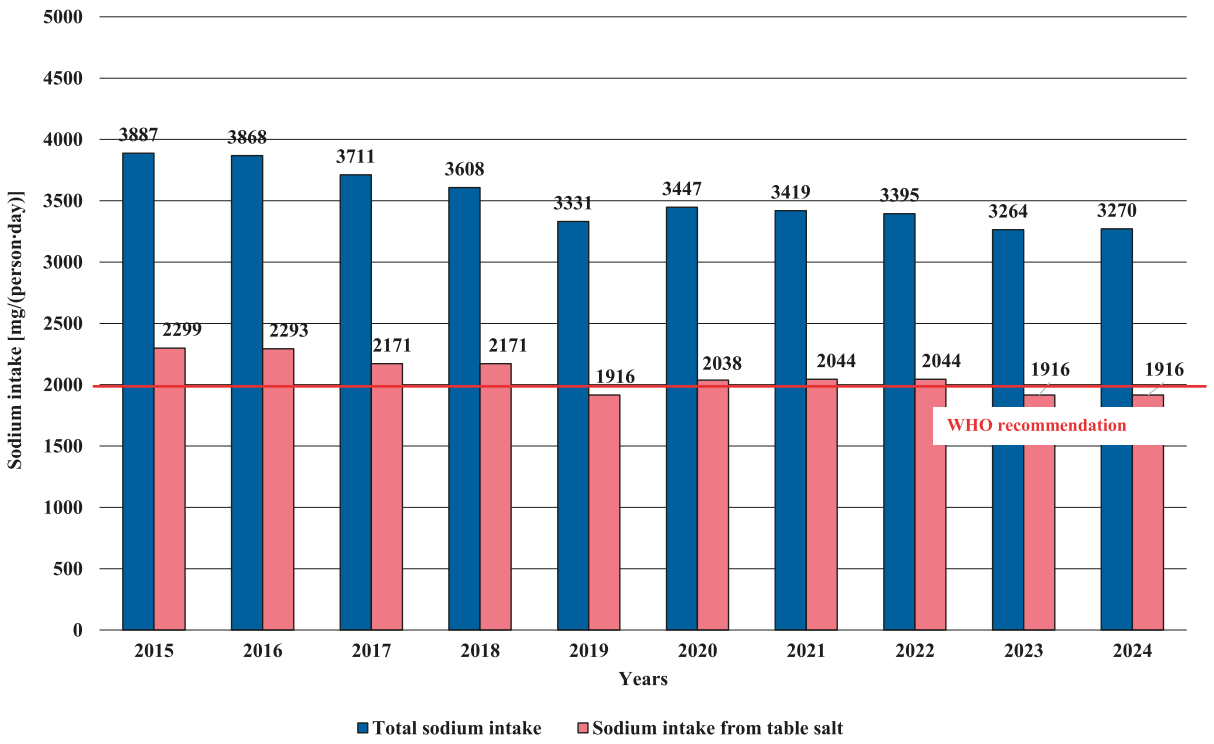


Figure 2. Total sodium intake and sodium intake from table salt in households in Poland from 2015 to 2024

2015 and 2024 year (15.3% and 14.1% respectively). Meat and meat products provided similar amounts of sodium. Milk and dairy products were also a significant source of this element. It should be noted that in 2024, the share of sodium from these products in the diet was clear higher than in 2015. Besides the table salt the above-mentioned food groups were the important source of sodium intake because of salt used by the food industry (e.g. bread, meat products, cheese).

The analyses of the table salt consumption in 2024 according to the administrative division of Poland (Figure 3) showed that the highest consumption was observed in Lubelskie and Podkarpackie voivodship in the south-east region of the country – 6.2 g/(person · day). In contrast the lowest table salt consumption was characterised for Opolskie, Pomorskie, Śląskie and Wielkopolskie voivodships – 4.3 g/(person · day).

An analysis of table salt consumption depending on place of residence (Figure 4) showed that it was highest in rural areas and small towns. In contrast, residents of large towns consumed significantly less table salt (by 2 g).

Table 1. The share of food groups as a source of sodium intake in household members diets in Poland in 2015 and 2024 (%)

| Food groups | 2015 | 2024 |
|---|---|---|
| Bread and cereals | 15.3 | 14.1 |
| Potatoes and their preparations[a] | 0.6 | 0.8 |
| Vegetables and their preparations | 1.1 | 1.1 |
| Fruit and their preparations | 0.1 | 0.1 |
| Raw meat and processed meat | 14.7 | 13.9 |
| Fish and fish products[b] | 1.3 | 1.2 |
| Fats | 0.3 | 0.2 |
| Milk nad milk products | 4.9 | 7.1 |
| Eggs | 0.6 | 0.7 |
| Sugar and and confectionery | 0.4 | 0.5 |
| Table salt | 59.1 | 58.6 |
| Coffee (grounds) | 0.6 | 0.8 |
| Tea (leaves) | 0.6 | 0.4 |
| Non alcoholic beverages[c] | 0.3 | 0.4 |

[a] – with chips; [b] – without canned fish; [c] – without fruit and vegetable juices

## DISCUSSION

Consumption data indicates that, for most people, the sodium content of their diet significantly exceeds the recommended amount.

According to data from the Household Budget Survey, the total salt intake in Poland in 2024 was 8.3 g per person per day, corresponding to 3,270 mg of sodium. While there was a positive trend towards a reduction in overall salt consumption between 2015 and 2024, particularly between 2015 and 2019, the content of salt in the Polish diet is still too high. Total salt intake in 2024 was significantly higher than the WHO's recommended maximum value of 5 g for

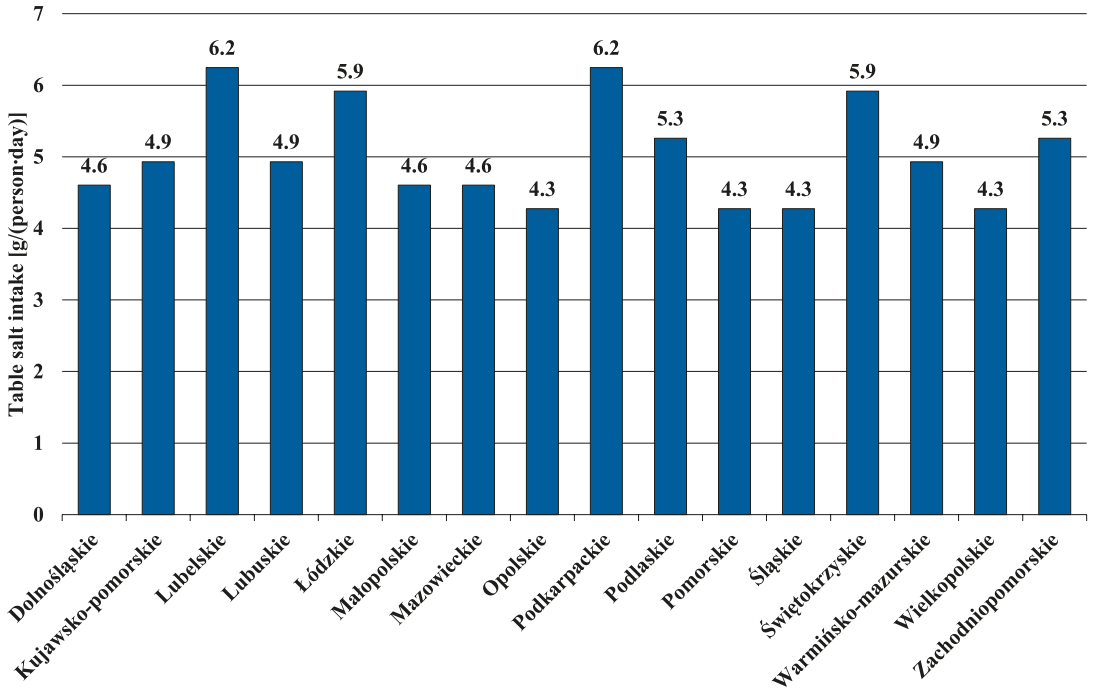


Figure 3. Table salt consumption in households in Poland in 2024 by voivodeship

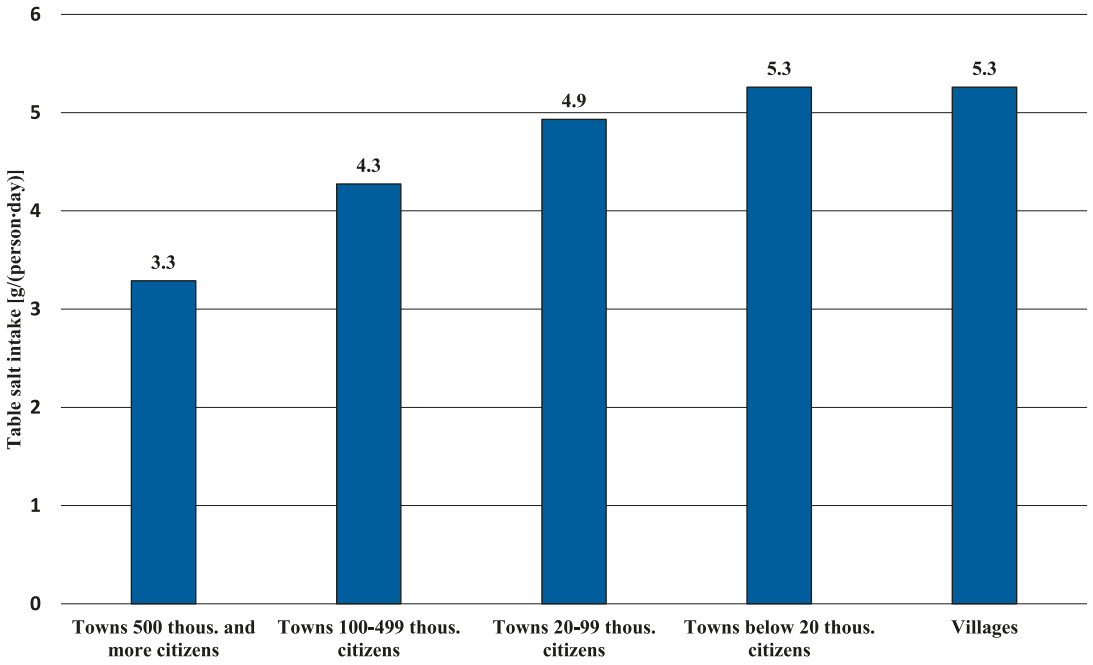


Figure 4. Table salt consumption in households in Poland in 2024 by place of residence

adults [30]. Polish dietary guidelines also recommend limiting salt intake to 5 g per day [31]. However, salt intake may be higher in reality, as the HBS does not cover consumption outside the home [26].

Data from individual consumption surveys confirm that sodium intake in Poland is too high. Between 2017 and 2020, research was conducted in Poland as part of the National Health Programme on the eating habits of adults, including elderly people. According to these data, the daily sodium intake was 4,887 mg for men aged 19-64 and 3,361 mg for women [32]. The diets of the elderly (aged 65 and over) contained 4,341 and 3,351 mg, respectively [33]. Pregnant women were also examined as part of the National Health Programme. Their sodium intake was found to be 3,763 mg in the first trimester and 3,832 mg in the third trimester of pregnancy [34].

Even the youngest age groups have high sodium intakes. A nationwide study of young children conducted in 2016 (PITNUTS) showed that, at the age of 1-3 years, sodium intake was 1,542 mg [35, 36]. Children aged six from Nowy Sącz (town in southern

Poland with the population of about 80,000) also consumed diets high in sodium: 3,194 mg for boys and 2,876 mg for girls [37]. In some groups, sodium intake may be higher. For example, in a study of 13-15-year-old boys from a sports school in Warsaw, sodium intake was estimated at 5,528 mg [38].

Polish dietary guidelines recommend not adding salt to prepared meals, choosing products without added salt or with a lower salt content, and replacing salt with herbs [31]. However, many Poles do not follow these recommendations. The HBS shows that table salt is the main source of sodium in the Polish diet. This suggests that Poles use a lot of salt when preparing food and when adding salt to prepared meals.

Apart from table salt, the main sources of sodium in the diets of European populations are bread, processed meat and cheese [39]. Traces of this mineral are also present in unprocessed food and drinking water. Data obtained from the HBS confirm these findings.

Among food groups, cereals were the most important source of sodium in the Polish diet. This is primarily because cereals are consumed in large quantities [40]. A study on the importance of cereal products in the Polish diet confirmed their significance as a source of sodium [41]. They provided 18.4% of the sodium in the diet. A study covering the years 2009-2018, conducted by Winiarska-Mieczan et al. [42], also showed that cereal products, particularly bread, were the main source of sodium in the diet.

However, cereals provide significant amounts of nutrients other than sodium. In the Polish diet, they are a valuable source of micronutrients, especially manganese, iron, folate, copper, magnesium, potassium, zinc and thiamine [41, 43].

In 2024, cereal products contributed less sodium than in 2025, mainly due to decreased bread consumption during that period [44].

Meat products are an important source of sodium in the Polish diet. A study assessing the nutritional value of meat and meat products found that they accounted for 17.47% of the sodium in the Polish diet [45]. Sodium was derived mainly from processed meat. Poles often consume processed meats such as cold cuts and sausages, which contain high levels of sodium [46, 47]. Similar data was obtained in a study of 16-19 year old adolescents from Kamień Pomorski, a small town (fewer than 10,000 inhabitants) in northwestern Poland [48]. These adolescents also consumed significant amounts of sodium from meat products, especially cold meats (17.6-19.4%). Furthermore, meat and meat products are a significant source of other nutrients in the Polish diet, including iron, zinc, niacin, thiamine, vitamins $B_6$ and $B_{12}$, and vitamin D. However, these nutrients are not only provided by processed meat, but also by other meat products [45].

Although the largest amounts of sodium in the Polish diet came from cereal and meat products, dairy products also provided significant quantities. A study evaluating dairy products as a source of various nutrients showed that they accounted for 7.26% of the sodium in the Polish diet [49]. The largest quantity came from ripened and melted cheeses. Besides milk, these cheeses are the most frequently consumed dairy products in Poland [50]. They also contain more sodium than other products in this category [29]. In some population groups, the proportion of sodium derived from dairy products may be higher. In the diet of young people from above-mentioned Kamień Pomorski, for example, dairy products provided 10.8-14.1% of sodium [48].

The higher proportion of sodium derived from dairy products in 2024 compared to 2015 was primarily due to increased cheese consumption [44, 51].

Salty snacks are a significant source of sodium, especially among children and adolescents. In the diets of children and adolescents in the Silesian Voivodeship aged 10-18 years, 0.433 g of sodium (1.1 g of salt) came from salty snacks alone. Consumption of these products covered nearly 31% of the daily sodium requirement. Children aged 10-12 had the highest sodium intake from snacks, while teenagers aged 16-18 had the lowest [52].

The main sources of sodium in the diets of people in different countries are similar, but their respective contributions to total sodium intake vary. A review of studies from 34 countries conducted between 1975 and 2018 showed that the proportion of daily salt intake from bread and bakery products was highest in European countries and the United States, ranging from 25% to 40%. In the US, meat products accounted for up to 31% of daily salt intake; meat was also a significant source of salt in some European and South American countries. In Argentina and New Zealand, dairy products provided the most salt – up to 15% of daily intake [53].

Salt consumption varied depending on place of residence. The Household Budget Survey indicated that rural households and those in small towns consumed more salt than households in large cities. During the analysed period, rural households had a higher sodium intake, due not only to their higher consumption of table salt, but also to their consumption of other sodium-rich foods such as bread and meat products [46, 51].

The main health effect associated with a high-sodium diet is elevated blood pressure, which increases the risk of cardiovascular disease. It can also impact other health outcomes, including stomach cancer, obesity, osteoporosis, and kidney disease [2].

Excess sodium in the diet is not only a problem among the Polish population. According to the WHO,

the average daily sodium intake for adults worldwide in 2019 was 4,310 mg, equivalent to 10.78 g of salt per day [2]. In the European region, this intake was lower at 3,445 mg of sodium (8.61 g of salt). The highest sodium intakes were reported in China (6,954 mg), Hungary (5,646 mg) and the Czechia (5,112 mg).

However, methods for estimating salt intake varied widely and underestimations are very likely [25]. In future studies, rigorous gold standard methods should be used wherever possible when collecting data on population salt intake to ensure the highest degree of accuracy, comparability, and validity. Furthermore, surveillance systems should be strengthened and policy measures implemented in all sectors that may influence population salt intake.

**Limitations of the study**

The information obtained on sodium and salt intake concerned all members of the households. No data was available on intake by gender or age. The data relates to food purchases or obtained either by themselves or from other sources; individual intake may be different. Sodium contained in products and dishes consumed outside the household was not taken into account. However, the methodology of the HBS does not include food quantities consumed in catering establishments, canteens, hospitals, nurseries, kindergartens, etc. This feature is common to these surveys in many countries and stems from the fact that expenditure on eating outside the home is intentionally underestimated [26].

**Strengths of the study**

The salt and sodium intake assessment based on the Household Budget Survey provided comparable data for the entire 2015-2024 period and was representative for Polish households. This enabled trends in salt intake and the contribution of food groups to sodium intake to be identified during long period. The results could be compared between households in different regions of the country, as well as between urban and rural areas.

## CONCLUSIONS

Between 2015 and 2024, a favourable trend of reduced sodium intake was observed. This was associated with a decrease in the consumption of table salt, which was the main source of sodium, and cereals, including bread.

Despite these favourable changes, salt consumption remained too high and exceeded the amounts recommended by the WHO and indicated in the Polish dietary recommendations.

Apart from table salt, the main sources of this mineral in the Polish diet were cereals products, meat products, and dairy products.

As excessive salt intake has an adverse effect on health, it is essential to intensify efforts to reduce this intake, including, in particular, consumer education, and food reformulation, especially high processed food.

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**Conflict of interest**

*The authors declare no conflict of interest.*

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ORIGINAL ARTICLE

# OBESITY, INSUFFICIENT PHYSICAL ACTIVITY AND LIFE EXPECTANCY ACROSS 172 COUNTRIES: A LONGITUDINAL ECOLOGICAL PANEL STUDY

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## ABSTRACT

**Background.** Obesity and insufficient physical activity are major global health risks, but their population-level associations with life expectancy may overlap because both evolve with economic and epidemiological transition.

**Objective.** To compare the strength and robustness of the associations of adult obesity prevalence and insufficient physical activity with life expectancy at birth in a longitudinal ecological panel of countries.

**Material and Methods.** Annual country-level data for 2000-2020 were analysed. The full source panel contained 4,095 country-year observations from 195 countries, and the primary complete-case sample included 3,365 observations from 172 countries. Life expectancy at birth was the outcome. Adult obesity prevalence and insufficient physical activity were the main exposures. Models included two-way fixed-effects specifications with country-clustered standard errors, one-year lagged exposures, a joint lagged specification, country-specific time trends, a non-linear obesity model, a smoking sensitivity analysis, and three-year and five-year lag sensitivity models.

**Results.** In standalone lagged models, obesity ($\beta = -0.3017$, $p < 0.001$) and insufficient physical activity ($\beta = -0.0716$, $p = 0.020$) were inversely associated with life expectancy. In the joint lagged model, obesity remained significant ($\beta = -0.2873$, $p < 0.001$), whereas insufficient physical activity attenuated to non-significance ($\beta = -0.0153$, $p = 0.643$). In the country-specific time-trends model, obesity remained significant ($\beta = -0.2496$, $p = 0.040$), but insufficient physical activity did not ($\beta = 0.1325$, $p = 0.457$). Three-year and five-year lag models supported this pattern.

**Conclusions.** In this country-level panel, adult obesity prevalence showed a more robust inverse association with life expectancy than insufficient physical activity. The findings should not be interpreted as evidence that obesity alone causes lower life expectancy. Rather, obesity may represent a cumulative marker of overlapping metabolic, social, environmental, and policy-related processes that shape population longevity.

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**Keywords:** *obesity, motor activity, life expectancy, epidemiology, longitudinal studies, public health, risk factors*

## INTRODUCTION

Obesity and insufficient physical activity are among the most important modifiable contributors to the global burden of non-communicable disease. The World Health Organization (WHO) defines obesity in adults as a body mass index of 30 kg/m² or higher [1]. Insufficient physical activity is also a major population health risk and contributes to the burden of non-communicable diseases (NCDs) [2].

Recent surveillance makes the public health relevance of both exposures clear. Global pooled estimates suggest that adult insufficient physical activity increased from 23.4% in 2000 to 31.3% in 2022, equivalent to approximately 1.8 billion adults not meeting recommended activity levels [3]. In parallel, evidence from NCD Risk Factor Collaboration (NCD-RisC) and the Global Burden of Disease (GBD) indicates that adult obesity has increased substantially and is projected to remain a major chronic-disease driver in the coming decades [4, 5]. Obesity is associated with multiple cardiometabolic complications and heterogeneous metabolic phenotypes [6, 7]. WHO guidance also emphasizes that regular physical activity supports cardiovascular, metabolic, musculoskeletal and mental health [8].

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Individual-level evidence indicates that physical activity, cardiorespiratory fitness and adiposity are interrelated but not interchangeable predictors of mortality and life expectancy [9-13]. At the population level, however, disentangling the independent epidemiological roles of obesity and insufficient physical activity remains methodologically challenging. Both indicators co-vary with economic development, urbanization, demographic ageing, shifts in occupational and transport systems, food environments, health-care access and broader epidemiological transition. As a result, cross-national associations may reflect shared macro-structural drivers rather than entirely separate population-level processes [14-16].

A key gap in the literature is that, although obesity and insufficient physical activity are both well-established population health risks, fewer longitudinal cross-national studies directly compare their relative associations with life expectancy within the same analytical framework. At the ecological level, it remains uncertain whether insufficient physical activity retains an independent association with life expectancy after obesity and structural time trends are included, or whether its statistical signal largely overlaps with obesity and shared macro-social change.

Therefore, the aim of this study was to compare the relative strength and robustness of the associations of adult obesity prevalence and insufficient physical activity with life expectancy at birth in a longitudinal ecological panel. The study addressed two questions: (1) Are adult obesity prevalence and insufficient physical activity each independently associated with life expectancy at birth in cross-national longitudinal models? (2) Do any of these exposures retain an independent association with life expectancy after adjustment for structural covariates, country and year fixed effects, and stricter temporal specifications?

## MATERIAL AND METHODS

### Study design

A longitudinal ecological panel design was used based on harmonized annual country-level data from 2000 to 2020.

### Data sources and variables

Data were derived from official international repositories, primarily the World Health Organization Global Health Observatory and the World Bank World Development Indicators [17-20]. The dependent variable was life expectancy at birth, measured in years. The two main explanatory variables were adult obesity prevalence, defined as the age-standardized percentage of adults with BMI ≥ 30 kg/m², and the age-standardized prevalence of insufficient physical activity among adults aged 18 years and older.

Time-varying country-level covariates were included to reduce omitted-variable bias. These covariates were log GDP per capita, urban population as a percentage of total population, current health expenditure as a percentage of GDP, alcohol consumption per capita in litres of pure alcohol, and the proportion of the population aged 65 years and older. Smoking prevalence was available only for a substantially smaller subset of country-year observations and was therefore used in a separate sensitivity analysis rather than in the main models.

### Reporting guideline

This study was reported in accordance with the STROBE recommendations, applied where relevant to an ecological design, including reporting of data sources, eligibility criteria, missing data, statistical methods and limitations [21, 22].

### Country and observation eligibility, missing data, and analytical sample

No eligibility restrictions were applied at the country level. All countries available in the source repositories were retained, and the analytical sample was determined solely by data availability under complete-case estimation. Countries were included when they had at least one available country-year record for the study period in the harmonized source panel. The full 2000-2020 source panel contained 4,095 country-year records from 195 countries with at least one available indicator. Because variables differed in temporal coverage, observation counts varied across indicators and model specifications. The main inferential sample was defined by complete-case availability for the joint lagged two-way fixed-effects model and included 3,365 country-year observations from 172 countries. Accordingly, the 172 countries reported in the title and main text refer to the restricted complete-case analytical sample used for the primary regression models. Because inclusion was based on data availability rather than probability sampling, the analytical sample should be interpreted as a broad data-available country panel rather than as a statistically representative sample of all countries. Nevertheless, the panel retained countries across diverse socioeconomic, demographic and epidemiological contexts.

Missing data were handled using listwise deletion within each model specification; no multiple imputation was applied. This approach was chosen because the study relied on secondary international indicators which are frequently modelled or smoothed by the original data providers and because the aim was to preserve transparent comparability across

fixed-effects specifications. The smaller smoking-observed sample comprised 744 country-year observations from 150 countries after applying the same lagged complete-case criterion.

**Life expectancy audit and data cleaning**

The life-expectancy variable was audited for implausible values before the final analyses. Six country-year records with life expectancy below 40 years were identified in the 2000-2020 panel. Because these values were inconsistent with plausible country-level life expectancy during the study period, they were treated as missing. No replacement values were imputed. Following this audit, the minimum observed life expectancy in the cleaned analytical panel was 40.27 years.

**Statistical analysis**

The analytical strategy was designed to reduce the risk of misleading inference arising from shared temporal trends and co-evolving macro-structural change. One-year lagged exposures were used in the primary models to establish temporal ordering between country-level risk indicators and life expectancy while preserving the largest possible complete-case analytical sample. First, separate one-year-lagged two-way fixed-effects (TWFE) models were estimated for obesity and for insufficient physical activity. These models included country fixed effects, year fixed effects and robust standard errors clustered by country. Second, a joint lagged model included both exposures simultaneously in order to assess whether each retained an independent association with life expectancy after adjustment for the other exposure.

Third, a country-specific time-trends (CSTT) specification added a separate linear time trend for each country as a stricter test against spurious associations driven by country-specific modernization trajectories. Fourth, a non-linear obesity model added current obesity prevalence and a quadratic obesity term to evaluate whether the association with life expectancy became stronger at higher obesity prevalence. Fifth, a smoking-based sensitivity analysis was estimated on the smaller smoking-observed subsample. Because the effects of obesity-related metabolic risk on mortality and population longevity may develop over longer periods, additional three-year and five-year lag sensitivity models were estimated.

All regression models adjusted for log GDP per capita, urbanization, health expenditure, alcohol consumption per capita and the share of the population aged 65 years and older. Statistical significance was assessed at $p < 0.05$. Analyses were conducted in Stata 14.2. For descriptive panel diagnostics, between-country and within-country standard deviations were calculated for the main indicators, where the between-country standard deviation captures cross-national heterogeneity and the within-country standard deviation captures temporal variation within countries over 2000-2020.

**Ethical considerations**

The study was ecological and used publicly accessible, aggregated country-level data. No individual patient data were analysed and ethics committee approval was not required. Because the study relied on secondary international data repositories, no informed consent procedures were applicable.

## RESULTS

**Descriptive statistics**

Table 1 summarizes the descriptive statistics for the 2000-2020 panel. Mean life expectancy across country-year observations was 69.63 years (SD = 8.87). Regarding the main exposures, the prevalence of insufficient physical activity averaged 26.46% (SD = 10.88), whereas the average prevalence of adult obesity was 18.51% (SD = 12.45). The mean urbanization level was 56.62%, mean current health expenditure was 6.17% of GDP, and mean alcohol consumption was 5.46 litres per capita. Observation counts differed across variables because of indicator-specific missingness. Table S1 (supplementary material) documents variable-specific country coverage and average years of observation, and Table S2 (supplementary material) reports between-country and within-country variation in the main indicators. The within-country standard deviations for life expectancy (2.33 years), insufficient physical activity (3.04 percentage points) and adult obesity prevalence (2.79 percentage points) indicate that the panel contained temporal variation relevant for fixed-effects estimation, although between-country heterogeneity was larger for most indicators.

In the 2000-2020 analytical panel, life expectancy ranged from 40.27 years in the Central African Republic in 2014 to 84.67 years in Japan in 2020.

**Main regression models**

In the lagged standalone models, both exposures were inversely associated with life expectancy (Table 2). The obesity-only coefficient was larger in magnitude ($\beta = -0.3017$, $p < 0.001$) than the coefficient for insufficient physical activity ($\beta = -0.0716$, $p = 0.020$). Once both exposures were introduced simultaneously, obesity remained negatively and statistically significantly associated with life expectancy ($\beta = -0.2873$, $p < 0.001$), whereas insufficient physical

Table 1. Descriptive statistics for the 2000–2020 analytical panel

| Variable | Obs. | Mean | SD | Min-Max |
|---|---|---|---|---|
| Life expectancy (years) | 3,732 | 69.63 | 8.87 | 40.27-84.67 |
| Insufficient physical activity (%) | 4,095 | 26.46 | 10.88 | 3.17-64.65 |
| Obesity prevalence (%) | 4,074 | 18.51 | 12.45 | 0.31-69.94 |
| GDP per capita | 3,914 | 21,274.47 | 23,126.92 | 702.60-145,591.02 |
| Log GDP per capita | 3,914 | 9.36 | 1.17 | 6.55-11.89 |
| Urbanization (%) | 4,053 | 56.62 | 22.94 | 8.04-100.00 |
| Health expenditure (% of GDP) | 3,934 | 6.17 | 2.83 | 1.11-24.23 |
| Alcohol consumption (litres per capita) | 3,891 | 5.46 | 4.18 | 0.00-19.40 |
| Smoking prevalence (%) | 984 | 25.14 | 11.45 | 3.60-68.00 |
| Population aged 65+ (%) | 4,053 | 7.68 | 5.55 | 0.86-28.92 |

Note. Life-expectancy values below 40 years (n = 6) were audited, considered implausible, and treated as missing. Observation counts are variable-specific because missingness differed across indicators. The primary complete-case joint TWFE model included 3,365 country-year observations from 172 countries.

Table 2. Main lagged regression models

| Variable | (1) Lagged obesity only | (2) Lagged inactivity only | (3) Joint lagged TWFE | (4) Joint lagged CSTT |
|---|---|---|---|---|
| Lagged obesity | -0.3017 (0.0591)** | | -0.2873 (0.0685) | -0.2496 (0.1207)* |
| Lagged inactivity | | -0.0716 (0.0306)* | -0.0153 (0.0329)** | 0.1325 (0.1779) |
| Log GDP per capita | 2.6720 (0.6814)** | 3.0200 (0.7445)** | 2.7163 (0.6948)** | 0.6082 (0.4518) |
| Urbanization | 0.0226 (0.0448) | 0.0497 (0.0458) | 0.0236 (0.0441) | -0.0989 (0.0835) |
| Health expenditure | 0.0968 (0.0663) | 0.1026 (0.0677) | 0.0977 (0.0660) | 0.0275 (0.0468) |
| Alcohol | -0.1906 (0.0833)* | -0.1792 (0.0839)* | -0.1862 (0.0822)* | -0.0280 (0.0592) |
| Population aged 65+ | -0.6674 (0.0926)** | -0.5720 (0.0926)** | -0.6561 (0.0873)** | -0.1572 (0.1002) |
| Country FE | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| Country-specific linear trends | No | No | No | Yes |
| Observations | 3,365 | 3,365 | 3,365 | 3,365 |
| Countries (clusters) | 172 | 172 | 172 | 172 |
| $R^2$/within $R^2$ | 0.7135 | 0.6922 | 0.7137 | 0.9946 |

Note. Unstandardized coefficients with country-clustered robust standard errors in parentheses. TWFE – two-way fixed effects; CSTT – country-specific time trends. * $p < 0.05$, ** $p < 0.001$.

activity attenuated markedly and was no longer statistically significant (β = -0.0153, p = 0.643).

The country-specific time-trends model provided a stricter temporal test because it included country fixed effects, year effects and each country's own linear trajectory. In this specification, lagged obesity remained statistically significant (β = -0.2496, p = 0.040), whereas lagged insufficient physical activity did not (β = 0.1325, p = 0.457).

**Additional analyses**

Table 3 presents the non-linear obesity model and smoking sensitivity models. In the non-linear model, the quadratic obesity term was negative and statistically significant (β = -0.0044, p = 0.010), suggesting that the association between obesity prevalence and life expectancy became more adverse at higher levels of obesity prevalence. The linear obesity coefficients were not individually significant, which is common when a variable enters the model in both linear and squared form.

Of the 984 country-year records with available smoking data, 744 remained after applying the one-year lag and complete-case criterion used in the regression model. In the smoking-observed subsample, obesity remained statistically significant before and after smoking adjustment, whereas insufficient physical activity remained non-significant. Lagged smoking itself was not statistically significant in the adjusted sensitivity model (β = -0.0278, p = 0.355).

Table 3. Additional analyses: non-linear obesity model and smoking robustness

| Variable | (1) Non-linear obesity model | (2) Smoking subsample, no smoking | (3) Smoking subsample + smoking |
|---|---|---|---|
| Lagged obesity | -1.2046 (0.8733) | -0.3106 (0.0720)*** | -0.3013 (0.0749)*** |
| Lagged inactivity | -0.0355 (0.0305) | -0.0047 (0.0332) | -0.0039 (0.0335) |
| Lagged smoking | | | -0.0278 (0.0299) |
| Obesity | 1.1851 (0.7968) | | |
| Obesity squared | -0.0044 (0.0017)* | | |
| Log GDP per capita | 2.0865 (0.6863)** | 1.8420 (0.5919)** | 1.8149 (0.5975)** |
| Urbanization | -0.0077 (0.0442) | 0.0483 (0.0290)† | 0.0444 (0.0290) |
| Health expenditure | 0.0876 (0.0638) | 0.1553 (0.0905)† | 0.1536 (0.0900)† |
| Alcohol | -0.1754 (0.0795)* | -0.1841 (0.0856)* | -0.1879 (0.0850)* |
| Population aged 65+ | -0.6118 (0.0852)*** | -0.6365 (0.0942)*** | -0.6413 (0.0937)*** |
| Country FE | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes |
| Observations | 3,365 | 744 | 744 |
| Countries (clusters) | 172 | 150 | 150 |
| Within $R^2$ | 0.7259 | 0.7556 | 0.7564 |

Note. The smoking analysis compares models on the same smoking-observed lagged subsample. Unstandardized coefficients with country-clustered robust standard errors in parentheses. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4. Sensitivity analysis: 3-year and 5-year lag models

| Variable | (1) 3-year lag | (2) 5-year lag |
|---|---|---|
| Lagged obesity | -0.3046 (0.0730)*** | -0.3185 (0.0785)*** |
| Lagged inactivity | -0.0130 (0.0343) | -0.0104 (0.0351) |
| Log GDP per capita | 2.5535 (0.7048)*** | 2.2967 (0.7081)** |
| Urbanization | 0.0060 (0.0520) | -0.0147 (0.0614) |
| Health expenditure | 0.0547 (0.0686) | 0.0127 (0.0762) |
| Alcohol | -0.1880 (0.0758)* | -0.1960 (0.0720)** |
| Population aged 65+ | -0.6486 (0.0858)*** | -0.6447 (0.0853)*** |
| Country FE | Yes | Yes |
| Year FE | Yes | Yes |
| Observations | 3,036 | 2,702 |
| Countries (clusters) | 172 | 172 |
| Within $R^2$ | 0.6893 | 0.6504 |

Note. Models include country fixed effects, year fixed effects and the same covariates as the main joint TWFE model. Unstandardized coefficients with country-clustered robust standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

### Lag sensitivity analysis

Because the biological and epidemiological effects of obesity-related metabolic risk may develop over longer periods than one year, 3-year and 5-year lag sensitivity models were estimated (Table 4). The pattern was consistent with the primary joint model. Lagged obesity remained inversely and significantly associated with life expectancy in both the 3-year lag model ($\beta = -0.3046$, $p < 0.001$) and the 5-year lag model ($\beta = -0.3185$, $p < 0.001$). By contrast, lagged insufficient physical activity remained non-significant in both sensitivity specifications.

## DISCUSSION

### Principal findings

The main finding was that adult obesity prevalence showed a more stable inverse association with life expectancy than insufficient physical activity once both exposures were modelled jointly. Insufficient physical activity was inversely associated with life expectancy in the standalone model, which is consistent with evidence linking physical activity and fitness to better health and longevity [2, 8-11]. However, this association attenuated after obesity was included, suggesting that

at the country level a substantial part of the statistical signal for insufficient physical activity overlaps with obesity and with broader structural processes that shape both behavioral and metabolic risk.

These ecological findings can be read alongside individual-level evidence that reaches a different emphasis. Using the UK Biobank cohort, Zaccardi and colleagues reported that participants with a brisk walking pace had longer life expectancy across the spectrum of body-mass index and other adiposity indices [10], and the accompanying commentary interpreted fitness as predicting longevity largely regardless of adiposity [11]. The present country-level results do not contradict this evidence; rather, they operate at a different level of analysis. At the individual level, fitness captures a proximal physiological capacity. At the population level, obesity prevalence and insufficient physical activity reflect more distal behavioral and structural exposures whose signals are partly shared with obesity and broader development trends. The attenuation of insufficient physical activity in the joint models is therefore consistent with either partial mediation through adiposity or common structural confounding, a distinction the present ecological design cannot resolve. The significant quadratic obesity term is also consistent with individual-level evidence that the BMI–mortality association is graded and non-linear [13].

The persistence of the obesity coefficient is consistent with recent global evidence showing the continuing growth of adult obesity and its substantial cardiometabolic burden [4-7, 13]. Importantly, the present findings should not be read as evidence that obesity is an isolated causal determinant of life expectancy. At the ecological level, obesity prevalence may operate as a cumulative marker of multiple overlapping processes, including food environments, socioeconomic conditions, chronic disease burden, health-care access and treatment quality, physical activity environments, transport systems, and national policy responses.

**Interpretation of lag sensitivity findings**

The three-year and five-year lag sensitivity models strengthened the robustness of the core result. Obesity remained significantly associated with life expectancy under both longer lag structures, while insufficient physical activity remained non-significant. This pattern is relevant because one-year lags may be too short to capture the full biological footprint of metabolic risk. Nevertheless, even the longer lags used here cannot fully represent lifetime exposure histories or cumulative disease pathways, and therefore the results should remain interpreted as longitudinal ecological associations rather than individual-level causal effects.

**Public health implications**

The findings support integrated public health strategies rather than a narrow one-risk approach. Obesity prevention remains central because obesity may reflect cumulative metabolic and structural risk at the population level. However, physical activity promotion should not be downgraded; instead, it should be positioned as part of broader systems-oriented strategies that include healthier food environments, active transport, safe and walkable urban spaces, equitable access to prevention and treatment services, and policies targeting the social determinants of non-communicable disease. From this perspective, the attenuation of insufficient physical activity in joint models does not imply that activity is unimportant; it suggests that physical activity policies may be most effective when embedded within wider obesity and NCD prevention frameworks.

**Strengths and limitations**

This study has several strengths. It used a large longitudinal country-level panel, compared obesity and insufficient physical activity within the same analytical framework, applied a multi-model strategy, included country and year fixed effects, used country-clustered standard errors, incorporated a country-specific time-trends specification, audited implausible life-expectancy values, documented both between-country and within-country variation in the main indicators, and added three-year and five-year lag sensitivity models.

Several limitations should also be noted. First, ecological designs cannot identify individual-level causal pathways and are vulnerable to ecological fallacy. Second, complete-case estimation reduced the effective sample from 195 countries with at least one available indicator to 172 countries in the main models. Third, the study relied on international indicators that may be modelled, smoothed or estimated differently across countries. Fourth, residual confounding remains possible because the models did not directly include educational attainment, income inequality, quality and accessibility of healthcare, dietary patterns, prevalence of chronic diseases, food-system indicators, or detailed national health policies. These indicators were not included in the main regression models because harmonized annual country-level coverage was incomplete and would have substantially reduced the complete-case sample and cross-national comparability. Fifth, smoking data were sparse and available only for a smaller subset of countries and years. Sixth, lag models improve temporal ordering but cannot fully represent long-run cumulative exposure histories.

## CONCLUSIONS

In this longitudinal country-level panel, adult obesity prevalence showed a more robust inverse association with life expectancy at birth than insufficient physical activity. Although insufficient physical activity was inversely associated with life expectancy in standalone models, this association attenuated after obesity and structural covariates were included. By contrast, the obesity association remained significant in the joint lagged model, in the country-specific time-trends specification and in three-year and five-year lag sensitivity models. These findings should be interpreted as ecological evidence and do not establish individual-level causality. Overall, the results support integrated public health strategies combining obesity prevention, physical activity promotion and broader non-communicable disease policy interventions.

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**Conflict of interest**
*The authors declare no conflict of interest.*

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