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Advances in fruit crop phytochemicals: Nutraceutical and therapeutic perspectives

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Abstract

Fruits are a good source of phytochemicals which play a critical role in promoting human health as well as preventive measures to chronic diseases. These biomolecules, such as phenolics, flavonoids, carotenoids, terpenoids and vitamins, have powerful nutraceutical and medicinal advantages, antioxidant, anti-inflammatory, anticancer and cardioprotective. The recent advancements in the analysis techniques and molecular biology have enhanced the detection, characterization and quantification of these compounds in various fruits. The synthesis and control of phytochemicals are complicated through metabolic pathways and that they are altered by genetic, environmental and development factors. Additionally, new technologies, such as the metabolic engineering, the editing of genomes and the omics-based approaches have offered new possibilities to increase the phytochemical content and quality of fruits. Although, they have great potentials, low bioavailability, instability during processing and storage and non standardization are some of the challenges that hinder their effective use in nutraceutical and pharmaceutical industries. New strategies are being considered to address these constraints, including nanoencapsulation, creation of functional foods and sustainable processes of extracting. As well, there is an interest in the economic and environmental benefits of fruit waste valorization as a source of valuable phytochemicals. This review presents the latest evolution of research in the topic of fruit crop phytochemicals, their biosynthesis, health and therapeutic applications, along with the existing limitations and future opportunities of their useful applications in human health and well-being.

1. Introduction

Fruit crop phytochemicals are a diversified form of bioactive secondary metabolites that plants synthesize, which is involved in defence mechanisms, environmental adaptation and reproduction. In fruits, they are very high in phenolic acids, flavonoids, carotenoids, alkaloids, terpenoids and in phytosterols which are important in determining the biological values of fruits. The phytochemicals unlike the primary metabolites are not directly associated with growth and development and play an important ecological role such as protection against pathogens, UV radiation and herbivores. The last few decades have seen these compounds becoming an object of great interest due to potentially positive effects on health (promotion of health benefits), as well as prevention of chronic diseases, which makes the focus on functions and therapeutic features of fruits less important than on basic nutrition (Giampieri and Battino, 2020; Noreen *et al*., 2025). The oxidative stress is one of the main factors leading to the occurrence of chronic diseases (cardiovascular diseases, cancer, diabetes, and neurodegenerative disorders). The effectiveness of phytochemicals such as flavonoids and carotenoids as antioxidants is due to the ability of these substances to provide electrons to the free radicals which stabilize them thereby preventing cell destruction. Moreover, they also regulate large-scale biochemical activities and expression of genes involved in inflammatory reactions and defense of the cell which further suggests their multimodality in disease prevention (Chang *et al*., 2019; Noreen *et al*., 2025). Besides antioxidant activity, fruit phytochemicals also have a numerous biological and pharmacological effects, such as anti-inflammatory, antimicrobial, anticancer, and cardioprotective activities. As an example, the polyphenols that are present in fruits, such as berries, grapes, and citrus, have been reported to prevent the growth of tumour cells, regulate the immune system and enhance vascularity. This has witnessed the use of fruits as a source of nutraceuticals which gaps the food-medicine divide. The current amount of scientific evidence has also justified the application of fruit-derived phytochemicals in the design of functional food, dietary supplements, and pharmaceutical preparations, and is a part of preventive care practices (Mesa *et al*., 2023; Barik *et al*., 2025). The organoleptic and quality properties of fruits like colour, flavour, aroma, and texture are also extremely important in determining the phytochemicals. Pigments such as anthocyanins, carotenoids amongst others give fruits their bright colours which not only appeals to the consumers, but also indicates that fruits have great antioxidant capacity. Still,

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volatile compounds and phenolics can be classified as a common smell and taste of fruits. These factors are necessary in consumer acceptance, marketability, and, postharvest quality. In addition, genetic factors, environmental, and production technologies of crops influence the concentration and composition of phytochemicals in fruits that will also play an important role in crop improvement practices (Chang *et al*., 2019; Giampieri and Battino, 2020).

Recent advancements in molecular biology and biotechnology have heightened our understanding about the biosynthesis, regulation and availability of fruit phytochemicals. Studies of metabolic pathways, genes, and enzyme activity have given leads to how these compounds can be produced and accrue in tissues of fruits. Other studies on bioaccessibility and bioavailability have also brought out the importance of the food matrix, the processing and digestion in determining the real health advantages of the phytochemicals. These innovations have extended impacts in the nutritional value added fruits and in the creation of functional foods with specific purposes. Overall, fruit phytochemicals represent an important touchpoint between horticulture and nutrition and medicine, which underscores their role in sustainable farming and encouraging the development of human health (Shahidi and Ambigaipalan, 2015; Mesa *et al*., 2023). Unlike earlier reviews, which primarily focused on general classification and health benefits of fruit phytochemicals, the present review emphasizes recent advances (2022-2026) in biosynthesis, omics-assisted discovery, genome editing (CRISPR) and AI-driven metabolomics. Additionally, this review uniquely integrates translational challenges, including bioavailability, standardization, and clinical validation, thereby bridging the gap between laboratory findings and real-world nutraceutical applications.

1.1 Phytochemicals and its classification

Phytochemicals are bioactive compounds that are synthesized by plants, mainly in their secondary metabolism. These compounds play no direct role in the required growth processes but rather play a significant role in the plant defense, ecological interactions and adaptation to environmental stresses. These protect plants against pathogens, abiotic conditions such as UV radiation and oxidative conditions as well as herbivores. Phytochemicals have become a new topic of interest in recent years due to their health-promoting effects, such as antioxidant, anti-inflammatory, and disease-preventative qualities, which make them a valuable ingredient of functional foods and nutraceuticals (Melini and Ruzzi, 2025; Yang and Ling, 2025). Phytochemicals have a very broad distribution in fruit, vegetables, cereal and medicinal plants, and are used in colour, flavour and aroma. They are important in human health because of their ability to regulate metabolic processes, regulate gene expression as well as combat oxidative challenges. The recent research indicates that they help prevent such chronic illnesses: cardiovascular disorders, cancer, diabetes, and neurodegenerative diseases, which justifies their usefulness in the context of the modern nutrition and preventive medicine (Ciccoritti *et al*., 2024; Yang and Ling, 2025).

Classification of phytochemicals

Phytochemicals are broadly classified based on their chemical structure and biosynthetic origin into several major groups:

i. Phenolic compounds

One of the most common groups of phytochemicals is the phenolic compounds and is defined by the aromatic rings having the hydroxyl group. Such group comprises flavonoid, phenolic acids, tannin, and lignan. They have fundamentally been researched to play strong antioxidant effects and inhibit oxidative stress and inflammation. They also contribute significantly to fruit pigmentation, specifically, red, blue and purple colours (Chen *et al*., 2023; Yang and Ling, 2025).

ii. Carotenoids

These are liposoluble pigments known as carotenoids and it is due to these that the fruits such as mango, papaya and citrus fruits are given the yellow, orange and red colour. The big carotenoids are comprised of 2-carotene, lycopene, lutein, and zeaxanthin. They are highly essential substances in human health both in the eyes, immune system and the antioxidant systems. They also precede the vitamin A, thus making them nutritionally relevant (Liu *et al*., 2022).

iii. Terpenoids (Isoprenoids)

The terpenoids are a massive and diverse family of compounds based on isoprene and include monoterpenes, diterpenes and triterpenes. These are mostly the smell and taste of the fruits and also play a role in defence of the plants. Recent sources show that they are pharmacologically relevant including antimicrobial, anti-inflammatory, and anticancer activities (Misra *et al.,* 2024).

iv. Nitrogen containing compounds (Alkaloids and others)

Phytochemicals that contain nitrogen are alkaloids, amines, and cyanogenic glycosides. These are highly bioactive and pharmacological compounds which are antimicrobial and analgesic. They are less productive than other parts of the plants, but given the great bioactivity and therapeutic potential, they are important (Kumar *et al*., 2023).

v. Organosulfur compounds

Organosulfur compounds are phytotrophic phytotoxic chemicals derived from sulfur which have relevance in human health and plant protection. They are known to have detoxification, cancer closing and anti-inflammatory properties. They are now being studied to be implicated in the control of metabolism and disease prevention (Yang and Ling, 2025).

vi. Other phytochemicals

There are also other phytochemicals, like phytosterols, saponins and glycosides in addition to the major groups. These substances are useful in various biochemical activities like cholesterol reduction, immune regulation and metabolism. Recent publications using metabolomics and phytochemical databases have expanded on the knowledge of these myriad compounds and their application in food, pharmaceutical and agricultural applications (Pandohee *et al*., 2023).

1.2 Importance of fruits as sources of bioactive compounds

The fruits themselves have a long reputation of being good sources of bioactive compounds; a naturally occurring phytochemicals with their beneficial actions to human health more than just nutritional values. These include phenolics, flavonoids, carotenoids and vitamins and dietary fibers which provide functional values to fruits. Against a backdrop of rising prevalence of chronic conditions such as cardiovascular diseases, cancer, diabetes as well as obesity, frequent consumption of fruits has been strongly associated with the risk of these conditions. To a large extent, this protective effect is a result of the synergistic effect of a variety of bioactive compounds that are antioxidants, anti-inflammatory and metabolic regulators (Slavin and Lloyd, 2012; Liu, 2013).

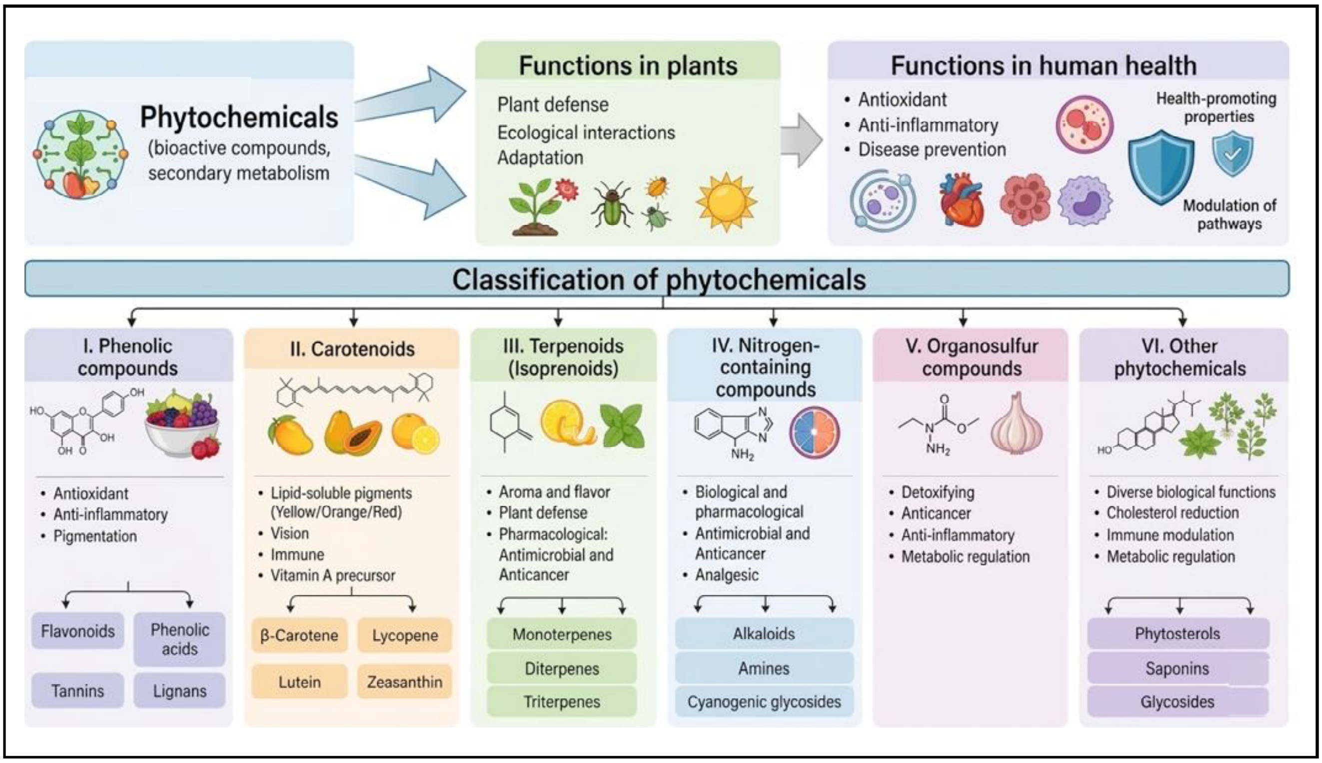

Figure 1: Classification of phytochemicals based on chemical structure and biosynthetic origin, highlighting major groups and their biological significance.

One of the key reasons as to why fruits are considered to be significant sources of bioactive compounds is the high antioxidant capacity. The fruits contain abundant amounts of antioxidant molecules which neutralize reactive oxygen species (ROS) and remove oxidative stress which is a major causal factor of chronic diseases. Significant compounds include vitamin C, flavonoids and carotenoids which contributes in stopping the oxidative damage of the cellular structures. Recent studies emphasize that the antioxidant activity of fruits is not in a single compound, but in a group of various phytochemicals, which enhances their overall performance in the maintenance of health (Shahidi *et al*., 2015; Kalt *et al*., 2020). Because of their various biological activities, fruits can be important in disease prevention and therapeutic use as well. Authored Fruits contain bioactive compounds which have been established to possess anti-inflammatory properties, antimicrobial properties, anticancer properties as well as cardioprotective properties. Polyphenols in grapes and berries have been known to improve the health of blood vessels and reduce inflammation, and carotenoids improve the health of the eyes and immunity. These health-promoting effects have led to the increased popularity of using fruits as ingredients to formulate functional foods and nutraceutical products that are designed to provide specific health benefits in addition to their role in mere nutrition provision (El-Saadony *et al*., 2024). In addition to health promotion, bioactive compounds in fruits also exhibit huge influence on sensorial, and quality parameters, including colour, taste, aroma and texture. The fruits are coloured due to the presence of pigments such as anthocyanins and carotenoids that normally signify good nutritional importance and appeal to consumers. Similarly, volatile substances and phenols are also producers of flavour and aroma, and enhance the overall experience of eating. The quality attribute of consumer preference is not the sole aspect that is modified by the presence of bioactive compounds in that they determine the commercial quantity and marketability of fruits, and consequently, bioactive compounds play a vital role in the nutritional and economic value of fruit production (Kumar *et al.,* 2023; Melini and Ruzzi, 2025).

Further, the fruit is an organic and eco-friendly source of bioactive compounds in food, pharmaceutical, and cosmetic sector. The recent advancements in technologies in the field of extraction technologies and bioprocessing have introduced an opportunity to make use of fruit-derived phytochemicals efficiently in a variety of applications, including dietary supplements, natural preservatives, and therapeutic agents. It has also become of interest that the use of fruit by-products such as peels and seeds can be used as a less expensive and sustainable process of extracting valuable bioactive compounds. This is why the role of fruits in the diet is highlighted along with their relevance as the valuable resource employed as the source of value products and green development (Ciccoritti *et al.*, 2024). In conclusion, fruits are critical in the provision of bioactive compounds which are necessary in the promotion of human health, enhancing quality of food and application in industry. They have become indispensable in the present-day nutrition and preventive health care due to their valuable phytochemical properties and a broad spectrum of biological actions. With increased awareness of the benefits of fruits, they are still an object of research and development of functional foods, nutraceuticals and sustainable farming.

2. Major classes of phytochemicals in fruit crops

Fruits are ideal providers of structurally diverse phytochemicals that play a role in the physiology of vegetation and in the well-being of humans. They are commonly categorized into groups based on their chemical structure, biosynthetic routes, and based on their biological functions which include phenolics, carotenoids, alkaloids, terpenoids and vitamins. The new studies emphasize the idea that these phytochemicals may be used in synergy which enhances antioxidant effects, regulation of metabolic functions and even in disease prevention (Meléndez-Martínez *et al*., 2026).

2.1 Phenolic compounds (Flavonoids, Phenolic acids, Tannins)

Phenolic compounds are characterized by the presence of one or more aromatic rings bearing hydroxyl (-OH) groups. Based on structural complexity, they are broadly classified into simple phenolic acids (*e.g*., hydroxybenzoic and hydroxycinnamic acids) and polyphenols such as flavonoids, tannins, and lignans. Flavonoids possess a common C6-C3-C6 backbone consisting of two aromatic rings (A and B) linked by a heterocyclic ring (C), giving rise to subclasses such as flavonols, flavones, flavanones, and anthocyanins. Structural variations due to hydroxylation, methylation, and glycosylation contribute to the diversity of phenolic compounds in fruits (Ciccoritti *et al*., 2024). Major phenolic compounds identified in fruits include flavonoids such as quercetin, kaempferol, and catechins, along with anthocyanins responsible for red, blue, and purple pigmentation. Phenolic acids such as caffeic acid, ferulic acid, and gallic acid are also widely distributed. Tannins, including condensed and hydrolysable forms, contribute to astringency in certain fruits like grapes and pomegranate. The composition and concentration of these compounds vary depending on fruit species, cultivar, and developmental stage (Vieira and Conte-Junior, 2024).

2.2 Carotenoids (β-carotene, Lycopene, Lutein)

Carotenoids are lipid-soluble pigments composed of a C40 isoprenoid backbone formed by the condensation of eight isoprene units. Structurally, they are divided into two major groups: carotenes (hydrocarbon carotenoids such as β-carotene and lycopene) and xanthophylls (oxygenated derivatives such as lutein and zeaxanthin). Their extended system of conjugated double bonds is responsible for their characteristic yellow, orange, and red coloration in fruits (Meléndez-Martínez *et al.,* 2026). Carotenoids are widely distributed in fruits such as mango, papaya, banana, citrus, and tomato. Lycopene is predominantly found in tomato and watermelon, while β-carotene is abundant in mango and papaya. Lutein and zeaxanthin are commonly present in citrus fruits and some tropical species. Their accumulation is influenced by genetic factors, environmental conditions, and fruit maturity, with significant increases observed during ripening due to chromoplast differentiation (Giovannucci *et al*., 2002).

2.3 Alkaloids and nitrogen-containing compounds

Alkaloids are nitrogen-containing organic compounds, typically characterized by the presence of one or more nitrogen atoms within heterocyclic rings. They are structurally diverse and may exist as simple amines, indole alkaloids, or complex polycyclic structures. In addition to alkaloids, other nitrogen-containing phytochemicals include amines and cyanogenic glycosides. These compounds are generally present in relatively low concentrations in fruits compared to other phytochemical classes (Leclerc and Fournier, 2024). Alkaloids and related nitrogen-containing compounds are found in certain fruits, though typically in smaller quantities compared to leaves or seeds. Examples include trace amounts of indole alkaloids in some tropical fruits and cyanogenic glycosides in fruit seeds and kernels. Amines such as serotonin and related compounds have also been reported in fruits like banana. Their occurrence and concentration vary depending on species, tissue type, and physiological conditions (Wink, 2012).

2.4 Terpenoids and essential oils

Terpenoids constitute a large and structurally diverse class of phytochemicals derived from repeating isoprene (C5) units. Based on the number of isoprene units, they are classified into monoterpenes (C10), sesquiterpenes (C15), diterpenes (C20), and triterpenes (C30). Structurally, terpenoids may occur as linear chains or cyclic compounds and often undergo modifications such as oxidation, reduction, and glycosylation, contributing to their diversity. Many volatile terpenoids are key constituents of essential oils responsible for the characteristic aroma of fruits. Terpenoids are widely distributed in fruits, particularly in citrus, mango, and other tropical species. Monoterpenes such as limonene and pinene are abundant in citrus peel oils, while sesquiterpenes and diterpenes contribute to complex aroma profiles. Triterpenes, including compounds like ursolic acid, are found in fruit cuticles and peels. The composition of terpenoids varies with species, cultivar, and ripening stage, and is strongly associated with fruit aroma and flavor characteristics (Meléndez-Martínez *et al*., 2026).

2.5 Vitamins and antioxidant molecules

Vitamins present in fruits are low-molecular-weight organic compounds with diverse chemical structures. Water-soluble vitamins include vitamin C (ascorbic acid) and B-complex vitamins, whereas fat-soluble vitamins include vitamin A (derived from carotenoids) and vitamin E (tocopherols and tocotrienols). Structurally, these compounds differ significantly, ranging from simple lactone structures in ascorbic acid to complex isoprenoid-derived molecules in vitamin E. Fruits are major sources of vitamin C, particularly citrus fruits, guava, and berries. Provitamin A carotenoids are abundant in mango, papaya, and other yellow-orange fruits. Vitamin E is present in smaller quantities in certain fruits and is more concentrated in seeds and pulp tissues. The concentration of vitamins varies with fruit type, maturity stage, and post-harvest conditions, often showing dynamic changes during ripening and storage (Verma *et al.,* 2026).

Table 1: Overview of key phytochemicals in selected fruit crops and associated functional significance

S. No.	Fruit crop	Major phytochemicals	Content availability/status	Functional significance	References
1	Mango (*Mangifera indica*)	Carotenoids (β carotene), Phenolics, Flavonoids	High carotenoid content (especially in ripe fruits)	Antioxidant, Provitamin A activity	Liu *et al.*, 2022
2	Banana (*Musa* spp.)	Phenolics, Dopamine, Serotonin (amines), Vitamins	Moderate; increases during ripening	Antioxidant, Neuroactive compounds	Wink, 2012
3	Citrus (*Citrus* spp.)	Flavonoids (hesperidin), Vitamin C, Carotenoids	Very high vitamin C and flavonoids	Antioxidant, Immune boosting	Liu *et al.*, 2022
4	Grape (*Vitis vinifera*)	Polyphenols (resveratrol), Flavonoids, Tannins	High in skin and seeds	Cardioprotective, Anti-inflammatory	Del Rio *et al.*, 2013
5	Pomegranate (*Punica granatum*)	Polyphenols (ellagitannins), Anthocyanins	Very high antioxidant capacity	Anticancer, Cardioprotective	Kumar *et al.*, 2023
6	Apple (*Malus domestica*)	Flavonoids (quercetin), Phenolic acids	Moderate to high (peel > pulp)	Antidiabetic, Antioxidant	Williamson, 2013
7	Strawberry (*Fragaria × ananassa*)	Anthocyanins, Flavonoids Vitamin C	High antioxidant phytochemicals	Anti-inflammatory, Antioxidant	Basu and Lyons, 2012

3. Biosynthesis and regulation of phytochemicals in fruits

The production of phytochemicals in fruits depends on the highly-coordinated enzyme-mediated conversion of simple building blocks to the structurally diverse production of secondary metabolites such as flavonoids, anthocyanins and tannins. The major enzymes in the central path are phenylpropanoid-flavonoid pathway that converts to different subclasses of flavonoids by consecutive reactions catalyzed by chalcone synthase (CHS), chalcone isomerase (CHI) and dihydroflavonol reductase (DFR). Their common C6C3C6 backbone can be synthesized through a set of diverging pathways that determine the overall phytochemical profile of fruits (Mao *et al*., 2025). The route is highly dynamic and along the way, the fruits can store some metabolites at various development stages, and it is involved in pigmentation, flavor and antioxidants. The regulation of the phytochemical biosynthesis in fruits is mediated by a complex of transcription factors, phytohormones and non-coding RNAs. Examples of transcription factors that are significant regulators include MYB, bHLH, WRKY, NAC, bZIP families since they activate or silence genes of biosynthetic enzymes. Moreover, plant hormones such as abscisic acid, ethylene, jasmonates and cytokinins have a positive effect on flavonoid accumulation, and auxin can have an inhibitory effect. There is also a growing body of evidence demonstrating the importance of microRNAs (miRNAs) and long non-coding RNAs (lncRNAs) in the fine-tuning of the expression of genes, with miRNAs typically having a suppressive effect and lncRNAs a promoting effect on phytochemical biosynthesis (Zheng *et al*., 2026). Moreover, the phytochemical biosynthesis is highly sensitive system and is highly responsive to environmental and developmental cues. Among the factors that have a significant effect on the metabolic flux to compounds synthesis like anthocyanins are light exposure, temperature changes, drought stress and salinity. These exogenous signals play with the endogenous genetic and hormonal signal transduction systems, forming a well-orchestrated regulatory system that specifies the concentration and composition of phytochemicals in fruits. Recently, advanced omics technologies, such as transcriptomics and metabolomics, have helped to gain a better understanding of these regulatory processes and develop more specific ways to improve the quality and nutritional value of fruits (Kuang *et al*., 2025; Zhang *et al*., 2025).

3.1 Key metabolic pathways (Shikimate and phenylpropanoid pathway)

The metabolic pathways that mediate the biosynthesis of phytochemicals in fruits are mainly interconnected and include the shikimate and phenylpropanoid pathways, which intermediately convert simple carbohydrates into aromatic amino acids such as phenylalanine, tyrosine and tryptophan and are the precursors to a broad range of bioactive compounds including phenolics, The shikimate pathway is a type of reaction in plastids, whereby it converts phosphoenolpyruvate and erythrose-4-phosphate into chorismate, an intermediate in a reaction that controls the flow of carbon to aromatic amino acid biosynthesis (Tzin and Galili, 2010; Maeda and Dudareva, 2012). The phenylalanine is one of these amino acids, and it is the main substrate of the phenylpropanoid pathway, the deamination of which through phenylalanine ammonia-lyase (PAL) indicates the beginning of the secondary metabolism. Then a series of enzymatic reactions that use cinnamate 4-hydroxylase (C4H) and 4-coumarate-CoA ligase (4CL) produce hydroxycinnamate derivatives, which become the precursors to numerous phytochemicals including flavonoids, lignins, stilbenes and coumarins. This pathway has a flavonoid branch which is especially significant in fruits and plays a role in pigmentation, antioxidant action, and defence, with anthocyanins being the most common compounds that accumulate during ripening. Even though, the pathway is conserved, there is variability in phytochemical profiles of fruits due to species-specific regulation. The activity of the pathways can be stimulated by environmental factors such as UV radiation, temperature and biotic stress leading to the production of more protective metabolites. Therefore, a combination of these pathways constitutes the biochemical foundation of phytochemical diversity and functionality of fruits (Liu *et al*., 2015; Salahin *et al*., 2021; Rahim *et al*., 2023).

3.2 Enzymes and genes involved in phytochemical synthesis

The production of phytochemicals in fruits is controlled by a complex network of enzymes coded by structural genes converting primary metabolites to a broad spectrum of secondary compounds that are required in plant defense and fruit quality. The entry of carbon into the phenylpropanoid pathway is regulated by core enzymes like phenylalanine ammonia-lyase (PAL), cinnamate 4-hydroxylase (C4H) and 4-coumarate-CoA ligase (4CL) which decisively affect the content of phenolics (Salahin *et al*., 2021). Downstream enzymes including chalcone synthase (CHS), chalcone isomerase (CHI) and flavanone 3-hydroxylase (F3H) catalyze key flavonoid biosynthetic steps leading to the formation of the core flavonoid structures. Production of anthocyanin is done by late biosynthetic enzymes including dihydroflavonol reductase (DFR) and anthocyanidin synthase (ANS), which has a direct effect on the colour of fruits and antioxidant activity. These enzymes are regulated by genes which are closely controlled and can be grouped into early biosynthetic genes (EBGs) and late biosynthetic genes (LBGs), to have a coordinated accumulation of metabolites. The improvement of transcriptomics and genomics has shown that these genes are oppositely regulated during the development of fruit and in reaction to the surrounding conditions (Xu *et al*., 2023). Also, the activities of the enzymes are regulated by post-translational mechanisms of phosphorylation and negative feedback and this is another one of the sources of control. Overall, the concerted action of enzymes and genes is one of the reasons that offers an efficient production of phytochemicals and contributes greatly to the nutritional value of fruits (Rahim *et al.,* 2023).

3.3 Role of transcription factors (MYB, bHLH, WD40 complexes)

The central role in controlling the expression of structural genes with functions in secondary metabolism is exerted by the transcription factors (TFs), and a central regulatory network is formed by MyB, basic helix-loop-helix (bHLH) and WD40. MYB transcription factors are regarded as some of the most important regulators of the phenylpropanoid metabolism, encompassing activators or repressors of the genes involved into the production of flavonoid and phenolic (Liu *et al*., 2015). In another way, it enables these MYB proteins to bind bHLH transcription factors as a way of giving specificity in their regulation and to form transcriptional complexes. WD40 proteins also stabilize the interactions among the subsequent two proteins: MYB and bHLH and form the complex of MYB, bHLH, and WD40 (MBW), which plays a role in the regulation of late biosynthetic genes in flowering flavonoid pathways (Shen *et al*., 2022). It has been known that MBW complex controls the synthesis of anthocyanin by manipulating the expression of genes such as DFR, ANS, UFGT, and resultantly influence the coloration and commercial value of the fruits. It is feasible to selectively regulate various arms of the phenylpropanoid pathway using these transcription factors to yield various phytochemicals due to different combinations of these transcription factors. In addition, the environmental cues, hormonal regulation, and developmental cues control the TF activity, enabling the plants to dynamically adjust the metabolites production. In this way, transcription factors play the role of master regulators that combine both internal and external cues to regulate phytochemical biosynthesis in fruits (Jue *et al*., 2021).

3.4 Environmental and developmental regulation

The environmental and developmental factors play a huge role in the accumulation of phytochemicals in fruits and control the metabolic pathways at various levels such as the expression of genes, activity of the enzymes, and accumulation of the metabolites. Another major trigger of phenylpropanoid metabolism that enhances the production of flavonoids and anthocyanin to counteract the oxidative stressing effects on plant tissues is light, particularly ultraviolet light (Petroni *et al*., 2011). Temperature is another key parameter with low temperatures being more favorable to the production of anthocyanin and improving fruit coloration and high temperatures putting certain biosynthetic routes down. These are also influenced by the water availability and nutrient condition, which may cause the secondary metabolism to occur due to moderate stress that induces a synthesis of antioxidant compounds as an adaptive response to the plant. The varying contents of phytochemicals with changes in the developmental stages such as growth, maturity, and ripening of fruits that have the anthocyanins as their major constituent are closely associated. Hormonal regulation in these developmental processes are in concert with ethylene, abscisic acid (ABA) and jasmonates which regulate gene expression in biosynthetic pathways. The interaction between the environmental and developmental cues results in dynamic and complex phytochemical profiles to determine fruit quality, flavour and nutritional value. Such interactions play an important role in comprehending the process of maximizing agricultural production that should lead to increasing the content of phytochemical in fruits (Shen *et al*., 2022; Rahim *et al*., 2023).

3.5 Post-harvest influence on phytochemical composition

The extent to which fruits are handled and/or stored post-harvest highly influences the phytochemical composition of the fruits since the metabolic activities of the fruits do not cease once they are picked leading to changes in the concentration and stability of the bioactive compounds. Other elements are storage temperature, humidity and the atmospheric composition which play a critical role in the process of determining phytochemical retention or degradation. Cold storage is employed to decelerate metabolic activities and maintain phytochemicals, but cold storage can also cause stress responses and change metabolite profiles (Jiang *et al*., 2020; Zhang *et al*., 2020). Controlled atmosphere storage, with altered oxygen and carbon dioxide concentrations has been shown to be effective in preserving phytochemical stability and prolonging shelf life. Processing (drying, juicing and thermal) and/or processes can cause degradation and or conversion of phytochemicals and heat can also reduce the susceptible compounds such as vitamin C and increase the bioavailability of other compounds. The degradation and browning of the phenolic compounds can be gained with the help of the enzymatic activity of polyphenol oxidase in particular. Nonetheless, after harvest interventions like UV irradiation, edible coating, and application of elicitors can be used to increase phytochemical levels by triggering stress-related metabolic pathways. Innovations in post-harvest technology are directed at reducing losses and increasing phytochemical retention to increase nutritional value of fruits. Fruit phytochemicals possessing health-promoting properties thus require post- harvest control to maintain them (Ekramirad *et al*., 2021).

4. Nutraceutical properties of fruit phytochemicals

It is an established fact that the fruit crops have a significant contribution towards human health more than just nutrition due to their wide-known fruit crop as a good source of nutraceutical compounds. The phytochemicals comprise a wide range of classes like polyphenols, flavonoids, carotenoids, anthocyanins and vitamins, all with different biochemical characteristics affecting the physiological processes. The build-up of these compounds in fruits are usually influenced by genetic, environmental and post-harvest factors which ultimately dictate the nutraceutical potential of fruits. The prevention of chronic diseases by fruit phytochemicals is gaining popularity in recent times as it may control the oxidative stress, inflammation, and metabolic disorders on the molecular-level (Myhrstad and Wolk, 2023). Fruits that contain these compounds in content are berry-like fruits, citrus, grape, mango and pomegranate fruits and in fact they are the fruits that are usually explored in their health promoting action. Efforts of various phytochemicals are synergetic, and thus their bioactivity is enhanced in comparison to that of isolated compounds, thus total fruit intake is more beneficial (Jain *et al*., 2025). Also, these bioactive molecules play a role in controlling gene expression and cellular signalling pathways and hence disease prevention processes. An increase in the popularity of lifestyle-related illnesses has brought an old-new interest towards diet interventions, and the fruit phytochemicals lie in the center of the interest. Advances in nutrigenomics have also sensitized concern regarding the association of these substances with human genes to compromised human health. In addition, the world dietary guidelines are more skewed towards increased intake of fruit since it is abundant in phytochemicals and has been associated with health benefits. Therefore, fruit phytochemicals are also essential in the diet health interface hence qualify as nutraceuticals and their application in prevention medicine and development of functional foods (Yan *et al*., 2024).

The ability of fruit phytochemicals to be naturally present as bioactive substances with minimal side effects over synthetic drugs is another factor that has made them of great therapeutic potential. These substances have the ability to affect various physiological systems at the same time such as the immune, cardiovascular and endocrine systems. An example is that flavonoids and phenolic acids have been demonstrated to decrease oxidative stress by balancing the free radicals and increasing the endogenous antioxidant defenses (Sun *et al.*, 2024). Moreover, carotenoids like β-carotene and lycopene are also important to the health of the eye and for the prevention of some cancers by preventing oxidative damage to the cells. The fiber content of fruits also improves its nutraceutical value, as it helps maintain the health of the gut, and increase the absorption of nutrients. The phytochemical-gut microbiota interaction is a new field of study, showing that these compounds have the ability to regulate the microbial composition and activity, and thus affect the total health (Ciccoritti *et al*., 2024). Moreover, the bioavailability of fruit phytochemicals is also a vital factor that determines their activity and recent studies have been carried out on their increase by employing advanced delivery methods. Fruit phytochemicals have been thought to be a natural and sustainable way of disease prevention by being incorporated into everyday food. As a result, realization of interest is present in using nutraceuticals based on fruits by the food and pharmaceutical industries in order to develop functional foods and therapeutic products. These breakthroughs underscore the importance of phytochemicals in fruits in the modern nutritional/ health care system.

4.1 Antioxidant activity and free radical scavenging

The fruit phytochemicals are the most potent natural antioxidants and they are necessary in the eradication of reactive oxygen species (ROS) and oxidative stress leading to cell damage. An example of the oxidative stress is where the production of free radicals is greater than the ability of the body to remove them, leading to the damage of lipids, proteins and DNA. Examples of phytochemicals that can serve as electron donors to stabilize free radicals and prevent chain reactions that can harm the cells include flavonoids, phenolic acids, and vitamin C (Affi *et al*., 2024). Antioxidant compounds occur particularly in fruits like blueberries, strawberries, citrus fruits and grapes and are the causes of the health promoting effects of such fruits. The assays, *e.g.,* DPPH and FRAP are some of the assays that are used to assess these fruits that prove the antioxidant ability of these fruits. In addition, the presence of anthocyanins in colored fruits are also associated with enhancing antioxidant properties, and therefore, they could be applied in disease aversion due to oxidative stress. These compounds do not only neutralize the free radicals, but also chelate metal ions catalysing oxidative reactions. The regular consumption of high-antioxidant fruits has been identified to result in a reduced incidence of chronic diseases such as cancer, cardiovascular and neurodegenerative diseases (Shahidi and Ambigaipalan, 2015). In addition, antioxidant phytochemicals could protect cellular components by preventing membrane integrity and lipid peroxidation. This is an important protective effect that is essential to the cellular functioning and prevention of further disease development. Therefore, the fruit phytochemicals are important in the antioxidative stress defense of the human body. Fruit phytochemicals complement the natural antioxidant defenses within the body, as well as direct free radical scavenging. They increase the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase and glutathione peroxidase which play a significant role in the process of eliminating reactive oxygen species (Lobo *et al*., 2010). This two-pronged action renders fruit phytochemicals very efficient in fighting against oxidative stress. Moreover, the compounds regulate the signalling of other pathways such as Nrf2 that regulate the expression of the antioxidant genes. It triggers Nrf2 pathway leading to the production of more protective enzymes that promotes the resistance of cells to oxidative stress. The interplay between antioxidants in the diet and the defense mechanisms of the body underscores the need to have a mixture of fruits in order to get the best health results. It has also been reported that antioxidant properties of fruit phytochemicals can also vary depending upon the nature of their ripening, storage and even processing them. Indicatively, fresh fruits possess a better antioxidant activity as compared to processed foods. However, it is possible to enhance the bioavailability of some compounds by some processing methods. Their collective action with other antioxidants in fruits also increases their effectiveness as the effect of each compound on its own is less than that of the combination of antioxidants. This underscores the need of a healthy diet with a variety of fruits. Thus, the phytochemicals that exist in fruits are essential in maintaining oxidative balance and disease prevention (Basu and Lyons, 2012).

4.2 Anti-inflammatory and immunomodulatory effects

Fruit phytochemicals demonstrate great anti-inflammatory effects by regulating major inflammatory pathways and decreasing the generation of pro-inflammatory substances. Chronic inflammation is one of the major causative factors of many diseases including cardiovascular disorders, diabetes and cancer. Phytochemical flavonoids, polyphenols and carotenoids inhibit synthesis of the inflammatory cytokines such as TNF-a, IL-6 and prostaglandins, which reduce inflammation. The grapes, berries and citrus are the best sources of these compounds and they can be utilized to treat inflammatory ailments. Fruit phytochemicals have a major effect in the anti-inflammatory pathway by blocking pathways involved in inflammation such as NF-kB and MAPK. Phytochemicals suppress the inflammatory response genes expression through inhibiting these pathways. In addition, the compounds can reduce the oxidative stress that is mostly linked with inflammation therefore provide a synergistic protective effect. The body has been observed to decrease normal intake of fruits that contain phytochemicals because of inflammatory markers in the body. This implies that nutrition interventions have the potential to contribute a lot in controlling diseases that are inflammatory. Additionally, phytochemicals in fruits are less toxic than synthetic anti-inflammatory drugs since they do not cause as many side effects and possess other health benefits (Santini *et al*., 2018).

Phytochemicals in fruits also play a role in the immune system regulation among other anti-inflammatory activities. They enhance the performance of immune cells such as the macrophages, natural killer cells and lymphocytes therefore enhancing the performance of the body in terms of resistance to infections (Gonzalez-Gallego *et al*., 2010). The production of antibodies and cytokines to a balanced immune response is also controlled by these chemicals. The phytochemicals can be extremely significant as fruit phyto-immunomodulators in maintaining immunostasis and preventing autoimmune diseases. Recently, the impacts of phytochemicals have been indicated in the modulation of gut microbiota, which in turn, impacts on immunological functioning. Food-microbiota-immunity interaction is a rapidly evolving area and fruit phytochemicals are in the limelight. Also, they have the potential to boost the body response to vaccination and decrease the severity of the infections. Consumption of such fruits which have phytochemicals is therefore recommended as a healthy diet in supporting immune functions. The study of nutraceuticals has also led to the establishment of fruit-based nutraceutical supplements able to boost immunity. The findings emphasize the use of fruit phytochemicals in maintaining good health and in the prevention of diseases (Yahfoubi *et al*., 2018).

4.3 Role in cardiovascular health

Fruit phytochemicals are crucial in sustaining cardiovascular health due to their ability to lower the risk factors that are related to heart diseases. CVDs rank amongst the leading causes or causes of death around the globe and dietary interventions have been said to be an effective prevention strategy. Phytochemicals flavonoids and polyphenols improve the activity of the endothelium, reduce blood pressure, and vascular status (Del rio *et al*., 2013). Grapes, citrus and the pomegranate fruits are particularly beneficial since they are loaded with a number of phytochemicals. The compounds also contribute to alleviating the oxidative stress and inflammation that are major causes that result in the development of atherosclerosis. The plaque-forming in the arteries is inhibited by fruit phytochemicals by affecting the oxidation of the low-density lipoprotein (LDL) cholesterol. They also augment the provision of nitric oxide that is vital in regenerating the tone of the blood and the vasculature. Intake of fruits rich in phytochemicals has been linked to a better lipid profile such as lowering LDL and improving high-density lipoprotein (HDL). This will help in maintaining a healthy and low cholesterol level and reduces the risk of heart disease. Also, the compounds can prevent platelet aggregation and, thus, reduce the risks of blood clots. Fruit phytochemicals possess cardioprotective effects and thus provides a valuable component of heart-friend diets.

Besides their direct action on cardiovascular activity, fruit phytochemicals affect metabolic routes leading to cardiovascular well-being. They control lipid metabolism, glucose homeostasis, and inflammatory reactions, which are all interrelated with cardiovascular diseases development (Aune *et al*., 2017). As an example, polyphenols may stimulate signal transduction that increases lipid metabolism and decreases tissue fat. This will assist in preventing obesity which is a major risk factor to cardiovascular diseases. Worse still, these compounds could also increase the insulin sensitivity consequently reducing the risk of metabolic syndrome. The impact of fruit phytochemicals to reduce hypertension has also been well studied and it has been discovered that it can also modulate the renin-angiotensin system. This results in better blood pressure and decreased strain. Also, the antioxidant effects of the compounds prevent the heart against oxidative damage. Extensive use of phytochemical rich fruits in the daily diet is therefore recommended in the cardiovascular maintenance. The latest advancements in the growth of functional foods led to the creation of fruit-based items that are specific in terms of promoting heart health (Castro-Barquero *et al*., 2020).

4.4 Antidiabetic and antiobesity effects

A lot of attention has been given to fruit phytochemicals and the potential they have in regulating diabetes and obesity which are two of the major health challenges in the world. These substances affect different metabolic processes that are related to glucose control and energy homeostasis (Hanhineva *et al*., 2010). This helps in controlling the postprandial blood sugar and an improvement in glycemic control. Have a high phytochemical level particularly the fruits- apples, citrus fruits and berries are particularly beneficial. Additionally, the compounds make the body highly responsive to insulin, through the effects of regulating the glucose metabolism pathways. Antioxidant and anti-inflammatory effect of fruit phytochemicals is also associated with the antidiabetic effects of the phytochemicals which are reflected in alleviating oxidative stress and inflammation that are linked to insulin resistance. Regular consumption of fruits with phytochemicals has been connected with a lower risk of having diabetes type 2. Additionally, the compounds can shield the pancreatic β-cells against oxidative damage, thus maintaining the production of insulin. Fruits should thus be included in diabetic diets as a home remedy to the disease (Williamson, 2013).

Fruit phytochemicals are of great importance in obesity management as far as controlling the lipid metabolism and fat build-up are concerned. They also influence the development of fat cells and their formation process, in terms of the regulation of gene expression and signal pathways (Bahadoran *et al*., 2013). Some phytochemicals are able to prevent preadipocyte differentiation to mature adipocytes, therefore, inhibiting fat storage. In addition, the compounds can raise energy expenditure through stimulating thermogenesis that helps in burning up the extra calories. The role of fruit phytochemicals in controlling the appetite has been studied too and its results have shown that it can influence hormones that are in charge of the hormone producing needs. This assists in lowering the food consumption and avoiding the gain of weight (Tsuda, 2016). Furthermore, fruits also contribute to the antiobesity effects, attributed to their fiber contents that aid in production of satiety, and improved digestion. A combination of phytochemicals and dietary fiber imparts to the fruits a crucial role in the weight management programs. The latest research has centred on using the compounds of the fruits in the production of the antiobesity supplement and the functional foods as well. These results point to the promising promise of fruit phytochemicals as natural and effective agents to treat metabolic disorders (Anhe *et al*., 2015).

4.5 Functional foods and dietary supplements

Fruit phytochemicals are increasingly conscious of their health values and they are therefore being included in the functional foods and diet supplements. Functional foods are targeted at providing an additional health effect to the standard nutrition and they tend to perform this by adding bioactive compounds to diet. Fruits are fortified with phytochemicals or antioxidants, polyphenols, and other antioxidants (Granato *et al*., 2020). These are highly utilised products which assist in promoting health and averting illness. The development of the functional foods is done using advanced methods of processing to preserve stability and bioactivity of phytochemicals. This makes sure that the end product is not destroyed in its health promoting qualities. Also, the use of encapsulation and nanotechnology have also increased bioavailability of these compounds and are more effective. The functional foods based on fruits have also been a result of the growth in consumption of natural and plant based food. These are said to be safer and more sustainable compared to the synthetic products. Claiming that fruit phytochemicals as a part of functional foods can counterbalance the everyday food consumption of the population could be an effective remedy to the problem of improving their health (Santini *et al*., 2018). There is also the development of fruit phytochemicals as dietary supplements due to its convenience and concentrated nutrient. These supplements can be of various types like capsules, tablets, and powders and are consumed to stay in good health and to avoid diseases (Ganesan and Xu, 2017). Typical ones are grape seed extracts, citrus bioflavonoid extracts and pomegranate extracts. These supplements have varying effects depending on their dosage, bioavailability and the condition of a given individual. Recent investigations have been engaged in the maximum involvement of these to enhance the effectiveness of phytochemical-based supplements. Also, there are regulatory bodies which have been established to ensure safety and quality of such products. Especially those people who may not be taking adequate fruits throughout the day may find dietary supplements useful. It is worth mentioning, though, that the supplements are not to substitute whole food, since the synergy between phytochemicals in the fruits is more beneficial in terms of health. The ongoing research and development in the area are likely to result in the development of more efficient and specific nutraceutical products. By doing so, fruit phytochemicals are on the forefront of the development of functional foods and dietary supplements that might positively impact the health of humans (Zhao *et al*., 2020).

5. Therapeutic applications and future prospects

Because of their broad biochemical effects and possible prophylaxis of chronic diseases, there is much interest in the therapeutic uses of fruit phytochemicals. Such bioactive molecules like polyphenols, flavonoid, carotenoid, terpenoid are also potent antioxidants and anti-inflammatory agents and help in counteracting the reactive oxygen species and relieving oxidative stress on the cellular level. These mechanisms play an important role in reducing the risk of non-communicable diseases like cancer, cardiovascular and diabetes. Recent research has shown that phytochemicals have the potential to regulate important signalling pathways, control gene expression, and affect enzymatic functions related to disease progression, which makes them promising as therapeutic options (Kumar *et al*., 2023; Hossain *et al*., 2025). Moreover, their role in modulation of immune and metabolism is also significant; hence, they are even more significant in the contemporary nutraceutical and pharmaceutical application. The pharmacological spectrum of use of phytochemicals has over the past few years been expanded to include the neuroprotective, antimicrobial and antiviral application. The positive effects of this compound on the human brain are still in its developmental phases, but the compounds are capable of bypassing the blood-brain barrier and exert protective effects on the neurodegenerative diseases associated with the induction of neuroinflammation and neuronal death such as Alzheimer and Parkinson. Moreover, phytochemicals have antimicrobial actions by interfering with the cell walls of microbes, inhibiting enzymatic activities, and interfering with the microbial reproduction process. This has been added to the risen interest of their use as natural substitutes to synthetic drugs particularly in the space of the rising antimicrobial resistance. Multifunctional therapeutic effects such as anti-inflammatory, antidiabetic and hepatoprotective properties have been reported in fruits, such as pomegranate, berries, and citrus (Noreen *et al.,* 2025; Yang and Ling, 2025). These results demonstrate the wide range of pharmacological activity of fruit-based phytochemicals in enhancing human health. Biotechnology and interdisciplinary studies are likely to enhance the future therapeutic effectiveness of the use of phytochemicals. It also explores methods such as metabolic engineering, delivery systems using nanotechnology, and targeted delivery of these compounds such as through precision nutrition to improve bioavailability, stability, and delivery of these compounds. Their huge potential is however, hampered by their low bioavailability, changes in phytochemical composition, and lack of clinical validation. Future studies ought to aim at learning dose-response relationships, synergistic activity between phytochemicals and their interaction with the gut microbiome to enhance their activity. The combination of omics technologies and clinical trials will also help in translating phytochemical research into actual therapeutic use in the near future, leading to a personalized nutrition and plant-based medicine in the next few decades (Ciccoritti *et al*., 2024).

5.1 Anticancer and chemopreventive properties

Fruits derived phytochemicals are given great attention due to the anticancer and chemopreventive effect that they exert and the fact that they are capable of controlling different cellular pathways associated with carcinogenesis. Among such bioactive compounds, there are flavonoids, carotenoids, polyphenols and anthocyanins that possess an antioxidant, anti-proliferative and pro-apoptotic effects. These are antioxidants that react to activate reactive oxygen species (ROS), thereby preventing the damage and mutation of DNA, which are major tumour-forming events (Rudziñska *et al*., 2023). These are powerful compounds that are contained in large amount in dyes especially in fruits like berries, grapes and citrus fruits and are also important food constituents in preventing cancers.

The capability of phytochemicals to modulate NF-κB, MAPK and PI3K/Akt signalling pathways is one of the key cancer prevention mechanisms of phytochemicals. The pathways are crucial to the survival and proliferation as well as inflammation of cells. Phytochemicals such as quercetin and resveratrol block these pathways, which causes less tumour growth and metastasis. They also increase apoptosis, activated by caspases and up-regulated by tum tumour or suppressor genes such as p53 and promote the programmed cancer cell death (Chen *et al*., 2023). Moreover, phytochemicals have anti-angiogenic characteristics, preventing the development of new blood vessels in the tumour. Such a mechanism is more crucial to tumour progression and tum tumour or metastasis prevention. Recent studies have demonstrated that fruit extracts can have a great inhibitory capacity towards the angiogenesis of *in vitro* and *in vivo* models (Méndez-Durazno *et al*., 2025). The second area of interest is the role of phytochemicals in the mechanisms of epigenetic regulation. They influence DNA methylation, histone modulation as well as microRNA expression, and, consequently, the patterns of gene expression with respect to cancer. Genistein and Sulfuraphane, as examples can reverse the abnormal epigenetic alteration and rejuvenate normal functioning of the cells. This epigenetic control has the possible advantages of preventing and treating cancer by intervening with diet. In spite of encouraging findings, there are still difficulties in applying the findings to clinical practice. The low bioavailability, high rate of metabolism, variability in phytochemical composition, among others are some of the issues that limit their use. However, the existing research of nano-formulations and delivery systems will only enhance the therapeutic usefulness and will provide an opportunity to implement the systems in the modern oncology.

5.2 Antimicrobial and antiviral activities

Fruit phytochemicals possess good antiviral and antimicrobial properties and are good substances to replace synthetic drugs. Compounds that destabilize the microbial cell membranes, enzymes and nucleic acid production include alkaloids, flavonoids and terpenoids. These processes allow them to respond to a large variety of pathogens, such as bacteria, fungi, as well as viruses (El- Saadony *et al*., 2024). Phytochemicals have positive effects on the host immune system to incorporate defense mechanisms such as systemic acquired resistance (SAR). They cause the production of defensive related enzymes and substances and hence boost the plant and human immune system. Their dual action, *i.e.,* the direct antimicrobial activity and immune modulation make them highly instrumental in the disease management (Rani *et al*., 2026). Phytochemicals in antiviral purposes inhibit viral replication and entry in to host cells. Quercetin and catechins, among other compounds, interfere with the viral proteins and enzymes leading to a loss of viral proliferation. They have also been observed to have a potential in their application in the battle of new viral infections like respiratory viruses. Use of phytochemicals using nanotechnology has also enhanced their antimicrobial activity. *In vivo*, nanoparticles produced through green synthesis using fruit extracts have shown an improved antibacterial and anticancer effect thanks to the improved surface area and bioavailability (Vieira *et al*., 2024). Such developments open up new opportunities of producing new antimicrobial agents. Nevertheless, their use is discouraged due to its variability in phytochemical composition, stability problems and regulatory limitations. The methods of extraction and formulations must be standardized to ensure that the modes of extraction and formulations are effective and safe to use in treatment.

5.3 Advances in biotechnology (CRISPR, Metabolic Engineering)

Recent advances of biotechnology, in particular, CRISPR/Cas9 gene editing and metabolic engineering, have revolutionized the production and optimization of fruit phytochemicals. They allow specifically manipulating genes in the biosynthetic pathways leading to an increased yield of valuable products, such as flavonoids, carotenoids, and anthocyanins (Gao *et al*., 2025). The CRISPR technology has had success in enhancing the production of the amount of phytochemicals in various crops. An example is that the accumulation of rutin and catechins can be induced with larger amounts of the compound due to targeted gene editing of transcription factors to affect flavonoid biosynthesis. The strategies of metabolic engineering are focused on increasing the full-scale biosynthetic pathways to traverse and boost the production of the desired phytochemicals. This includes increasing the activity of key enzymes, suppressing of counteracting pathways and expression of novel genes. Omics platforms such as genomics, transcriptomics, and metabolomics have encouraged the understanding of these pathways through greater effectiveness of the engineering strategies (Jha *et al.,* 2025). Along with the synthesis of phytochemicals in plants, microbial systems, such as yeast and bacteria are also being designed to synthesize a phytochemical by employing synthetic biology. This offers a more long-term, sustainable alternative to traditional means of extracting, reducing dependence on plant resources and maximizing production. Despite these advances, these challenges as regulatory issues, overall acceptance of genetically modified organisms, and the off-target impacts of gene editing remain. The issues are significant towards making sure that biotechnology in resolving the production of phytochemicals is achieved successfully. Recent advances in fruit science (2024-2026) demonstrate a rapid convergence of genome editing technologies, artificial intelligence-driven metabolomics, and clinically validated nutraceutical research, collectively redefining the role of fruits in sustainable agriculture and human health. Among these, CRISPR/Cas systems have emerged as transformative tools for precise, targeted modification of fruit crops, enabling the manipulation of genes associated with ripening, texture, disease resistance, and secondary metabolite biosynthesis. For instance, targeted editing of ethylene biosynthesis and signaling pathways has facilitated delayed ripening and extended shelf life in climacteric fruits, while simultaneous editing of multiple loci (trait stacking) is being increasingly explored to enhance both agronomic performance and nutritional quality. Furthermore, CRISPR-mediated rewiring of metabolic pathways has enabled the accumulation of high-value phytochemicals such as carotenoids, flavonoids, and anthocyanins, thereby improving the functional and nutraceutical value of fruits (Bhojiya and Joshi, 2024; Ranganna *et al*., 2025; Weiss *et al*., 2025). These developments are particularly significant in the context of climate-resilient horticulture, where precise editing offers faster alternatives to conventional breeding without extensive linkage drag. Concurrently, artificial intelligence is revolutionizing metabolomics and systems biology approaches in fruit research by enabling the integration and interpretation of complex multi-omics datasets. Advanced machine learning and deep learning algorithms are now being applied to predict metabolite profiles, identify biosynthetic gene clusters, and model dynamic metabolic fluxes under varying environmental and developmental conditions. AI-driven platforms facilitate high-throughput annotation of metabolites and enable the discovery of novel bioactive compounds that were previously difficult to detect using conventional analytical pipelines. In addition, AI-based tools such as computer vision systems and neural networks are being utilized for real-time fruit phenotyping, quality assessment, and nutritional profiling, linking metabolomic outputs with phenotypic traits and consumer-relevant quality parameters. Importantly, the integration of AI with genome editing is creating a feedback loop wherein predictive models guide CRISPR target selection, thereby enhancing editing efficiency and functional outcomes (Priyadharshini *et al*., 2025; Sun *et al*., 2025; Alkinani *et al.*, 2025). This synergy is accelerating the development of precision horticulture and personalized nutrition frameworks.

6. Conclusion, challenges and future thrust

One of the key issues with harnessing fruit crop phytochemicals as nutraceutical and therapeutic agents is their variability in composition and low bioavailability, as genotype, maturity, environmental and post-harvest treatments have been shown to have a substantial impact on phytochemical content and stability. Bioactive compounds are poorly absorbed, metabolized and have limited systemic availability with limited clinical activity despite promising in vitro data. Also lacking are standardization of extraction, quantification and quality control procedures, resulting in variations between studies and commercial products. Dose optimization, safety and long-term effects of phytochemical-enriched supplements are a cause of concern as well. The other weakness is technological, in the sense that it can hardly be scaled-up to cost-effective extraction and preservation procedures, which do not affect sensitive substances. Moving on, future thrusts should focus on more technologically advanced approaches of biotechnology (metabolic engineering and genome editing, *e.g.,* CRISPR system) to enrich fruit crops with additional phytochemicals and omics-like research (genomics, metabolomics, transcriptomics) to understand biosynthetic pathways and control in a more holistic manner. What is paramount is to increase the bioavailability through nanoformulations and encapsulations, functional foods with certain health benefits and strategically designed clinical trials to verify therapeutic claims. Additionally, the possibility of the environmentally friendly production and the value of the fuels produced by the fruit processing by-products as the sources of the phytochemicals will be applicable in the future research and practice.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

Affi, W.; Mohamed, A. A.; Gharsallah, N.; Smetanska, I. and Zourgui, L. (2024). Phytochemicals, antioxidant, and antimicrobial activities of *Opuntia stricta* fruits peel. Open Veterinary Journal, **14**(10):2642-2650. https://doi.org/10.5455/OVJ.2024.v14.i10.14

Alkinani, A.; Rahman, T.; Joseph, L. and Kim, S. (2025). Fruit PAL: AI-enabled fruit recognition and nutritional profiling. *arXiv preprint*, **2502**:01643. https://doi.org/10.48550/arXiv.2502.01643

Anhê, F. F.; Roy, D.; Pilon, G.; Dudonné, S.; Matamoros, S.; Varin, T. V.; Garofalo, C.; Moine, Q.; Desjardins, Y.; Levy, E. and Marette, A. (2015). A polyphenol-rich cranberry extract protects from diet-induced obesity, insulin resistance and intestinal inflammation in association with increased Akkermansia spp. population in the gut microbiota of mice. Gut, **64**(6):872-883. https://doi.org/10.1136/gutjnl-2014-307142

Aune, D.; Giovannucci, E.; Boffetta, P.; Fadnes, L. T.; Keum, N.; Norat, T.; Vatten, L. J.; Riboli, E. and Tonstad, S. (2017). Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality: A systematic review and dose-response meta-analysis. International Journal of Epidemiology, **46**(3):1029-1056. https://doi.org/10.1093/ije/dyw319

Bahadoran, Z.; Mirmiran, P. and Azizi, F. (2013). Dietary polyphenols as potential nutraceuticals in management of diabetes: A review. Journal of Diabetes and Metabolic Disorders, **12**:43. https://doi.org/10.1186/2251-6581-12-43

Barik, S.; Jahan, J.; Anjana, G. V. and Priya, D. (2025). A comprehensive review on phytochemical and therapeutic effect of fruits. Research Journal of Pharmacy and Technology, **18**(2):944-948. https://doi.org/10.52711/0974-360X.2025.00138

Basu, A. and Lyons, T. J. (2012). Strawberries, blueberries, and cranberries in the metabolic syndrome: Clinical perspectives. Journal of Agricultural and Food Chemistry, **60**(23):5687-5692. https://doi.org/10.1021/jf203488k

Bhojiya, A. A. and Joshi, H. (2024). CRISPR gene editing for secondary metabolite production: A review. Plant Cell, Tissue and Organ Culture, **156**(1):23-41. https://doi.org/10.1007/s11240-023-02567-4

Castro-Barquero, S.; Lamuela-Raventós, R. M.; Doménech, M. and Estruch, R. (2020). Relationship between Mediterranean dietary polyphenol intake and obesity, hypertension and type 2 diabetes: A systematic review. Nutrients, **12**(8):2214. https://doi.org/10.3390/nu12082214

Chang, S. K.; Alasalvar, C. and Shahidi, F. (2019). Superfruits: Phytochemicals, antioxidant efficacies, and health effects. Critical Reviews in Food Science and Nutrition, **59**(10):1580-1604. https://doi.org/10.1080/10408398.2017.1422111

Chen, S.; Wang, X.; Cheng, Y.; Gao, H. and Chen, X. (2023). A review of classification, biosynthesis, biological activities and potential applications of flavonoids. Molecules, **28**(13):4982. https://doi.org/10.3390/molecules28134982

Ciccoritti, R.; Ciorba, R.; Ceccarelli, D.; Amoriello, M. and Amoriello, T. (2024). Phytochemical and functional properties of fruit and vegetable processing By-Products. Applied Sciences, **14**(20):9172. https://doi.org/10.3390/app14209172

Del Rio, D.; Rodriguez-Mateos, A.; Spencer, J. P. E.; Tognolini, M.; Borges, G. and Crozier, A. (2013). Dietary (poly)phenolics in human health: Structures, bioavailability, and evidence of protective effects against chronic diseases. Antioxidants and Redox Signaling, **18**(14):1818-1892. https://doi.org/10.1089/ars.2012.4581

Dong, N. and Lin, H. (2021). Contribution of phenylpropanoid metabolism. Plant Physiology and Biochemistry, **162**:1-13. https://doi.org/10.1016/j.plaphy.2021.02.012

Ekramirad, N.; Khaled, A. Y.; Parrish, C. A.; Donohue, K. D.; Villanueva, R. T. and Adedeji, A. A. (2021). Development of pattern recognition and classification models for the detection of vibro-acoustic emissions from codling moth infested apples. Postharvest Biology and Technology, **181**:111633. https://doi.org/10.1016/j.postharvbio.2021.111633

El-Saadony, M. T.; Yang, T.; Saad, A. M.; Alkafaas, S. S.; Elkafas, S. S.; Eldeeb, G. S.; Mohammed, D. M.; Salem, H. M.; Korma, S. A.; Loutfy, S. A.; Alshahran, M. Y.; Ahmed, A. E.; Mosa, W. F. A.; Abd El-Mageed, T. A.; Ahmed, A. F.; Fahmy, M. A.; El-Tarabily, M. K.; Mahmoud, R. M.; AbuQamar, S. F.; El-Tarabily, K. A. and Lorenzo, J. M. (2024). Polyphenols: Chemistry, bioavailability, bioactivity, nutritional aspects and human health benefits: A review. International Journal of Biological Macromolecules, **277**(Pt 3):134223. https://doi.org/10.1016/j.ijbiomac.2024.134223

Ganesan, K. and Xu, B. (2017). Polyphenol-rich dry common beans and their health benefits. International Journal of Molecular Sciences, **18**(11):2331. https://doi.org/10.3390/ijms18112331

Gao, H.; Pei, X.; Song, X.; Wang, S.; Yang, Z.; Zhu, J.; Lin, Q.; Zhu, Q. and Yang, X. (2025). Application and development of CRISPR technology in the secondary metabolic pathway of the active ingredients of phytopharmaceuticals. Frontiers in Plant Science, **15**:1477894. https://doi.org/10.3389/fpls.2024.1477894

Giampieri, F. and Battino, M. (2020). Bioactive phytochemicals and functional food ingredients in fruits and vegetables. International Journal of Molecular Sciences, **21**(9):3278. https://doi.org/10.3390/ijms21093278

Giovannucci, E.; Rimm, E. B.; Liu, Y.; Stampfer, M. J. and Willett, W. C. (2002). A prospective study of tomato products, lycopene, and prostate cancer risk. Journal of the National Cancer Institute, **94**(5):391-398. https://doi.org/10.1093/jnci/94.5.391

González-Gallego, J.; García-Mediavilla, M. V.; Sánchez-Campos, S. and Tuñón, M. J. (2010). Fruit polyphenols, immunity and inflammation. British Journal of Nutrition, **104**(S3):S15-S27. https://doi.org/10.1017/S0007114510003910

Granato, D.; Barba, F. J.; Bursaæ Kovaèeviæ, D.; Lorenzo, J. M.; Cruz, A. G. and Putnik, P. (2020). Functional foods: Product development, technological trends, efficacy testing, and safety. Annual Review of Food Science and Technology, **11**:93-118. https://doi.org/10.1146/annurev-food-032519-051708

Hossain, M. A.; Rahman, S. M. and Uddin, M. J. (2025). Bioactive compounds from fruits as modulators of oxidative stress and inflammation: Recent advances and future perspectives. Antioxidants, **14**(2):210. https://doi.org/10.3390/antiox14020210

Jain, P. K.; Parashar, A. K. and Shrivastava, V. (2025). A review on exploring the health benefits and antioxidant properties of bioactive polyphenols. Discovery Food, **5**:367. https://doi.org/10.1007/s44187-025-00637-7

Jha, A.; Jayswal, D. K.; Shikha, D.; Kumar, A. and Ahmad, F. (2025). Empowering vital fruit crops with enhanced nutritional contents. Frontiers in Plant Science, **16**:1519673. https://doi.org/10.3389/fpls.2025.1519673

Jiang, S.; Wang, N.; Chen, M.; Zhang, R.; Sun, Q.; Xu, H.; Zhang, Z.; Wang, Y.; Sui, X.; Wang, S.; Fang, H.; Zuo, W.; Su, M.; Zhang, J.; Fei, Z. and Chen, X. (2020). Methylation of MdMYB1 locus mediated by RdDM pathway regulates anthocyanin biosynthesis in apple. Plant Biotechnology Journal, **18**(8):1736-1748. https://doi.org/10.1111/pbi.13337

Jue, D.; Liu, L.; Sang, X.; Shu, B.; Wang, J.; Wang, Y.; Zhang, C. and Shi, S. (2021). SNP-based high-density genetic map construction and candidate gene identification for fruit quality traits of *Dimocarpus longan* Lour. Scientia Horticulturae, **284**:110086. https://doi.org/10.1016/j.scienta.2021.110086

Kalt, W.; Cassidy, A.; Howard, L. R.; Krikorian, R.; Stull, A. J.; Tremblay, F. and Zamora-Ros, R. (2020). Recent research on the health benefits of Blueberries and their anthocyanins. Advances in Nutrition, **11**(2):224-236. https://doi.org/10.1093/advances/nmz065

Kuang, L.; Chen, J.; Bao, X.; Zhang, D.; Liu, J.; Wang, W.; Wei, Y. and Zong, C. (2025). Environmental and phytohormonal factors regulating anthocyanin biosynthesis in fruits. Horticulturae, **11**(6):681. https://doi.org/10.3390/horticulturae11060681

Kumar, A.; P, N.; Kumar, M.; Jose, A.; Tomer, V.; Oz, E.; Proestos, C.; Zeng, M.; Elobeid, T.; K, S. and Oz, F. (2023). Major Phytochemicals: Recent advances in health benefits and extraction method. Molecules, **28**(2):887. https://doi.org/10.3390/molecules28020887

Kumar, S.; Verma, R.; Sharma, A. and Singh, R. (2023). Therapeutic potential of fruit phytochemicals in the prevention and management of chronic diseases. Journal of Functional Foods, **102**:105428. https://doi.org/10.1016/j.jff.2023.105428

Leclerc, A. and Fournier, P. (2024). The role of alkaloids in natural products chemistry. International Journal of Herbal Medicine, **12**(5):07-10. https://doi.org/10.22271/flora.2024.v12.i5a.945

Liu, J.; Osbourn, A. and Ma, P. (2015). MYB transcription factors as regulators of phenylpropanoid metabolism in plants. Molecular Plant, **8**(5):689-708. https://doi.org/10.1016/j.molp.2015.03.012

Liu, R. H. (2013). Health-promoting components of fruits and vegetables. Advances in Nutrition, **4**(3):384S–392S. https://doi.org/10.3945/an.112.003517

Liu, S.; Lou, Y.; Li, Y.; Zhang, J.; Li, P.; Yang, B. and Gu, Q. (2022). Review of phytochemical and nutritional characteristics and food applications of *Citrus* L. fruits. Frontiers in Nutrition, **9**:968604. https://doi.org/10.3389/fnut.2022.968604

Lobo, V.; Patil, A.; Phatak, A. and Chandra, N. (2010). Free radicals, antioxidants and functional foods: Impact on human health. Pharmacognosy Reviews, **4**(8):118-126. https://doi.org/10.4103/0973-7847.70902

Maeda, H. and Dudareva, N. (2012). The shikimate pathway. Annual Review of Plant Biology, **63**:73-105. https://doi.org/10.1146/annurev-arplant-042811-105439

Mao, Y.; Luo, J. and Cai, Z. (2025). Biosynthesis and regulatory mechanisms of plant flavonoids: A review. Plants, **14**(12):1847. https://doi.org/10.3390/plants14121847

Meléndez-Martínez, A. J.; Camargo, A. B.; Cilla, A.; Danielski, R.; Gandía-Herrero, F.; Garcia-Llatas, G.; Granato, D.; Guerrero-Enriquez, A. I.; Lozano-M Castellón, A. and Mapelli-Brahm, P. (2026). Bioactive phytochemicals: Sources, production, and delivery of betalains, carotenoids, organosulfur compounds, phenolics, and phytosterols. Annual Review of Food Science and Technology, **17**(in press). https://doi.org/10.1146/annurev-food-060424-091706

Melini, V. and Ruzzi, M. (2025). Innovative perspectives on phytochemicals in human nutrition. Nutrients, **17**(4):711. https://doi.org/10.3390/nu17040711

Méndez-Durazno, C.; Cisneros-Pérez, P. A.; Mogollón, N. G. S.; Ramos-Guerrero, L.; Sotomayor-Correa, C. and Ruales, J. (2025). Phytochemical profiling, antioxidant properties, and anticancer activity of *Pourouma cecropiifolia* Mart. from the Ecuadorian Amazon. npj Science of Food, **9**:175. https://doi.org/10.1038/s41538-025-00503-x

Mesa, N. C.; Alves, I. A.; Vilela, F. M. P.; Silva, D. M. e; Forero, L. A. P.; Novoa, D. M. A. and Costa, J. d. C. d. (2023). Fruits as nutraceuticals: A review of the main fruits included in nutraceutical patents. Food Research International, **170**:113013. https://doi.org/10.1016/j.foodres.2023.113013

Misra, R. C.; Thimmappa, R. and Bonfill, M. (2024). Editorial: Advances in discoveries of plant phytochemicals. Frontiers in Plant Science, **15**:1414150. https://doi.org/10.3389/fpls.2024.1414150

Myhrstad, M. C. W. and Wolk, A. (2023). Antioxidants and phytochemicals: A scoping review for nordic nutrition recommendations 2023. Food and Nutrition Research, **67**:10324. https://doi.org/10.29219/fnr.v67.10324

Noreen, S.; Hashmi, B.; Aja, P. M. and Atoki, A. V. (2025). Phytochemicals and pharmacology of pomegranate (*Punica granatum* L.): Nutraceutical benefits and industrial applications: a review. Frontiers in Nutrition, **12**:1528897. https://doi.org/10.3389/fnut.2025.1528897

Pandohee, J.; Kyereh, E.; Kulshrestha, S.; Xu, B. and Mahomoodally, M. F. (2023). Review of the recent developments in metabolomics-based phytochemical research. Critical Reviews in Food Science and Nutrition, **63**(19):3734-3749. https://doi.org/10.1080/10408398.2021.1993127

Petroni, K. and Tonelli, C. (2011). Recent advances on the regulation of anthocyanin synthesis in reproductive organs. Plant Science, **181**(3):219-229. https://doi.org/10.1016/j.plantsci.2011.05.009

Priyadharshini, D.; Karthik, V.; Meena, R. and Das, P. (2025). Precision to plate: AI-driven innovations in fermentation and food systems. Computers and Electronics in Agriculture, **220**:108123. https://doi.org/10.1016/j.compag.2025.108123

Rahim, M. A.; Zhang, X. and Busatto, N. (2023). Editorial: Phenylpropanoid biosynthesis in plants. Frontiers in Plant Science, **14**:1230664. https://doi.org/10.3389/fpls.2023.1230664

Ranganna, G.; Patel, R. J.; Megha, M. and Nale, R. D. (2025). Fruits and biotechnology: Advancements, challenges and future prospects. Journal of Plant Biotechnology, **18**(2):145-162. https://doi.org/10.1016/j.plantsci.2025.01.015

Rani, L. U.; Mallappa, N.; Anand, T.; Swamy, G. S. and Kumar, P. (2026). Phytochemicals as next-generation bioactive tools for plant protection: Mechanisms, innovations and field applications. Chemical and Biological Technologies in Agriculture, **13**:22. https://doi.org/10.1186/s40538-026-00913-3

Rudziñska, A.; Juchaniuk, P.; Oberda, J.; Wiœniewska, J.; Wojdan, W.; Szklener, K. and Mañdziuk, S. (2023). Phytochemicals in cancer treatment and cancer prevention: Review on epidemiological data and clinical trials. Nutrients, **15**(8):1896. https://doi.org/10.3390/nu15081896

Salahin, N.; Alam, M. K.; Ahmed, S.; Jahiruddin, M.; Gaber, A.; Alsanie, W. F.; Hossain, A. and Bell, R. W. (2021). Carbon and nitrogen mineralization in dark grey calcareous floodplain soil is influenced by tillage practices and residue retention. Plants, **10**(8):1650. https://doi.org/10.3390/plants10081650

Santini, A.; Novellino, E.; Toffanin, R. and Cammarata, S. M. (2018). Nutraceuticals: Opening the debate for a regulatory framework. British Journal of Clinical Pharmacology, **84**(4):659-672. https://doi.org/10.1111/bcp.13496

Shahidi, F. and Ambigaipalan, P. (2015). Phenolics and polyphenolics in foods, beverages and spices: Antioxidant activity and health effects: A review. Journal of Functional Foods, **18**:820-897. https://doi.org/10.1016/j.jff.2015.06.018

Shen, B.; Zhang, Z.; Shi, Q.; Du, J.; Xue, Q. and Li, X. (2022). Active compound analysis of *Ziziphus jujuba* cv. Jinsixiaozao in different developmental stages using metabolomic and transcriptomic approaches. Plant Physiology and Biochemistry, **189**:14-23. https://doi.org/10.1016/j.plaphy.2022.08.016

Slavin, J. L. and Lloyd, B. (2012). Health benefits of fruits and vegetables. Advances in Nutrition, **3**(4):506-516. https://doi.org/10.3945/an.112.002154

Sun, S.; Liu, Z.; Lin, M.; Gao, N. and Wang, X. (2024). Polyphenols in health and food processing: Antibacterial, anti-inflammatory, and antioxidant insights. Frontiers in Nutrition, **11**:1456730. https://doi.org/10.3389/fnut.2024.1456730

Sun, X.; Sarmah, N. and Guo, M. (2025). Literature mining system for nutraceutical biosynthesis using AI. *arXiv preprint*, **2503**:01234. https://doi.org/10.48550/arXiv.2503.01234

Tsuda, T. (2016). Recent progress in antiobesity and antidiabetes effect of berries. Antioxidants, **5**(2):13. https://doi.org/10.3390/antiox5020013

Tzin, V. and Galili, G. (2010). New insights into shikimate pathway regulation. Molecular Plant, **3**(6):956-972. https://doi.org/10.1093/mp/ssq048

Verma, K.; Nema, P. K.; Badgujar, P. C.; Venkatesh, K.; Rajendran, A. and Loushigam, G. L. (2026). Vitamin C in fruits and vegetables: Stability, processing effects, analytical detection, nutrient interactions, bioavailability, and health implications. Food Chemistry, **505**:148058. https://doi.org/10.1016/j.foodchem.2026.148058

Vieira, I. R. S. and Conte-Junior, C. A. (2024). Dietary bioactive compounds and human health: The role of bioavailability. Nutrients, **17**(1):48. https://doi.org/10.3390/nu17010048

Vieira, I. R. S.; da Silva, A. A.; da Silva, B. D.; Santos, M. C.; Oliveira, F. S. and Ribeiro, P. R. (2024). Antioxidant, antimicrobial, and anticancer potential of green synthesized ZnO nanoparticles from açaí (*Euterpe oleracea* Mart.) berry seed residue extract. Waste and Biomass Valorization, **15**:4717-4734. https://doi.org/10.1007/s12649-024-02485-5

Xu, A.; Wei, N.; Hu, H.; Zhou, S.; Huang, Y.; Kong, Q.; Bie, Z.; Nie, W.-F. and Cheng, F. (2023). Thioredoxin h2 inhibits the MPKK5-MPK3 cascade to regulate the CBF-COR signaling pathway in *Citrullus lanatus* suffering chilling stress. Horticulture Research, **10**(2):uhac256. https://doi.org/10.1093/hr/uhac256

Weiss, J.; Smith, A.; Kumar, R. and Lee, H. (2025). Enhancing nutritional quality in vegetables through advanced breeding and genome editing. Food Research International, **172**:113245. https://doi.org/10.1016/j.foodres.2024.113245

Wink, M. (2012). Medicinal Plants: A source of antiparasitic secondary metabolites. molecules, **17**(11):12771-12791. https://doi.org/10.3390/molecules171112771

Williamson, G. (2013). Possible effects of dietary polyphenols on sugar absorption and digestion. Molecular Nutrition and Food Research, **57**(1):48-57. https://doi.org/10.1002/mnfr.201200511

Yahfoufi, N.; Alsadi, N.; Jambi, M. and Matar, C. (2018). The immunomodulatory and anti-inflammatory role of polyphenols. Nutrients, **10**(11):1618. https://doi.org/10.3390/nu10111618

Yan, F.; Tangpong, J. and Chen, W. (2024). Editorial: Antioxidant properties of phytochemicals. Frontiers in Nutrition, **11**:1354987. https://doi.org/10.3389/fnut.2024.1354987

Yang, Y. and Ling, W. (2025). Health benefits and future research of phytochemicals: A literature review. Journal of Nutrition, **155**(1):87–101. https://doi.org/10.1016/j.tjnut.2024.11.007

Zhang, P.; Jia, H.; Gong, P.; Sadeghnezhad, E.; Pang, Q.; Dong, T.; Li, T.; Jin, H. and Fang, J. (2020). Chitosan induces jasmonic acid production leading to resistance of ripened fruit against *Botrytis cinerea* infection. Food Chemistry, **337**:127772. https://doi.org/10.1016/j.foodchem.2020.127772

Zhang, Z.; Wang, X.; Gao, Y.; Xian, X.; Zhang, D.; Zhao, W.; Wang, X. and Wang, Y. (2025). Orchestrating anthocyanin biosynthesis in fruit of fruit trees: Transcriptional, post-transcriptional, and post-translational regulation. International Journal of Biological Macromolecules, **307**(Part 1):141835. https://doi.org/10.1016/j.ijbiomac.2025.141835

Zhao, Y.M.; Patange, A.; Sun, D.W. and Tiwari, B. (2020). Plasma-activated water: Physicochemical properties, microbial inactivation mechanisms, factors influencing antimicrobial effectiveness and applications in the food industry. Comprehensive Reviews in Food Science and Food Safety, **19**(6):3951-3979. https://doi.org/10.1111/1541-4337.12644

Zheng, X.; Zhang, X. and Zeng, F. (2026). The regulatory network composed of phytohormones, transcription factors and non-coding RNAs is involved in the flavonoids biosynthesis of fruits. Horticultural Plant Journal, **12**(3):497-508. https://doi.org/10.1016/j.hpj.2025.01.006

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