POLYPHENOLS IN PLANT-BASED FOODS: IMPLICATIONS FOR HEALTH, ANTIOXYDANT ACTIVITY, COMPOSITION FACTORS, AND PROCESSING APPROACHES: A SYSTEMATIC REVIEW

S. Elqarnifa[1] https://orcid.org/0000-0003-0371-3578, A. Alahyane[1, 2] *https://orcid.org/0000-0001-9770-9080*

[1]*Laboratory of Agro-Food, Biotechnologies and Valorization of Plant Bioresources. Agrobiotechnology and Bioengineering Center, CNRST-labeled Research Unit (AgroBiotech-URL-CNRST-05 Center) Cadi Ayyad University, 40000 Marrakech, Morocco;*

[2]*Higher Institute of Nursing Professions and Health Techniques of Guelmim (ISPITSG), Morocco; Corresponding author: ab.alahyane@gmail.com*

ABSTRACT:

Polyphenols are bioactive compounds found in plants, with diverse health benefits and antioxidant properties. They have anti-inflammatory, anti-carcinogenic, anti-diabetic, antiviral activity and heart-protective effects. Research links polyphenol-rich foods to a lower risk of chronic diseases like cardiovascular issues, cancer, and neurodegenerative disorders. For instance, resveratrol in grapes and red wine shows promise in protecting against age-related diseases, and polyphenols like quercetin and epigallocatechin gallate (EGCG) provide significant antioxidant and anti-inflammatory benefits. These bioactive compounds play a crucial role in reducing oxidative stress and mitigating the risk of chronic diseases, though the antioxidant capacity varies among different types of polyphenols. However, the main problem lies in the variability and optimization of polyphenol content and bioavailability, which are influenced by genetic, environmental, and agronomic factors. Plant species, maturity, climate, soil conditions, and agricultural practices all affect polyphenol composition. Additionally, processing techniques such as extraction, fermentation, cooking, and storage can significantly alter polyphenol content, potentially diminishing their health benefits. For instance, thermal methods like boiling or baking may degrade or transform polyphenols, reducing their efficacy. Therefore, innovations in processing methods are essential to preserve or enhance polyphenol content and bioavailability, ensuring their optimal health benefits.

In conclusion, polyphenols hold great promise for promoting human health and preventing chronic diseases. To harness their potential as functional food ingredients, understanding their effects on health, the relationship between antioxidant activity and phenolic content, factors influencing polyphenol composition, and processing methods is crucial. This review explores these areas and their potential applications in polyphenol research.

Keywords: Extraction, Antiviral activity, Phenolic compound, Health, Food processing.

✉ Alahyane Abderrahim

ab.alahyane@gmail.com

[1]*Laboratory of Agro-Food, Biotechnologies and Valorization of Plant Bioresources. Agrobiotechnology and Bioengineering Center, CNRST-labeled Research Unit (AgroBiotech-URL-CNRST-05 Center) Cadi Ayyad University, 40000 Marrakech, Morocco;*

[2]*The Higher Institute of Nursing Professions and Health Techniques of Guelmim (ISPITSG), Morocco;*

INTRODUCTION:

Polyphenols are a diverse group of bioactive compounds found abundantly in plants, including fruits, vegetables, grains, and herbs. They have attracted considerable attention in recent years due to their potential health benefits and antioxidant properties. Polyphenols exhibit a wide range of biological activities, including anti-inflammatory, anti-carcinogenic, anti-diabetic, and cardioprotective effects (1). Understanding the effects of polyphenols on human health, the relationship between their antioxidant activity and phenolic content, factors influencing polyphenol composition, and various processing methods is essential for harnessing their potential in promoting well-being and preventing chronic diseases. However, the main problem lies in the variability and optimization of polyphenol content, bioavailability, and bioactivity, which are influenced by a complex interplay of genetic, environmental, agronomic, and processing factors.

Numerous studies have explored the health benefits of polyphenols and their impact on various physiological processes. The consumption of polyphenol-rich foods has beenassociated with a reduced risk of chronic diseases, including cardiovascular diseases, cancer, and neurodegenerative disorders (2). For instance, resveratrol, a well-known polyphenol found in grapes and red wine, has shown promising effects in protecting against age-related diseases (3). Other polyphenols, such as quercetin and epigallocatechin gallate (EGCG), have demonstrated antioxidant and anti-inflammatory properties that contribute to their health-promoting effects (4). Investigating the mechanisms underlying the health benefits of polyphenols is crucial for developing therapeutic strategies and functional foods targeting specific health conditions.

Polyphenols are known for their potent antioxidant activity, which plays a crucial role in protecting cells against oxidative stress and reducing the risk of chronic diseases (5). The antioxidant capacity of polyphenols is closely related to their phenolic content and structural characteristics. Different classes of polyphenols, such as flavonoids, phenolic acids, and stilbenes, exhibit varying degrees of antioxidant activity (6). Understanding the structure-activity relationships of polyphenols and their antioxidant potential is essential for identifying bioactive compounds with enhanced health benefits.

The composition and concentration of polyphenols in plants are influenced by various factors, including genetic, environmental, and agronomic factors. Plant species, cultivars, maturity stage, climate, soil conditions, and agricultural practices significantly impact the polyphenol profile of plant-based foods (7). For example, studies have shown that the polyphenol content in fruits and vegetables can vary widely depending on the cultivation methods, post-harvest handling, and storage conditions (8). Understanding these factors can help optimize agricultural practices and food processing techniques to enhance the polyphenol content and bioactivity of plant-based products. The processing of plant-based foods can significantly affect the stability and bioavailability of polyphenols. Techniques such as extraction, fermentation, cooking, and storage can alter the composition and concentration of polyphenols (9). For instance, thermal processing methods, such as boiling or baking, can lead to the degradation or transformation of certain polyphenols, affecting their bioavailability and health benefits (10). Exploring innovative processing methods that preserve or enhance polyphenol content and bioactivity is crucial for the development of functional food products with optimized health benefits.

In conclusion, polyphenols have shown great promise in promoting human health and preventing chronic diseases. To fully harness their potential as functional food ingredients, it is critical to address the challenges posed by the variability in polyphenol content, bioavailability, and bioactivity, as well as the impact of processing methods on their stability and efficacy. We will delve into the multidimensional aspects of polyphenols, focusing on their impact on health, the intricate relationship between their antioxidant activity and phenolic content, the factors influencing their composition, and the various processing methods employed to harness their potential. The following review will be organized into four main axes: (1) The effect of polyphenol compounds on health, where we will explore the diverse health benefits associated with polyphenols and their mechanisms of action; (2) The relationship between antioxidant activity and phenols of plants, which will delve into the intricate link between phenolic content and the antioxidant potential of polyphenols; (3) Factors affecting polyphenol composition, where we will examine the genetic, environmental, and agronomic factors that influence the composition of polyphenols in plant-based sources; and (4) Processing methods of polyphenols, where we will discuss the various techniques used to process and preserve the bioactivity of polyphenols. By addressing these challenges, this review seeks to contribute to the development of optimized strategies for maximizing the health benefits of polyphenols in food and therapeutic applications.

1. EFFECT OF POLYPHENOLS COMPOUNDS ON HEALTH

Polyphenols are probably the most studied molecules of nutritional interest. Bioactive polyphenols are natural compounds of various chemical structures. These compounds are arguably the largest group of chemicals in the plant kingdom. There are more than 8,000 different polyphenolic structures known, including several hundred isolated from edible plants. Their sources are, among others, fruits, vegetables, nuts and seeds, roots, bark, leaves of different plants, herbs, whole grain products, processed foods, as well as tea, coffee and red wine (11). Phenolic compounds can be divided into several sub-groups according their structural characteristics; however, thosecommonly found in plant food can be categorized into three main sub-groups: phenolic acids, flavonoids and non-flavonoids (Figure 1).

- Flavonoids: Have a potential effect on radical scavenging and inflammatory reactions. They are predominantly found in fruits, vegetables, legumes, red wine, and green tea.
- Non flavonoids: including Stilbenes (found in graphs, red wine, and peanuts) and Lignans (found in seeds like flax, linseed, legumes, cereals, grains, fruits, algae, and certain vegetables)
- Phenolic acids: Found in coffee, tea, cinnamon, blueberries, kiwis, plums, apples, and cherries and have two subgroups, namely hydroxybenzoic acids, and hydroxycinnamic acids.

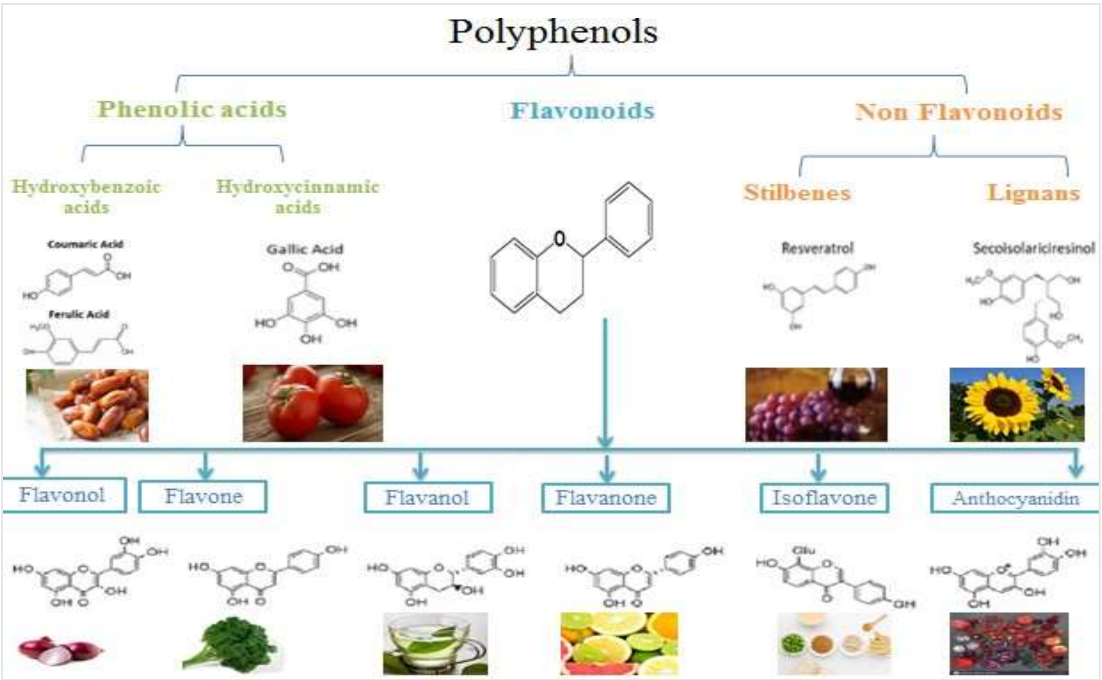


Fig 1: Schematic classification of polyphenols

Several prospective studies have scientifically linked this class of molecules to proven health benefits. Evidence generated by those studies shows that the antioxidant and anti- inflammatory properties of polyphenols may potentially prevent or serve as treatment against many diseases (Figure 2). A relevant consideration is the amounts of these compounds that must be consumed to produce positive health effects. When the amounts of polyphenols required producing health benefits are within the ranges found in commonly consumed foods, it is possible to conclude that there is no toxicological danger (12).

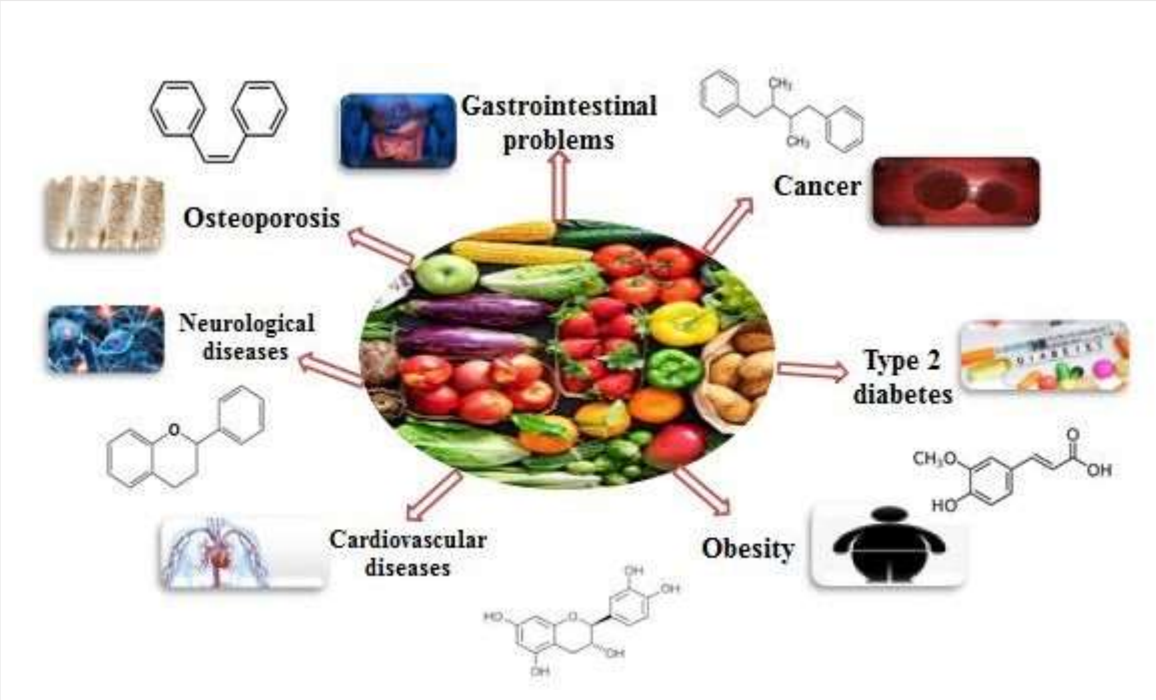


Fig 2: Main health benefits of polyphenols related to chronic diseases

The long-term consumption of diets rich in polyphenols protects against certain cancers, cardiovascular diseases, type 2 diabetes, osteoporosis, pancreatitis, gastrointestinal problems, lung damage, obesity and neurological diseases (13; 14; 15). Many of the health benefits associated with polyphenols may be related to their role as antioxidants. Antioxidants are known for their ability to combat cell damage.

Polyphenols provide health benefits by several mechanisms, including the elimination of free radicals by forming stabilized chemical complexes, the protection and regeneration of other dietary antioxidants (e.g. vitamin E) and the protection against oxidative stress by chelation of pro-oxidant metals, which can then help to regulate immune response actions, like cellular growth (16). The nature and content of phenolic compounds varies among plants, which are mainly esterified or glycosylated (17). Polyphenolics exhibit a wide range of biological effects including antibacterial, anti- inflammatory, antiallergic, hepato-protective, antithrombotic, antiviral, anticarcinogenic and vasodilatory actions; many of these biological functions have been attributed to their free radical scavenging and antioxidant activity (18.). Catechins are natural polyphenolic phytochemicals that exist in food and medicinal plants, (green and black tea, chocolate, red wine, apricot, peach, apples, blackberry and red raspberry…etc). An increasing number of studies have associated the intake of catechins-rich foods with the prevention and treatment of chronic diseases in humans. Catechin polyphenols have been associated with antioxidant, anti-inflammatory and anti-mutagenic effects (19). Catechins show anti-atherosclerotic properties, which prevent low-density lipoprotein (LDL) oxidation. In addition, catechins have anti-carcinogenic and antimutagenic activity by inhibition of mutagens and carcinogens, invasion and metastasis (20). Catechins are thought to prevent weight gain by promoting greater energy expenditure and fat oxidation. Catechins and caffeine show synergistic activity, which may stimulate thermogenesis, in addition, catechins are suggested as antidiabetic substances (21). EGCG (Epigallocatechin-3-gallate), the major constituent of polyphenol, has antiviral activities on a diverse range of viruses such as human immunodeficiency virus, influenza virus and hepatitis C virus (22). Polyphenolic compounds that have been reported in very preliminary in silico and in vitro studies to exhibit anti-SARS-CoV activity include quercetin, acacetin, apigenin, baicalein, hesperidin, morin, rutin, naringin, naringenin, (–)-catechin, (–)-catechin gallate, (–)-gallocatechin gallate, diosmin, daidzein, genistein, glycitein, kaempferol, luteolin, myricetin, silibinin, silymarin, orientin, curcumin, and oroxylin A (23; 24; 25; 26). Tea polyphenols (Figure 3) has been shown to have good effects on antioxidant, anti- inflammatory, cancer prevention and regulation of lipid metabolism (27). Regular consumption of tea is also associated with reduced risk of developing type 2 diabetes in meta-analyses and this consumption indicates reduced risks of total mortality, cardiac death, coronary artery disease, and stroke (28). Polyphenols can also ameliorate the risk of type 2 Diabetes. They are involved in attenuating postprandial glycemic responses, fasting hyperglycemia, and improving insulin secretion and sensitivity. These implications might be explained by their ability to inhibit the digestion of carbohydrates and intestinal glucose absorption, stimulate insulin secretion, modulate the liver-related release of glucose, and trigger both gene expression and cell signaling pathways (29). It has been reported that Black soybeans seed coat may ameliorate obesity and insulin resistance (30). A black soybean has more fibers, which have a vital role to reduce the blood sugar. Notably, one cup of Black soybeans contributes around 15 g of fibers (31). According to (32); flavan-3-ols may be especially beneficial for lowering insulin resistance. These authors also found that flavonoids seem to be the type of polyphenol most often associated with a lower risk for type 2 diabetes. These compounds remarkably prevent obesity and diabetes by enhancing energy expenditure and suppressing inflammation (33). Flavonoids are believed to have beneficial effects on obesity and diabetes (34). (35) compared the intake of flavonoids with body mass index (BMI) and waist circumference, and found that a higher flavonoid intake was associated with lower BMI and waist circumference. On the other hand, (36) showed that Polyphenols affect obesity by inhibiting pre-adipocyte differentiation, reducing adipocyte proliferation, stimulating adipocyte apoptosis, suppressing lipogenesis and contributing to lipolysis and beta oxidation of fatty acids in in vitro conditions. However, a number of other possible biochemical and molecular mechanisms have been identified, including multifaceted effects in intracellular and intercellular signaling pathways, such as the regulation of nuclear transcription factors and fat metabolism, and the modulation of synthesis of inflammatory mediators, certain flavonoids have been shown to play a role in glucoregulation via downstream signaling that increases insulin secretion, reduces apoptosis, promotes β cell proliferation, and reduces resistance to insulin, inflammation and oxidative stress in muscle and other cells (37). Observational studies have reported that flavan-3-ol intake from various dietary sources produces positive effects on cardiometabolic outcomes, including reducing the risk for diabetes, and cardiovascular-related outcomes (i.e. cholesterol levels, blood pressure, and myocardial infarction) (38; 39). (40) indicated that total flavonoid intake, including flavan-3-ols, was also associated with a lower risk of fatal cardiovascular disease. Flavan-3-ols found in cocoa and tea have been shown to reduce the risk for cardiovascular disease mortality. The flavonols of dark chocolate and cocoa mainly produce a decrease in blood pressure; In addition, they regulate inflammatory and metabolic processes that result in the improvement of chronic, cardiometabolic and vascular diseases (41). Polyphenol-rich lentils have potential health benefits as complementary and alternative medicines, which are exerted in the form of antioxidant, antibacterial, anti-fungal, Antiviral, Cardioprotective, anti-inflammatory, antidiabetic, anticancer, anti-obesity, hypolipidemic and chemopreventive activities. Furthermore, lentils are useful as a prognostic marker for various cancers including thyroid and hepatic carcinoma (33). Propolis and its flavonoid constituents have been reported to exert neuroprotective properties in vitro and in vivo studies through their antioxidant, anti-inflammatory, and immunomodulatory actions (42). There has been a considerable interest in the neuroprotective effects of propolis because of biological activities based on its flavonoids and rare side effects (43). Polyphenolic dietary supplementation may have an impact on cognitive deficits in individuals of advanced age. Fruits and vegetables rich in polyphenols are potential neuroprotective agents which can modulate many cellular processes like apoptosis, redox balance signaling, differentiation and proliferation. Polyphenols being antioxidative agents can protect against various neurological diseases. Resveratrol shows neuroprotective effect against models of AD (44). Several human observational and intervention studies have found beneficial impact of tea consumption on neurodegenerative impairment, such as cognitive dysfunction and memory loss. These studies indicated that green tea polyphenols aimed to alter brain aging processes and to serve as possible neuroprotective agents in progressive neurodegenerative disorders such as Parkinson's and Alzheimer's diseases (45).

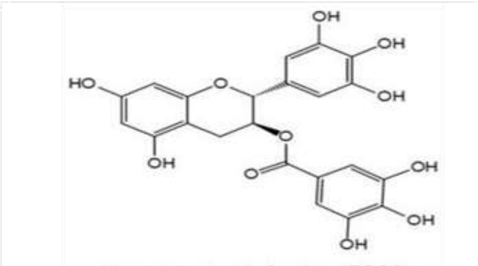
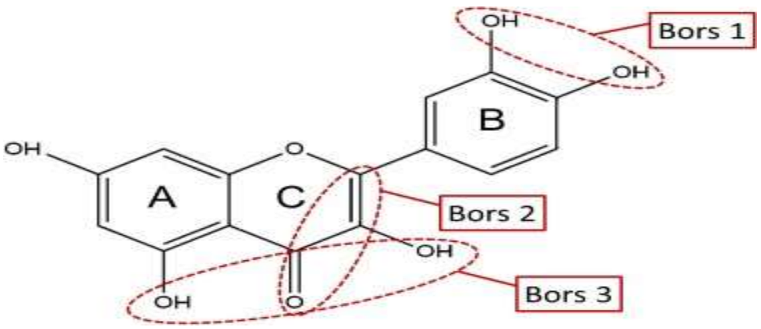


Fig 3: Structure of the major tea polyphenols

2. RELATION BETWEEN ANTIOXYDANT ACTIVITY AND PHENOLS OF PLANTS

Phenolic compounds are considered the most important antioxidants and are widely distributed among various plant species. Therefore, the assessment of antioxidant properties and phenolic content remains an interesting and useful task, particularly for finding new sources for natural antioxidants, functional foods, and nutraceuticals. The antioxidant activity of medicinal plants is generally studied with respect to total phenolic compounds and their free radical scavenging assays as they may be responsible forvarious bioactivities (46; 47). The antioxidant properties of polyphenols are due to their redox properties, which allow them to act as reducing agents, hydrogen donators, metal chela-tors and single oxygen quenchers (48). Based on the results obtained by (49), it is concluded that the methanolic leaf extracts of four different varieties of Lantana camara, which contains large amount of phenolic compounds, exhibit high antioxidant, free radical scavenging and in vitro lipid peroxidation inhibition activities. A high correlation is found between the total phenolic content, Flavonoids content and the antioxidant activities using skins of fifteen onion cultivars (50). As another example, a strong correlation was found between total polyphenolic and total flavonoid content of onions against the observed antioxidant activities from Ontario grown onion varieties (51). Phenolic compounds exhibit their antioxidant activity by several mechanisms such as donating hydrogen atoms to free radicals, scavenging other reactive species such as $OH^{\bullet}$, $NO_2^{\bullet}$, N_2O_3, ONOOH and HOCl. They reduce or inhibit free radicals by transfer of a hydrogen atom, from its hydroxyl group. The reaction mechanism of a phenolic compound with a peroxyl radical ($ROO^{\bullet}$) involves a concerted transfer of the hydrogen cation from the phenol to the radical, forming a transition state of an H-O bond with one electron. The antioxidant capacity of the phenolic compounds is strongly reduced when the reaction medium consists of a solvent prone to the formation of hydrogen bonds with the phenolic compounds (52). Three criteria have been proposed to explain the antioxidant behavior of phenolic compounds, and these are known as Bors criteria (Figure 4).

Fig 4: Structure activity relationship based on Bors criteria.



Bors 1—catechol group on the B-ring; Bors 2—2,3 double bond and 4-oxo group on the C-ring; Bors 3— OH groups at position 3 and 5 OH group on the

A- and C-rings and 4-oxo group on the C-ring (53)

The first is the presence of a catechol group on the B- ring (Bors 1), which increases the stability of the resulting antioxidant radical. The second is the presence of a 2,3 double bond combined with a 4-oxo group on the C-ring (Bors 2), which facilitates electron delocalization. The third is the presence of OH groups at positions 3 and 5 in combination with a 4-oxo group, which enables electron delocalization via hydrogen bonds (Bors 3) (53).

3. FACTORS AFFECTING POLYPHENOLS COMPOSITION

Polyphenols constitute a diverse class of secondary plant compounds. The term polyphenols is increasingly being used in a broader sense and now includes a large varietyof compounds produced in plants, via either the shikimate or the acetate. The quality and quantity of polyphenols is strongly influenced by several intrinsic and extrinsic factors such as growing conditions (Water availability, temperature, altitude, soil and humidity), plant genotype, physiological maturity, storage, and processing methods (54; 55; 56).

3.1. EFFECT OF ENVIRONMENTAL CONDITIONS

The environmental conditions under which fresh crops are produced, transported and displayed have a significant effect on the keeping quality of the food. These factors have amajor effect on polyphenol content and composition. They may be pedoclimatic (soil type, sun exposure, rainfall) or agronomic (culture in greenhouses or fields, biological culture, hydroponic culture, fruit yield per tree, etc) (57). Mineral composition, soil type, temperature, light and water content are among the frequently reported factors that affect the total phytochemical contents in plants (54). In addition, agronomic practices can also affect the quality of fruit, organically grown strawberry fruits were found to have longer shelf life, greater dry matter, higher antioxidant activity and concentrations of ascorbic acid and phenolic compounds than their conventional counterpart (58). Many studies have been conducted to study the effect of environmental conditions on the polyphenols. (59) investigated the influence of environmental factors on the active substance contents and antioxidant activity of *Potentilla fruticosa* L. from different regions of China. The results showed that annual mean temperature was significantly and negatively correlated to the content of total phenolic compounds, while altitude was significantly and positively correlated to the content of total phenolic compounds ($P < 0.05$). (60) suggests that there is a relevant influence of environmental factors over production of phenolic compounds in the leaves of *S. jambos*, with foliar nutrients (Pl, Kl, Cal, Nal, Fel, Col and Mol) soil nutrients (Als, Ks, Ss, Nas and Mns) and climatic factors (temperature and rainfall), being the main variables that may change the levels of phenolic compounds in this plant tissue. Although quality parameters and phenolic composition vary over growing seasons, chokeberry juices from all three seasons have very high contents of phenolic substances and high values of antioxidant properties. The results of (61) confirm that weather conditions affect the concentration of antioxidative compounds. Juices from growing season 2012, in which climate was warm and dry and with low accumulated rainfall compared to 2013 and 2014 growing seasons, have higher amount of total phenolic compounds, total non-flavonoids and total anthocyanins compared to juices from the two other seasons. (62) were also demonstrating that the total phenol content in olive oil varied from 50 to 1000 mg/kg, depending on the geographical area, including rainfall distribution and temperature.

3.2. EFFECT OF GENOTYPE

Many studies have been conducted to investigate the effect of genetic factor on the polyphenol composition. The work of (63) showing a unique profile for each genotype cultivated under the same cultural practices. The qualitative and quantitative differences in phenolic composition among genotypes assessed emphasize the importance of the distribution of these compounds in different berry parts for cultivar authentication and differentiation. The results of (64) showed differences between the studied cultivars and oleasters. Furthermore, the phenolic profiles depended to the varieties sylvestris and europaea of *Olea europaeasubsp*. Europaea. Also, (65) evaluated the phenolic content of different strawberry species and showed that the highest phenolic content was observed in F. *chiloensis subsp*. *chiloensis f. patagonica*, followed by *Fragaria vesca*, and the lowest value was observed in F. x ananassa "Chandler." Pepper cultivars show variation in the levels of carotenoids and phenolic compounds due to genetic variability (66). (67) studied Influence of genetic and environmental factors on the contents of carotenoids and phenolic acids in red pepper fruits (*Capsicum annuum* L.); reported that the results from variance component analysis showed that the year and genotype mainly accounted for the variation of total phenolic acids.

On the other hand, (68) have concluded that the polyphenols properties of lentils are significantly influenced by the genotype. In addition, (69) indicated that the phenolic profiles and contents in sorghum grains were affected strongly by genotype and by growth temperature.

3.3. EFFECT OF MATURITY

Fruit maturation begins when growth stops, reaching the competence to ripen, but the ripening process itself is a subsequent step. Ripening is a complex process whereby several metabolic changes related to softening and flavor characteristics as well as organoleptic traits take place (70). During the maturity several changes take place in the fruit, some biochemical, physiological, and structural modifications occur during ripening that alter its bioactive composition (71). (72) showed that pumpkin total phenolic and flavonoid contents are dependent on the fruit maturity stage. The unripe stage contains a good quantity of total polyphenols (77.5 mg GAE. 100 g^{-1} FW) and flavonoids (23.4 mg QE. 100 g^{-1} FW). At the end of fruit maturity, the levels of both polyphenols and flavonoids decrease (55.6 mg GAE. 100 g^{-1} FW and 19.6 mg QE. 100 g^{-1} FW). These findings suggest that the phenolic content increase during the first stages of maturity, but these levels start to drop off with the maturity of the fruit. The decrease in total phenolic content during fruit maturity was referred to as the oxidation of polyphenols by polyphenol-oxidase. (73) marked a progressive decrease of phenolic content occurred during fruit development together with marked changes in polyphenol profiles. The results of (74) showed that, the bioactive compounds, including titratable acidity, reducing sugar, total ascorbic acid, total polyphenol and total flavonoids, significant changes occurred at different ripening stages of maturity. The contents of total polyphenol and total flavonoids were directly proportional to the maturity stages. (75)

investigated the effect of ripening on the characteristics of Argane fruits including the variation of total phenol and flavonoid present in the pulp of the fruit, the kernel and the oil as well as their antioxidant potential. The rate of total phenol and flavonoid increases upon ripeness process in fruit parts and its oil; however, it decreases again in latest stages of ripeness. (76) found that the concentrations of individual polyphenolic compounds during maturity were similar, whereas their values differed significantly. Immature fruits showed the lowest level of polyphenolic compounds, which increased in semi-mature cranberry fruits and did not change remarkably in commercially mature cranberry fruits. In fact, depending on the plant growth phase, the content of polyphenols varies. For example, phenolic acid content increases during ripening of tomatoes. In red, ripe strawberries, the phenolic content is higher than in green, immature ones, whereas in the case of apples, the opposite trend is observed (77).

3.4. EFFECT OF STORAGE

Phenolic compounds are not very stable and are easily degraded during storage after harvest. Subsequently, their biological activity may be altered. Multiple storage parameters such as light, temperature, oxygen and pH have been highlighted to have affected the stability of the phenolic compounds (78). Both light and temperature significantly influenced total polyphenols and its corresponding antioxidant activity over time. More than 95% total polyphenols and antioxidant activity was retained at 5 °C in dark condition after 180 days of storage of Dried Piper betle Extracts. Hydroxychavicol demonstrated the best stability with no degradation while eugenol and isoeugenol displayed moderate stability in low temperature (5 °C) and dark conditions (79). (80) reported reduction of more than 7% in the total polyphenols of different varieties of olive oil at temperatures of 18 and 25 °C in the dark over storage period during 24 months. These authors supposed that the reason behind the degradation of phenolic compounds in the above temperatures were oxidation and hydrolysis. The results clearly showed the immense effect of storage temperature on the stability of the phenolic compounds which can be facilitated in the presence of light. (81) reported a reduction of 36% in the total polyphenols of the herb, Anemopsis californica, extracts stored at 50, 25 and 4 °C with exposure to light after 180 days. These authors reported that high temperature and light degraded the structure of the polyphenols. (82) found that there was a reduction in all phenolic compounds in both sorghum grain and flour within the first 60 days of storage, and that the retention of phenols ranged from 89.4% to 100% after 180 days of storage. (83) evaluated the influence of storage conditions on black rice phenolic compounds, showing an increase in total flavonoid content in the free form and a decrease in the bound part in grains stored under conventional and vacuum conditions, as well as illustrating a decrease in the total phenolic content regardless of the storage conditions. Storage time did not result in any important changes in the physical and nutritional characteristics, but it had a significant effect on the number of bioactive compounds in the antioxidant activity of pitanga jam, and the contents of these components decreased over time (84).

4. PROCESSING METHODS

Food processing is a series of operations to convert unprocessed food-to-foodstuffs with prolonged shelf life and enable storage that abolishes or reduces time or effort spent in culinary procedures for increased consumption (85). Food processing methods can have many beneficial effects. However, processing may also alter the food properties. Generally, processed products have lower nutritional values than their respective fresh commodities mainly due to the loss of nutrients during processing (86). A wide variety of processing methods is available and their use depends largely on the food to be processed. Different processing techniques are presented in Figure 5.

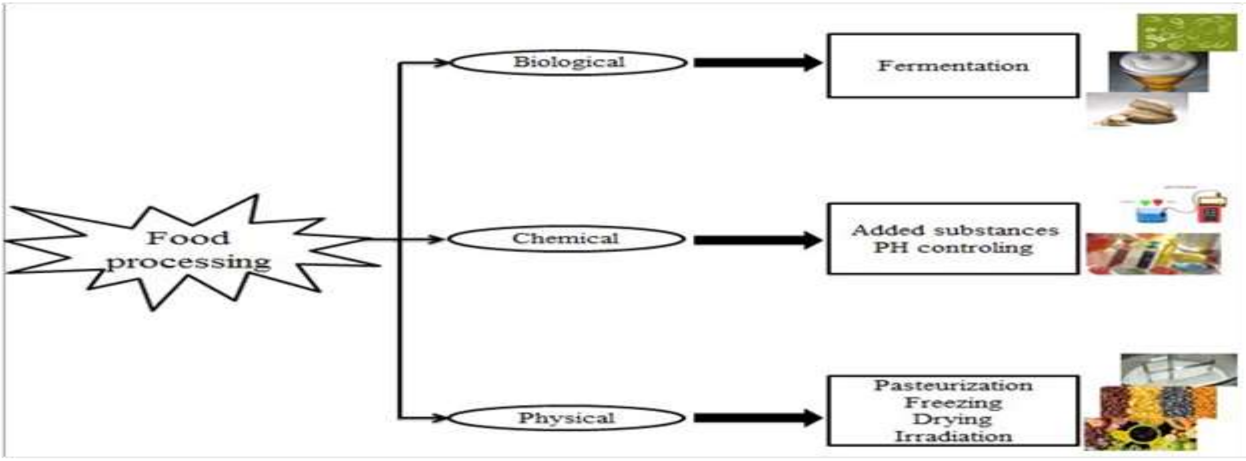


Fig 5: Graphical illustration of different processing techniques of food.

4.1. BIOLOGICAL PROCESSING: FERMENTATION

Fermentation method uses microorganisms to preserve food. This method involves decomposition of carbohydrates with the action of microorganisms and/or the enzymes. Bacteria, yeasts, and molds are the most common groups of microorganisms involved in fermentation of a wide range of foods (87). During the fermentative process, several biochemical changes occur in the food matrix, and nutritive and anti- nutritive components are modified in terms of bioactivity and digestibility. In non- fermented grains, phenolic compounds are mainly present in bound form, that is, conjugates with sugars, fatty acids, or proteins (88). During fermentation, a decrease of free phenolic compound content can occur, because they may bind with other molecules present in the food matrix, they might be degraded by microbial enzymes, and they might be hydrolysed by specific microbial strains (89). Phenolic compounds also contribute to food antioxidant capacity. Fermentation can have multiple effects on phenolic compounds, such as modifications of their content and/or profile, as well as formation of metabolites. Fermentation can thus increase or reduce phenolic compound content and antioxidant capacity of grains (90). The effect and the degree of influence depend on the species of microorganisms involved in the process (91). (92) reported higher bioactive compounds (catechin, gallic acid, and quercetin) after fermentation in a study on ting from fermented Whole grain-sorghum with a concurrent decrease in total flavonoid content, total tannin content, and total phenolic content. Reported decreases in levels of total phenolic content, total flavonoid content and total tannin content were attributed to degradation and hydrolysis of the phenolic compounds, while a corresponding increase in catechin, gallic acid, and quercetin was attributed to a release of these bioactive compounds after fermentation with Lactobacillus strains. reported an increase in total phenolic compounds during the fermentation of WG-maize. (93) reportedly through the activities of β-glucosidase, which is capable of hydrolyzing phenolic phucosides to release free phenolics. Increased extractability of phenolic compounds, synthesis of new bioactive compounds, and consequent liberation of phenolic compounds due to structural breakdown of cereal cell walls have all been attributed to such increases in whole grain- Phenolic compounds after fermentation. Through metabolic activities of microbes, fermentation also induces structural breakdown of the cell wall, which leads to synthesis of various bioactive compounds (94). (95) reported that Total phenols, antioxidant activity and flavonoids contents of fermented table olive decrease significantly during 0, 1, 2 and 3 months of storage, due to the diffusion into brine solution of fermentation. (96) found that during Spanish-style green olive fermentation of different varieties of olives treated with NaOH, the hydrolysis of glycosides occurs due to the NaOH treatment, caused increased in total phenolic compound then decreased due to diffusion into brine solution leading to differentiation on total phenolic content between varieties.

4.2. CHEMICAL PROCESSING

Food preservation using chemical reagents is one of the ancient and traditional methods. Preservatives are defined as the substances capable of inhibiting, retarding, or arresting the growth of microorganisms or any other deterioration resulting from their presence (97). Artificial preservatives are produced industrially. These can be classified as antimicrobial, antioxidant, and antienzymatic (Figure 6).

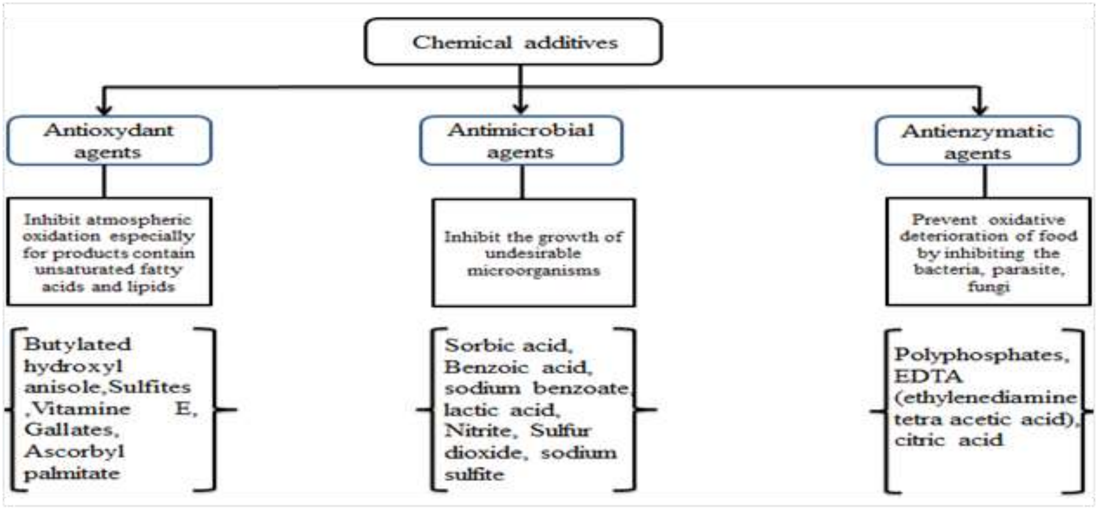


Fig 6: Classification of artificial additives (98;99)

(100) reported that the berries treated with ascorbic acid had higher total phenol content, total antioxidant capacity, quercetin and catechin composition than untreated ones. The use of ascorbic acid as a reducing agent prevented a decrease of the phenolic content in fruits and vegetables, that has a great impact on the quality of fresh-cut fruits because of the participation of phenols in enzymatic browning reactions and its nutritional value of fresh-cut product (101).

Antioxidants, such as ascorbic acid (vitamin C), tocopherols (vitamin E), and synthetic compounds like butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), are commonly employed to inhibit oxidative degradation of polyphenols during processing and storage (102). These compounds scavenge free radicals and delay polyphenol oxidation, thus preserving their bioactivity. Chelating agents, such as ethylenediaminetetraacetic acid (EDTA), can also be used to minimize the catalytic Microencapsulation involves the entrapment of polyphenols within a protective matrix, such as proteins, carbohydrates, or lipids, forming micro- or nanoparticles. This technique provides physical protection, shielding polyphenols from environmental factors, including oxygen, light, and temperature fluctuations. Microencapsulation can improve polyphenol stability, control release, and enhance their bioavailability in food matrices (103), effects of metal ions that accelerate polyphenol degradation (104). Coating food surfaces with edible films or coatings containing polyphenols can help maintain their concentration and bioactivity. Edible films act as barriers, preventing polyphenol loss, and protecting against environmental degradation factors. Natural polymers, such as chitosan, gelatin, or starch, can be used as film-forming materials to retain polyphenols in foods (105). Chemical preservatives, such as sodium benzoate, sorbic acid, and propylparaben, can inhibit microbial growth and enzymatic activity that may degrade polyphenols. The use of appropriate preservatives in food formulations can contribute to the preservation of polyphenols during storage (106). It is worth noting that the application of chemical methods for polyphenol preservation in food requires careful consideration, as the safety and regulatory aspects of these chemical compounds need to be addressed. Additionally, the potential interactions between Polyphenols and chemical agents, as well as their impact on sensory attributes, need to be thoroughly studied.

4.3. PHYSICAL PROCESSING

Different phytochemicals are affected by these factors differently. Carotenoids are very sensitive to heat, and can incur significant losses during different vegetable processing steps (107). The main cause of carotenoid degradation in foods is oxidation. Flavonoids and other phenolic compounds are relatively stable at high temperature and over long storage (108). The degradation of anthocyanins is primarily caused by oxidation, cleavage of covalent bonds or enhanced oxidation reactions due to thermal processing. Probably during heat treatment, anthocyanins or their conjugated sugars are broken down into small molecules such as aldehydes and benzoic acid derivatives or their corresponding anthocyanidins, respectively (109). In addition to polymerization, many other factors can affect the stability of anthocyanins including exposure to elevated temperatures, light, oxygen, metals, sugars, and ascorbic acid (110). Different Industrial processing including blanching, canning, sterilizing and freezing, as well as various cooking methods boiling, steaming and microwaving, of fruits and vegetables can affect the content and composition of nutrients including phytochemicals, normally leading to reduced availability of these compounds (111). Studies have shown that blanching leads to reduced content of vitamins, carotenoids and phenolic compounds, which are relatively labile to heat treatments (112). (113) also found that blanching alone or in combination with freezing preserved ascorbic acid and antioxidant activity in broccoli, carrots and green beans.

Studies applying thermal treatments have shown that boiling causes the most detrimental polyphenol composition changes in treated samples. Canning is reported to reduce total phenolic and flavonoid contents, mostly because phenolic compounds leach into the surrounding medium (brine or syrup). This results from the applied heat treatment, which disintegrates the cells and tissues, enabling the migration of polyphenols into the medium (56). One study examined the differences in the effects of domestic and industrial canning on apricots. Thermal processing imitating industrial conditions induced a higher loss of total phenolics (13–47%), while domestic processing led to lower losses (2–33%). This is proposed to be the consequence of the difference in temperature regimes, the more intensive one being employed in industrial processing (114). Steaming and frying can preserve higher amounts of these compounds (56). (115) found that conventional heating significantly reduced the anthocyanin content and antioxidant activity of pomegranate and black mulberry juices compared with microwave heating. Four sweet potato varieties were subjected to four different heat treatments (boiling, steaming, microwaving, and baking). In general, heating had adverse effects on phenolic acid levels. Boiling was shown to have the most detrimental effect: it lowered the levels of chlorogenic acid by 29% (in the 414-purple variety from Slovakia), neochlorogenic acid by 69% (in the 414-purple variety from Croatia), and trans-ferulic acid by 29% (in the Beauregard variety from Croatia). In contrast, all these treatments increased the levels of total polyphenols, total anthocyanins, and total antioxidant activity, mostly in all analyzed samples (116). High-temperature regimes are also applied to preserve food by inactivating enzymes and pathogen microbes, with sterilization and pasteurization as two commonly applied treatments. In white beans, sterilization significantly decreased the total polyphenol content after 4 and 12 months of storage (by 30 and 46%, respectively) (56). Moreover, the microwave-assisted drying method produced higher total phenolic content and antioxidant activity in grape, cranberry, strawberry and potato compared with conventional processing, such as hot-air drying and vacuum-freeze drying (117). Drying process can also enhance the nutritional value; for example, the total flavonoids, total phenolics and lycopene contents of tomatoes were increased in processed tomatoes, and the increases by the different drying processes (fresh, freeze-dried and hot-air-dried) led to enhanced antioxidant activity (118). Since drying involves heat treatment, the temperature regime affects the degree of degradation of dietary polyphenols, as observed in jujube fruits. Jujube fruits were subjected to different drying procedures: vacuum– microwave (480, 120 W), hot air (70, 60, and 50 ◦C), and combined methods such as pre- drying and finish-drying (60 ◦C + 480/120 W).

Freezing is a preservation technique to stop or slow down biochemical reactions in fruit and vegetable preservation (119). During the freezing process, the water of aquatic products is converted into ice crystals, inhibiting microorganism growth, slowing enzyme activities that degrade proteins or fats, and helping to extend the shelf life (120). Consequently, this method processing can inhibit the reproduction of microorganisms, inhibit enzyme activity, slow fat oxidation, protein denaturation, which can make the freshness of fish for several months or even more than a year. Nonetheless, quality deterioration still inevitably occurs during freezing and frozen storage, such as texture softening, fluid losses, color changes, and flavor deterioration. stops the activity of most pathogenic microorganisms and enables longer shelf life of foods (121). Freezing of either blanched or cooked kale leaves did not induce notable changes while freezing decreased the polyphenol levels by 3% and their antioxidative activity by 7% (122). In some cases, these techniques can even enhance the content of polyphenols, such as in maqui fruits in which cooling (5 °C) and freezing (−20 °C) increased the total polyphenol concentration. The frozen samples had higher levels of anthocyanins, and the changes were variable. In addition, the freezing technique was better in terms of preserving these antioxidants, as they were present in these samples even after six months of storage (123). One study reported that freezing by immersion in liquid nitrogen and freeze-drying at −50 °C decreased the levels of total polyphenols and antioxidant activity in apples, both before and during in vitro gastric digestion. Raw apples, which served as control samples, retained the highest amount of polyphenols and exhibited small decreases in total polyphenol concentrations and antioxidant activity during in vitro gastric digestion (124).

CONCLUSION:

In conclusion, this review has provided a comprehensive overview of the multifaceted aspects of polyphenols, focusing on their profound effects on human health, the relationship between their antioxidant activity and phenolic content, the diverse factors influencing their composition, and the various processing methods that impact their stability and bioavailability. The findings underscore the remarkable potential of polyphenols in preventing and managing chronic diseases, including cardiovascular diseases, cancer, and neurodegenerative disorders. Their antioxidant properties, which are closely tied to their phenolic structure and concentration, play a central role in mitigating oxidative stress and inflammation, thereby contributing to their health-promoting effects.

This review has highlighted the factors that affect the composition of polyphenols in plant-based sources, including genetic, environmental, and agronomic factors, such as plant species, cultivars, maturity stages, climate conditions, soil quality, and agricultural practices, significantly shape the polyphenol profile of fruits, vegetables, and other plant-derived foods. Understanding these factors is crucial for optimizing cultivation practices and enhancing the polyphenol content and bioactivity of agricultural products.

Furthermore, the review has emphasized the importance of innovative processing techniques, as methods such as extraction, fermentation, thermal processing, and storage can either degrade or enhance polyphenol content and bioavailability. Developing advanced processing methods that preserve or even amplify the bioactivity of polyphenols is crucial for maximizing their health benefits in functional foods and dietary supplements.

The implications of this review extend beyond the scientific understanding of polyphenols. By comprehensively examining the interplay between polyphenols, health effects, antioxidant activity, composition factors, and processing methods, this review provides a foundation for future research and practical applications. It highlights the need for interdisciplinary approaches that integrate agriculture, food science, nutrition, and medicine to fully harness the potential of polyphenols. For instance, elucidating the mechanisms by which polyphenols exert their health benefits, particularly their interactions with gut microbiota and their role in modulating metabolic pathways, remains a promising area for further investigation. Additionally, more in-depth studies are needed to explore the variability in polyphenol composition across different plant species, cultivars, and growing conditions, as well as the impact of emerging processing technologies on polyphenol stability and functionality.

Looking ahead, future research should prioritize the development of novel processing techniques that minimize the degradation of polyphenols while enhancing their bioavailability and bioactivity. The exploration of polyphenol-rich functional foods and their role in personalized nutrition also holds significant promise. By addressing these research gaps, scientists and practitioners can unlock the full potential of polyphenols as powerful tools for promoting human health and preventing chronic diseases.

In summary, polyphenols represent a dynamic and promising field of study with far-reaching implications for nutrition, health, and disease prevention. Their diverse biological activities, coupled with their natural abundance in plant-based foods, make them invaluable for developing innovative dietary strategies and therapeutic interventions. Continued research and collaboration across disciplines will be essential to translate these findings into practical applications that improve public health and well-being. As we deepen our understanding of polyphenols, we move closer to realizing their potential as key components of a healthier and more sustainable future.

Declarations:

Declaration of Interest Statement: The authors declare no competing financial interest.

Data availability: No new data were created or analyzed during this study. Data sharing is not applicable to this article

Acknowledgment: The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

1. Sánchez-Rabaneda, F., Jáuregui, O., Lamuela-Raventós, R. M., & Viladomat, F. (2021). Evaluation of the Bioactivity of Polyphenols. In Dietary Polyphenols and Human Health (pp. 171- 189). Academic Press

***2**. González-Sarrías, A., Núñez-Sánchez, M. A., Tomé-Carneiro, J., & Tomás-Barberán, F. A. (2021).A Critical Review of the Determinants of Polyphenol Bioavailability: Challenges, Mechanisms, and Implications for Health. Current Pharmaceutical Design, 27(21), 2261-2284.*

***3.** Kumar, R., Gautam, S., Verma, R., & Verma, A. (2022). Resveratrol as an Anti-Cancer Agent: A Review. BioFactors, 48(1), 7-25.*

***4**. Bhullar, K. S., Rupasinghe, H. P. V., & Parich, A. (2021). Polyphenols: Multipotent Therapeutic Agents in Neurodegenerative Diseases. Oxidative Medicine and Cellular Longevity, 2021, 6635425.*

***5**. Cirillo, G., Gallo, M., & Borrelli, A. (2022). Polyphenols: Beneficial Effects on Cardiovascular Health and Their Mechanisms of Action. Nutrients, 14(3), 339.*

***6**. Rufino, A. T., Ribeiro, M., Judas, F., & Salgueiro, L. (2021). Insights on Polyphenols Structure- Activity Relationship. Molecules, 26(1), 154.*

***7**. Mazzeo, T., Núñez-Sánchez, M. A., & Fratianni, F. (2021). Polyphenol Composition and Nutritional Quality of Fruits and Vegetables. In Dietary Polyphenols and Human Health (pp. 57- 76). Academic Press.*

***8**. Valero-Muñoz, M., Li, S., Wilson, R., Fernández-Acevedo, R., & Fernández-Ortiz, A. (2022). Environmental Factors and Cardiovascular Disease. European Heart Journal Supplements, 24(Supplement_C), C2-C7.*

***9**. Núñez-Sánchez, M. A., García-Villalba, R., García-Talavera, N. V., & Tomás-Barberán, F. A. (2021). In Vitro and In Vivo Health Effects of Polyphenol-Rich Foods: Current Knowledge and Future Directions. Nutrients, 13(8), 2553.*

***10**. Zhang, Y., Zhang, D., Chen, Q., & He, S. (2023). Effects of Thermal Processing on Phenolic Compounds and Antioxidant Activity in Fruits and Vegetables: A Review. Food Research International, 150, 110860.*

***11**. Gorzynik-Debicka, M., Przychodzen, P., Cappello, F., Kuban-Jankowska, A., Marino Gammazza, A., Knap, N., ... & Gorska-Ponikowska, M. (2018).*

Potential health benefits of olive oil and plant polyphenols. International journal of molecular sciences, 19(3), 686.

12. *Fraga, C. G., Croft, K. D., Kennedy, D. O., & Tomás-Barberán, F. A. (2019). The effects of polyphenols and other bioactives on human health. Food & function, 10(2), 514-528.*

13. *Fujiki, H., Sueoka, E., Watanabe, T., & Suganuma, M. (2015). Primary cancer prevention by green tea, and tertiary cancer prevention by the combination of green tea catechins and anticancer compounds. Journal of cancer prevention, 20(1), 1.*

14. *Xiao, J. B., & Hogger, P. (2015). Dietary polyphenols and type 2 diabetes: current insights and future perspectives. Current medicinal chemistry, 22(1), 23-38.*

15. *Cory, H., Passarelli, S., Szeto, J., Tamez, M., & Mattei, J. (2018). The role of polyphenols in human health and food systems: A mini-review. Frontiers in nutrition, 5, 87.*

16. *Ponnampalam, E.N.; Kiani, A.; Santhiravel, S.; Holman, B.W.B.; Lauridsen, C.; Dunshea, F.R. The Importance of Dietary Antioxidants on Oxidative Stress, Meat and Milk Production, and Their Preservative Aspects in Farm Animals: Antioxidant Action, Animal Health, and Product Quality—Invited Review. Animals 2022, 12, 3279. https://doi.org/10.3390/ani12233279*

17. *Tian, Y., & Yang, B. (2023). Phenolic compounds in Nordic berry species and their application as potential natural food preservatives. Critical Reviews in Food Science and Nutrition, 63(3), 345-377*

18. *Adnan, M., Siddiqui, A. J., Arshad, J., Hamadou, W. S., Awadelkareem, A. M., Sachidanandan, M., & Patel, M. (2021). Evidence-based medicinal potential and possible role of selaginella in the prevention of modern chronic diseases: Ethnopharmacological and ethnobotanical perspective. Records of Natural Products, 15(5), 355.*

19. *Fan FY, Sang LX, Jiang M. Catechins and Their Therapeutic Benefits to Inflammatory Bowel Disease. Molecules. 2017 Mar 19;22(3):484. doi: 10.3390/molecules22030484. PMID: 28335502; PMCID: PMC6155401.*

20. *Guven H, Arici A, Simsek O. Flavonoids in Our Foods: A Short Review J Basic Clin Health Sci 2019; 3:96-106. https://doi.org/10.30621/jbachs.2019.555*

21. *Samarghandian S, Azimi-Nezhad M, Farkhondeh T. Catechin Treatment*

Ameliorates Diabetes and Its Complications in Streptozotocin

***22**. Musarra-Pizzo, M.; Pennisi, R.; Ben-Amor, I.; Mandalari, G.; Sciortino, M.T. Antiviral Activity Exerted by Natural Products against Human Viruses. Viruses 2021, 13, 828. https://doi.org/10.3390/v13050828*

***23**. Praditya, D., Kirchhoff, L., Brüning, J., Rachmawati, H., Steinmann, J., and Steinmann, E. (2019). Anti-infective Properties of the Golden Spice Curcumin. Front. Microbiol. 10, 912. doi:10.3389/fmicb.2019.00912*

***24**. Vestergaard, M., and Ingmer, H. (2019). Antibacterial and Antifungal Properties of Resveratrol. Int. J. Antimicrob. Agents 53 (6), 716–723. doi:10.1016/j.ijantimicag.2019.02.015*

***25**. Jennings, M. R., and Parks, R. J. (2020). Curcumin as an Antiviral Agent. Viruses 12 (11), 1242. doi:10.3390/v1211124*

***26**. Gansukh, E., Nile, A., Kim, D. H., Oh, J. W., and Nile, S. H. (2021). New Insights into Antiviral and Cytotoxic Potential of Quercetin and its Derivatives - A Biochemical Perspective. Food Chem. 334, 127508. doi:10.1016/j.foodchem.2020.127508*

***27**. Yan, Z., Zhong, Y., Duan, Y., Chen, Q., & Li, F. (2020). Antioxidant mechanism of tea polyphenols and its impact on health benefits. Animal Nutrition, 6(2), 115-123.*

***28**. Yi, M., Wu, X., Zhuang, W., Xia, L., Chen, Y., Zhao, R., ... & Zhou, Y. (2019). Tea consumption and health outcomes: Umbrella review of meta-analyses of observational studies in humans. Molecular nutrition & food research, 63(16), 1900389.*

***29**. Da Porto A, Cavarape A, Colussi G, Casarsa V, Catena C, Sechi LA. Polyphenols Rich Diets and Risk of Type 2 Diabetes. Nutrients. 2021 Apr 24;13(5):1445. doi: 10.3390/nu13051445. PMID: 33923263; PMCID: PMC8146556.*

***30**. Hironao, K. Y., Ashida, H., & Yamashita, Y. (2022). Black soybean seed coat polyphenol ameliorates the abnormal feeding pattern induced by high-fat diet consumption. Frontiers in Nutrition, 9, 1006132.*

***31**. Ríos, J.L.; Francini, F.; Schinella, G.R. Natural Products for the Treatment of Type 2 Diabetes Mellitus. Planta Med. 2015, 81, 975–994*

***32**. Marta Guasch-Ferré, M., Merino, J., Sun, Q., Fitó, M., & Salas-Salvadó, J. (2017). Dietary polyphenols, Mediterranean diet, prediabetes, and type 2 diabetes: a narrative review of the evidence. Oxidative medicine and cellular* *longevity, 2017.*

***33**. Ganesan, K., & Xu, B. (2017). Polyphenol-rich lentils and their health promoting effects. International journal of molecular sciences, 18(11), 2390*

***34**. Cremonini, E., Bettaieb, A., Haj, F. G., Fraga, C. G., & Oteiza, P. I. (2016). (-)-Epicatechin improves insulin sensitivity in high fat diet-fed mice. Archives of biochemistry and biophysics, 599, 13-21.*

***35**. Vernarelli, J. A., & Lambert, J. D. (2017). Flavonoid intake is inversely associated with obesity and C-reactive protein, a marker for inflammation, in US adults. Nutrition & diabetes, 7(5), e276-e276.*

***36**. Güneş Bayir, A., Aksoy, A., & KOÇYİĞİT, A. (2019). The importance of polyphenols as functional food in health. Bezmialem Science, 7(2).*

***37**. Al-Ishaq RK, Abotaleb M, Kubatka P, Kajo K, Büsselberg D. Flavonoids and Their Anti-Diabetic Effects: Cellular Mechanisms and Effects to Improve Blood Sugar Levels. Biomolecules. 2019 Sep 1;9(9):430. doi: 10.3390/biom9090430. PMID: 31480505; PMCID: PMC6769509.*

***38**. S. C. Larsson, A. Akesson, B. Gigante and A. Wolk, Chocolate consumption and risk of myocardial infarction: a prospective study and meta-analysis, Heart, 2016, 102, 1017–1022*

***39**. N. P. Bondonno, C. P. Bondonno, L. C. Blekkenhorst, M. J. Considine, G. Maghzal, R. Stocker, R. J. Woodman, N. C. Ward, J. M. Hodgson and K. D. Croft, Flavonoid-rich apple improves endothelial function in individuals at risk for cardiovascular disease: a randomized controlled clinical trial, Mol. Nutr. Food Res., 2018, 62(3)*

***40**. J. I. Dower, J. M. Geleijnse, P. Hollman, S. S. Soedamah-Muthu and D. Kromhout, Dietary epicatechin intake and 25-y risk of cardiovascular mortality: the Zutphen Elderly Study, Am. J. Clin. Nutr., 2016, 104, 58–64*

***41**. García, L. C., & Hernández, A. N. M. (2020). Beneficial effects of cocoa and dark chocolate polyphenols on health. The FASEB Journal, 34(S1), 1-1.*

***42**. Chavda VP, Chaudhari AZ, Teli D, Balar P, Vora L. Propolis and Their Active Constituents for Chronic Diseases. Biomedicines. 2023 Jan 18;11(2):259. doi: 10.3390/biomedicines11020259. PMID: 36830794; PMCID: PMC9953602.*

***43**. Zullkiflee N, Taha H, Usman A. Propolis: Its Role and Efficacy in Human Health and Diseases. Molecules. 2022 Sep 19;27(18):6120. doi: 10.3390/molecules27186120. PMID: 36144852; PMCID: PMC9504311.*

44. *Rahman, M. H., Akter, R., Bhattacharya, T., Abdel-Daim, M. M., Alkahtani, S., Arafah, M. W., et al. (2020). Resveratrol and Neuroprotection: Impact and its Therapeutic Potential in Alzheimer's Disease. Front. Pharmacol. 11, 619024. doi:10.3389/fphar.2020.619024*

45. *Pervin, M.; Unno, K.; Ohishi, T.; Tanabe, H.; Miyoshi, N.; Nakamura, Y. Beneficial Effects of Green Tea Catechins on Neurodegenerative Diseases. Molecules 2018, 23, 1297. https://doi.org/10.3390/molecules23061297*

46. *Iqbal, E., Salim, K. A., and Lim, L. B. L. (2015). Phytochemical screening, total phenolics and antioxidant activities of bark and leaf extracts of Goniothalamus velutinus (Airy Shaw) from Brunei Darussalam. J. King Saud Univ. Sci. 27, 224–232. doi: 10.1016/j.jksus.2015.02.003*

47. *Afshar, M., Najafian, S., & Radi, M. (2022). Seasonal variation on the major bioactive compounds: total phenolic and flavonoids contents, and antioxidant activity of rosemary from shiraz. Natural Product Research, 36(16), 4287-4292.*

48. *Olszowy, M. (2019). What is responsible for antioxidant properties of polyphenolic compounds from plants?. Plant Physiology and Biochemistry, 144, 135-143.*

49. Kumar, S., Kumar, V., and Prakash, O. (2011a). Antidiabetic and antihyperlipidemic effects of Dillenia indica (L.) leaves extract. Braz. J. Pharm. Sci. 47, 373–378. doi: 10.1590/S1984-82502011000200018

50. *Sagar NA, Pareek S, Gonzalez-Aguilar GA. Quantification of flavonoids, total phenols and antioxidant properties of onion skin: a comparative study of fifteen Indian cultivars. J Food Sci Technol. 2020 Jul;57(7):2423-2432. doi: 10.1007/s13197-020-04277-w. Epub 2020 Feb 5. PMID: 32549592; PMCID: PMC7271087.*

51. *Manohar CM, Xue J, Murayyan A, Neethirajan S, Shi J. Antioxidant activity of polyphenols from Ontario grown onion varieties using pressurized low polarity water technology. J Funct Foods. 2017;31:52–62. doi: 10.1016/j.jff.2017.01.037.*

52. *Francenia Santos-Sánchez N, Salas-Coronado R, Villanueva-Cañongo C, Hernández-Carlos B. Antioxidant Compounds and Their Antioxidant Mechanism [Internet]. Antioxidants. IntechOpen; 2019. Available from: http://dx.doi.org/10.5772/intechopen.85270*

53. *Platzer M, Kiese S, Tybussek T, Herfellner T, Schneider F, Schweiggert-*

Weisz U, Eisner P. Radical Scavenging Mechanisms of Phenolic Compounds: A Quantitative Structure-Property Relationship (QSPR) Study. Front Nutr. 2022 Apr 4;9:882458. doi: 10.3389/fnut.2022.882458.

***54**. Yang, Q. Q., Gan, R. Y., Ge, Y. Y., Zhang, D., & Corke, H. (2018). Polyphenols in common beans (Phaseolus vulgaris L.): Chemistry, analysis, and factors affecting composition. Comprehensive Reviews in Food Science and Food Safety, 17(6), 1518-1539.*

***55.** Kabtni, S., Sdouga, D., Bettaib Rebey, I., Save, M., Trifi-Farah, N., Fauconnier, M. L., & Marghali, S. (2020). Influence of climate variation on phenolic composition and antioxidant capacity of Medicago minima populations. Scientific reports, 10(1), 1-15.*

***56**. Arfaoui, L. (2021). Dietary plant polyphenols: effects of food processing on their content and bioavailability. Molecules, 26(10), 2959.*

***57**. Sama H, Traoré DK, Guenné S, Hilou A, Dicko MH. Effect of pedo-climatic conditions on physicochemical characteristics and agro-industrial potential of three native oilseeds fruits from Burkina Faso. BMC Plant Biol. 2022 Jul 4;22(1):321. doi: 10.1186/s12870-022-03713-7.*

***58**. Taghavi, T., Siddiqui, R., & Rutto, L. K. (2019). The effect of preharvest factors on fruit and nutritional quality in strawberry. Strawberry Pre-and Post-harvest Management Techniques for Higher Fruit Quality.*

***59.**. Liu, W., Yin, D., Li, N., Hou, X., Wang, D., Li, D., & Liu, J. (2016). Influence of environmental factors on the active substance production and antioxidant activity in Potentilla fruticosa L. and its quality assessment. Scientific reports, 6(1), 1-18.*

***60**. Rezende, W. P. D., Borges, L. L., Santos, D. L. D., Alves, N. M., & Paula, J. R. D. (2015). Effect of environmental factors on phenolic compounds in leaves of Syzygium jambos (L.) Alston (Myrtaceae).*

***61**. Tolic, M. T., Krbavcic, I. P., Vujevic, P., Milinovic, B., Jurcevic, I. L., & Vahcic, N. (2017). Effects of weather conditions on phenolic content and antioxidant capacity in juice of chokeberries (Aronia melanocarpa L.). Polish Journal of Food and Nutrition Sciences, 67(1).*

***62**. El Qarnifa, S., El Antari, A., & Hafidi, A. (2019). Effect of maturity and environmental conditions on chemical composition of olive oils of introduced cultivars in Morocco. Journal of Food Quality, 2019.*

***63**. Pérez-Navarro, J., Izquierdo-Cañas, P. M., Mena-Morales, A., Martínez-*

Gascueña, J., Chacón-Vozmediano, J. L., García-Romero, E., ... & Gómez-Alonso, S. (2021). Genotypic variation in phenolic composition of novel white grape genotypes (Vitis vinifera L.). Journal of Food Composition and Analysis, 102, 103987.

***64**. Guebebia, S., Othman, K. B., Yahia, Y., Romdhane, M., Elfalleh, W., & Hannachi, H. (2022). Effect of genotype and extraction method on polyphenols content, phenolic acids, and flavonoids of olive leaves (Olea europaea L. subsp. europaea). International Journal of Plant Based Pharmaceuticals, 2(1), 17-24.*

***65**. Parra-Palma, C.; Fuentes, E.; Palomo, I.; Torres, C.A.; Moya-León, M.A.; Ramos, P. Linking the platelet antiaggregation effect of different strawberries species with antioxidants: Metabolomic and transcript profiling of polyphenols. Bol. Latinoam. Caribe Plant Med. Aromat. 2018, 17, 36–52.*

***66**. Alu´datt MH, Rababah T, Alhamad MN, Gammoh S, Ereifej K, Al-Karaki G, Tranchant CC, Al-Duais M, Ghozlan KA, (2019) Contents, profiles and bioactive properties of free and bound penolics extracted from selected fruits of the Oleaceae and Solanaceae families. LWT Food Sci Technol 109:367–377*

***67**. Kim, EH., Lee, K.M., Lee, SY. et al. Influence of genetic and environmental factors on the contents of carotenoids and phenolic acids in red pepper fruits (Capsicum annuum L.). Appl Biol Chem 64, 85 (2021). https://doi.org/10.1186/s13765-021-00657-8*

***68**. Sun, Y., Deng, Z., Liu, R., Zhang, H., Zhu, H., Jiang, L., & Tsao, R. (2020). A comprehensive profiling of free, conjugated and bound phenolics and lipophilic antioxidants in red and green lentil processing by-products. Food Chemistry, 325, 126925.*

***69**. Wu, G., Johnson, S. K., Bornman, J. F., Bennett, S. J., Clarke, M. W., Singh, V., & Fang, Z. (2016). Growth temperature and genotype both play important roles in sorghum grain phenolic composition. Scientific reports, 6(1), 1-10.*

***70**. Lira, B. S., Rosado, D., Almeida, J., de Souza, A. P., Buckeridge, M. S., Purgatto, E., et al. (2016). Pheophytinase knockdown impacts carbon metabolism and nutraceutical content under normal growth conditions in tomato. Plant Cell Physiol. 57, 642–653. doi: 10.1093/pcp/pcw021*

***71**. Belwal T, Pandey A, Bhatt ID, Rawal RS, Luo Z. Trends of polyphenolics and anthocyanins accumulation along ripening stages of wild edible fruits of Indian Himalayan region. Sci Rep. 2019;9(1):1–11.*

***72**. Mokhtar, M., Bouamar, S., Di Lorenzo, A., Temporini, C., Daglia, M., &*

Riazi, A. (2021). The Influence of Ripeness on the Phenolic Content, Antioxidant and Antimicrobial Activities of Pumpkins (Cucurbita moschata Duchesne). Molecules, 26(12), 3623.

***73**. Rodríguez, J. C., Gómez, D., Pacetti, D., Nunez, O., Gagliardi, R., Frega, N. G., ... & Lucci, P. (2016). Effects of the fruit ripening stage on antioxidant capacity, total phenolics, and polyphenolic composition of crude palm oil from interspecific hybrid Elaeis oleifera× Elaeis guineensis. Journal of agricultural and food chemistry, 64(4), 852-859.*

***74**. Xie, G., Wang, J., Xu, X., Wang, R., Zhou, X., & Liu, Z. (2016). Effect of different ripening stages on bioactive compounds and antioxidant capacity of wild Rosa laevigata Michx. Food Science and Technology, 36, 396-400.*

***75**. Atifi, H., Jadouali, S. M., Laknifli, A., Bouzoubaâ, Z., Mamouni, R., Faouzi, A., & Achemchem, F. (2019). Effect of Ripening Degree of Argane Fruit on the Phenolic Composition and Antioxidant Activity of the fruit Pulp, Kernel and Oil. Moroccan Journal of Chemistry, 7(2), 7-2.*

***76**. Oszmiański, J., Lachowicz, S., Gorzelany, J., & Matłok, N. (2018). The effect of different maturity stages on phytochemical composition and antioxidant capacity of cranberry cultivars. European Food Research and Technology, 244(4), 705-719.*

***77**. De Beer D, Joubert E, Gelderblom WCA, Manley M (2017) S Afr J Enol Vitic 23(2):48–61*

***78**. Sharma, K., & Lee, Y. R. (2016). Effect of different storage temperature on chemical composition of onion (Allium cepa L.) and its enzymes. Journal of food science and technology, 53(3), 1620-1632.*

***79**. Ali, A., Chong, C. H., Mah, S. H., Abdullah, L. C., Choong, T. S. Y., & Chua, B. L. (2018). Impact of storage conditions on the stability of predominant phenolic constituents and antioxidant activity of dried Piper betle extracts. Molecules, 23(2), 484.*

***80**. Kotsiou, K., & Tasioula-Margari, M. (2016). Monitoring the phenolic compounds of Greek extra-virgin olive oils during storage. Food chemistry, 200, 255-262.*

***81**. Del-Toro-Sánchez, C. L., Gutiérrez-Lomelí, M., Lugo-Cervantes, E., Zurita, F., Robles-García, M. A., Ruiz-Cruz, S., ... & Guerrero-Medina, P. J. (2015). Storage effect on phenols and on the antioxidant activity of extracts from Anemopsis californica and inhibition of elastase enzyme. Journal of Chemistry, 2015.*

82. *De Oliveira, K. G., Queiroz, V. A. V., de Almeida Carlos, L., de Morais Cardoso, L., Pinheiro-Sant'Ana, H. M., Anunciação, P. C., ... & Barros, F. (2017). Effect of the storage time and temperature on phenolic compounds of sorghum grain and flour. Food Chemistry, 216, 390-398.*

83. *Lang, G. H., da Silva Lindemann, I., Ferreira, C. D., Hoffmann, J. F., Vanier, N. L., & de Oliveira, M. (2019). Effects of drying temperature and long-term storage conditions on black rice phenolic compounds. Food chemistry, 287, 197-204.*

84. *Tobal, T. M., & Rodrigues, L. V. (2019). Effect of storage on the bioactive compounds, nutritional composition and sensory acceptability of pitanga jams. Food Science and Technology, 39, 581-587.*

85. *Ghoshal, G. (2018). Recent trends in active, smart, and intelligent packaging for food products. In Food packaging and preservation (pp. 343-374). Academic Press.*

86. *Augustin, M. A., Riley, M., Stockmann, R., Bennett, L., Kahl, A., Lockett, T., ... & Cobiac, L. (2016). Role of food processing in food and nutrition security. Trends in Food Science & Technology, 56, 115-125.*

87. *Amit, S. K., Uddin, M., Rahman, R., Islam, S. M., & Khan, M. S. (2017). A review on mechanisms and commercial aspects of food preservation and processing. Agriculture & Food Security, 6(1), 1-22.*

88. *Melini, F., & Melini, V. (2021). Impact of Fermentation on Phenolic Compounds and Antioxidant Capacity of Quinoa. Fermentation, 7(1), 20.*

89. *Adebo, O. A., & Gabriela Medina-Meza, I. (2020). Impact of fermentation on the phenolic compounds and antioxidant activity of whole cereal grains: A mini review. Molecules, 25(4), 927.*

90. *Gan, R. Y., Shah, N. P., Wang, M. F., Lui, W. Y., & Corke, H. (2017). Lactobacillus plantarum WCFS1 fermentation differentially affects antioxidant capacity and polyphenol content in mung bean (Vigna radiata) and soya bean (Glycine max) milks. Journal of Food processing and Preservation, 41(1), e12944.*

91. *Hur, S. J., Lee, S. Y., Kim, Y. C., Choi, I., & Kim, G. B. (2014). Effect of fermentation on the antioxidant activity in plant-based foods. Food chemistry, 160, 346-356.*

92. *Adebo, O. A., Njobeh, P. B., Adeboye, A. S., Adebiyi, J. A., Sobowale, S. S., Ogundele, O. M., & Kayitesi, E. (2018). Advances in fermentation technology* *for novel food products. In Innovations in technologies for fermented food and beverage industries (pp. 71-87). Springer, Cham.*

***93**. Salar, R. K., Certik, M., & Brezova, V. (2012). Modulation of phenolic content and antioxidant activity of maize by solid state fermentation with Thamnidium elegans CCF 1456. Biotechnology and bioprocess engineering, 17(1), 109-116.*

***94**. Wang, Y., Wu, Y., Yu, Y., Pan, T., Li, D., Lambropoulou, D., & Yang, X. (2020). Natural polyphenols enhanced the Cu (II)/peroxymonosulfate (PMS) oxidation: The contribution of Cu (III) and HO•. Water Research, 186, 116326.*

***95**. Rababah, T. M., Al-u'datt, M., Al-Mahasneh, M., Gammoh, S., Mahili, H., & Ajouly, T. E. (2020). Effect of different fermentation processes on the phytochemical properties of green table Olives. Revista Brasileira de Fruticultura, 42.*

***96.** Oliveira, T., Ramalhosa, E., Nunes, L., Pereira, J. A., Colla, E., & Pereira, E. L. (2017). Probiotic potential of indigenous yeasts isolated during the fermentation of table olives from Northeast of Portugal. Innovative Food Science & Emerging Technologies, 44, 167-172.*

***97**. Olatunde, O. O., & Benjakul, S. (2018). Natural preservatives for extending the shelf-life of seafood: a revisit. Comprehensive Reviews in Food Science and Food Safety, 17(6), 1595-1612.*

***98**. Rahman MS (eds). Handbook of food preservation. 2nd ed. Food science and technology. Boca Raton: CRC Press; 2007.*

***99**. Garg N, Garg KL, Mukerji KG. Laboratory manual of food microbiology. New Delhi: I.K. International Publishing House Pvt. Ltd; 2010*

***100**. Shiri, M. A., Ghasemnezhad, M., Bakhshi, D., & Dadi, M. (2011). Changes in phenolic compounds and antioxidant capacity of fresh-cut table grape ('Vitis vinifera') cultivar' Shahaneh'as influence by fruit preparation methods and packagings. Australian Journal of Crop Science, 5(12), 1515-1520.*

***101.** Altunkaya, A., & Gökmen, V. (2008). Effect of various inhibitors on enzymatic browning, antioxidant activity and total phenol content of fresh lettuce (Lactuca sativa). Food chemistry, 107(3), 1173-1179.*

***102**. Serrano, M. J., Martinez-Romero, D., et al. (2021). Application of Antioxidant Compounds for Food Preservation: A Review. Comprehensive*

Reviews in Food Science and Food Safety, 20(2), 976-1017.

***103**. Zhou, S., Xiao, J., et al. (2023). Microencapsulation of Polyphenols for Improved Stability and Delivery: A Review. Trends in Food Science & Technology, 124, 36-47.*

***104**. Carocho, M., Soković, M., et al. (2022). Chemical Preservatives for Food Preservation: From Popular Choices to the Recent Developments. Molecules, 27(5), 1373.*

***105**. Guo, H., Xiao, W., et al. (2021). Advances in the Application of Edible Coatings/Films Loaded with Plant Polyphenols to Preserve Food Quality: A Comprehensive Review. Trends in Food Science & Technology, 116, 1-13.*

***106**. Kacem, I., Chograni, H., et al. (2022). Effect of Different Preservatives on the Stability of Polyphenols and Antioxidant Activity of a Fruit Juice-Based Beverage during Storage. Food Control, 132, 108469.*

***107**. Turner, E. R., Luo, Y., & Buchanan, R. L. (2020). Microgreen nutrition, food safety, and shelf life: A review. Journal of food science, 85(4), 870-882.*

***108**. González-Peña, M. A., Ortega-Regules, A. E., Anaya de Parrodi, C., & Lozada-Ramírez, J. D. (2023). Chemistry, Occurrence, Properties, Applications, and Encapsulation of Carotenoids—A Review. Plants, 12(2), 313*

***109**. Turturică, M., Stănciuc, N., Bahrim, G., & Râpeanu, G. (2016). Effect of thermal treatment on phenolic compounds from plum (Prunus domestica) extracts–A kinetic study. Journal of Food Engineering, 171, 200-207.*

***110**. Marszałek, K., Woźniak, Ł., Kruszewski, B., & Skąpska, S. (2017). The effect of high pressure techniques on the stability of anthocyanins in fruit and vegetables. International Journal of Molecular Sciences, 18(2), 277.*

***111**. Martínez, S., Armesto, J., Gómez-Limia, L., & Carballo, J. (2020). Impact of processing and storage on the nutritional and sensory properties and bioactive components of Brassica spp. A review. Food Chemistry, 313, 126065.*

***112**. Deng, L. Z., Mujumdar, A. S., Zhang, Q., Yang, X. H., Wang, J., Zheng, Z. A., ... & Xiao, H. W. (2019). Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics and quality attributes–a comprehensive review. Critical reviews in food science and nutrition, 59(9), 1408-1432.*

***113**. Patras, A., Tiwari, B. K., & Brunton, N. P. (2011). Influence of blanching and low temperature preservation strategies on antioxidant activity and* *phytochemical content of carrots, green beans and broccoli. LWT-Food Science and Technology, 44(1), 299-306*

***114**. Le Bourvellec, C., Gouble, B., Bureau, S., Reling, P., Bott, R., Ribas-Agusti, A., ... & Renard, C. M. (2018). Impact of canning and storage on apricot carotenoids and polyphenols. Food Chemistry, 240, 615-625.*

***115.** Fazaeli, M., Emam-Djomeh, Z., Ashtari, A. K., & Omid, M. (2012). Effect of spray drying conditions and feed composition on the physical properties of black mulberry juice powder. Food and bioproducts processing, 90(4), 667-675.*

***116.** Musilova, J., Lidikova, J., Vollmannova, A., Frankova, H., Urminska, D., Bojnanska, T., & Toth, T. (2020). Influence of Heat treatments on the content of bioactive substances and antioxidant properties of sweet potato (Ipomoea batatas L.) tubers. Journal of Food quality, 2020*

***117**. Li, H., Tsao, R., & Deng, Z. (2012). Factors affecting the antioxidant potential and health benefits of plant foods. Canadian journal of plant science, 92(6), 1101-1111.*

***118.** Zalewska, M., Marcinkowska-Lesiak, M., & Onopiuk, A. (2022). Application of different drying methods and their influence on the physicochemical properties of tomatoes. European Food Research and Technology, 248(11), 2727-2735*

***119**. Muthukumarappan K., Tiwari B., Swamy G.J. Refrigeration and freezing preservation of vegetables. Handb. Veg. Veg. Process. 2018:341–363. doi: 10.1002/9780470958346.ch12.*

***120**. Sun, Q.; Zhao, X.; Zhang, C.; Xia, X.; Sun, F.; Kong, B. Ultrasound-assisted immersion freezing accelerates the freezing process and improves the quality of common carp (Cyprinus carpio) at different power levels. LWT 2019, 108, 106–112*

*1**21**. Nakazawa, N.; Wada, R.; Fukushima, H.; Tanaka, R.; Kono, S.; Okazaki, E. Effect of long-term storage, ultra-low temperature, and freshness on the quality characteristics of frozen tuna meat. Int. J. Refrig. 2020, 112, 270–280.*

***122.** Korus, A., & Lisiewska, Z. (2011). Effect of preliminary processing and method of preservation on the content of selected antioxidative compounds in kale (Brassica oleracea L. var. acephala) leaves. Food chemistry, 129(1), 149-154.*

***123**. González, B., Vogel, H., Razmilic, I., & Wolfram, E. (2015). Polyphenol,* *anthocyanin and antioxidant content in different parts of maqui fruits (Aristotelia chilensis) during ripening and conservation treatments after harvest. Industrial Crops and Products, 76, 158-165.*

124. *Dalmau, M. E., Bornhorst, G. M., Eim, V., Rosselló, C., & Simal, S. (2017). Effects of freezing, freeze drying and convective drying on in vitro gastric digestion of apples. Food Chemistry, 215, 7-16.*