Fruit Skin Color: A Reliable Tool Revealing the Potential of Bioactive Compounds in Apricots (Prunus armeniaca L.)

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REVIEW

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ABSTRACT

This review examines the key bioactive compounds contributing to the coloration of apricot fruits, notably anthocyanins, flavonoids, carotenoids, and other phytochemicals. These compounds not only impart color but also offer antioxidant properties, anti-inflammatory activity, and disease prevention. It highlights the evolution of skin pigmentation through research into pigment biosynthesis and its regulatory mechanisms. Additionally, various methods for assessing fruit skin color and its correlation with bioactive compound accumulation are discussed. The review identifies genetic factors, environmental conditions, agricultural practices, and post-harvest management as critical influences on the content and efficacy of these compounds. Health benefits associated with apricot pigments, including combating oxidative stress and reducing inflammation, are emphasized, underscoring their potential as natural colorants and functional food ingredients. The correlation between apricot skin color, bioactive compound content, and health benefits is highlighted, suggesting that skin color can serve as a valuable indicator for fruit quality and marketing strategies. The article integrates specific colorimetric traits, pigment biosynthesis, and variability across cultivars and environments, positioning skin color as a predictive measure for bioactive composition. It also identifies research gaps and provides directions for breeding, post-harvest practices, and functional food innovations.

1 | Introduction

The fruit skin color is a crucial indicator of quality or ripeness for sale, taste, and nutritional quality, while pigment is a central visual feature. Apricots (*Prunus armeniaca* L.) are one of the most common species of the stone (drupaceous) fruits, and their skin color is the most abundant, as it varies significantly from pale yellow, red to dark orange. The color differences are attributed to the varying composition of bioactive compounds, such as phenolic compounds, carotenoids, and flavonoids. These pigments determine the color of the fruit but contribute much to the health-supporting properties by their antioxidant, anti-inflammatory, and disease-preventing action [1, 2].

Interest in the biochemical basis of fruit skin coloration has increased in recent years. The nature of the pigments present in fruit skins makes them a non-invasive marker for determining the phytochemical profile of fruits, hence their application in agricultural and nutritional research. In this respect, this is all the more important because the compounds responsible for such coloring, especially in apricots, have a host of health benefits. For example, carotenoids, among which is beta-carotene, highly contribute to antioxidant protection, while anthocyanins contribute anti-inflammatory effects [3]. Advances in the analytical technique and mass spectrometry methods have greatly improved the capability to isolate and quantify these bioactive compounds in apricot. These technologies enabled researchers not only to identify the pigments but also to investigate their interactions, stability, and bioavailability within the fruit [4].

Such diversity in the pigmentation pattern of apricot cultivars might be due to the complex interaction between genetic background, environmental conditions, and agricultural practices. Many studies have focused on the genetic control of pigment biosynthesis, determining the main genes and transcription factors responsible for the accumulation of pigments in apricot skin. For example, MYB family transcription factors were found to be involved in anthocyanin biosynthesis regulation in apricots [5]. Environmental factors, such as light exposition and temperature, modulate the pigment content. Generally, higher light intensity and cooler temperatures increased the concentration of anthocyanins and carotenoids in apricot skins [6]. Moreover, agricultural methods, such as selection and nutrition factor management, could be further optimized to improve the pigment content for new biofortification perspectives for apricots [7].

The review aims to update the state of the art on the bioactive compounds responsible for skin coloration in apricot, the molecular mechanisms governing pigment biosynthesis, and health benefits associated with these compounds. The understanding of biochemical pathways that control pigment production in apricots allows a deep view into how these fruits can be cultivated to maximize their nutritional value. In this work, the authors review how diverse agricultural and environmental practices could influence the accumulation of bioactive compounds in apricot skin, with special emphasis on improving fruit quality and enhancing the health benefits associated with apricot consumption. The outcome of this study has very important implications for the food, nutraceutical, and healthcare industries, where apricot pigments could be used in functional foods, supplements, and as natural colorants in various products [8, 9].

Although the relationship between fruit coloration and phytochemical composition has been described in various fruit species, no comprehensive synthesis has yet examined this relationship specifically in apricots. Existing studies are fragmented, often cultivar-specific, and rarely integrate genetic, environmental, physiological, and health-related dimensions. Therefore, the present review aims to fill this gap by providing a critical and integrative examination of apricot skin color in relation to pigment composition, antioxidant activity, and potential health relevance. To our knowledge, this is the first review to combine biochemical, agronomic, molecular, and functional perspectives to understand how apricot skin color can serve as a practical and reliable indicator of bioactive compound richness.

2 | Key Bioactive Compounds in Colorful Apricot Fruits

2.1 | Anthocyanins and Flavonoids

Anthocyanins are water-soluble pigments responsible for the red, blue, and purple colors of apricots, contributing much to its appearance and health value. The biosynthesis of anthocyanins proceeds via the phenylpropanoid pathway, involving enzymes such as chalcone synthase (CHS) and anthocyanidin synthase (ANS), which determine the intensity of the pigment. Cyanidin-3-glucoside and cyanidin-3-rutinoside are major anthocyanins identified in apricots, whose contents depend on genetic and environmental factors [10, 11]. In this fact, it has been attributed to antioxidant properties of polyphenols due to its hydrogen-atom or electron-donating nature to neutralize reactive oxygen species (ROS) and thereby protect cellular components against oxidative stress.

Quercetin, kaempferol, and their glycoside derivatives are some examples of flavonoids that make anthocyanins more stable and bioactive [12]. These interact with anthocyanins to enhance the overall antioxidant capabilities of the fruit synergistically. Flavonoids also contribute to the UV protection of apricots by their absorption of UV light that reduces the light-induced stress, important for the quality of fruits in its growth and postharvest handling [12]. Knowledge of such mechanisms allows the understanding of breeding and cultivation strategies oriented at anthocyanin and flavonoid content optimization for both aesthetic and health-promoting purposes. In a recent work, we reported this strong correlation between polyphenols and apricot skin color in relation to antioxidant activity [11] (Figure 1). The work reported that among studied genotype, apricot clones characterized by red and orange skin had significant phenolic contents and higher antioxidant activities than light apricots. This indicates the importance of fruit color to predict apricot bioactive compounds and the crucial role of phenolic compounds in the antioxidant activity of these fruits. However, ripening impact on antioxidant activity was very limited compared to the genotype effect, especially skin color. Therefore, the choice of genotype is a decisive factor in the nutritional and functional quality of apricot [11].

2.2 | Carotenoids

Carotenoids are responsible for yellow to orange skin coloration in apricot. Among them, beta-carotene and lutein prevail and are precursors of vitamin A, thus highly valuable for vision. The biosynthesis of carotenoids is strongly affected by environmental factors. For example, it has been reported that with the rise in temperature, an increase in the content of beta-carotene was observed, while continuous sunshine increased the accumulation of carotenoids in general. Carotenoid content is also affected by agricultural practices, such as nutrient management and irrigation. Application of potassium fertilizers, for example, increases carotenoid concentrations. More recently, postharvest handling has been recognized as playing an important role, with cold storage being one of the means to ensure stability of carotenoids and hence better retention of these bioactive compounds [13]. Besides their function in coloring, carotenoids exhibit antioxidant and anti-inflammatory activities and hence are of utmost importance in disease prevention. The major carotenoids, beta-carotene and lutein are precursors to vitamin A and promote eye health. In addition to their skin and eye health properties all carotenoids have antioxidant and anti-inflammatory properties and support disease prevention [14].

2.3 | Other Phytochemicals

In apricot skin, a wide array of phytochemicals is found apart from the two major groups of pigments, namely carotenoids and

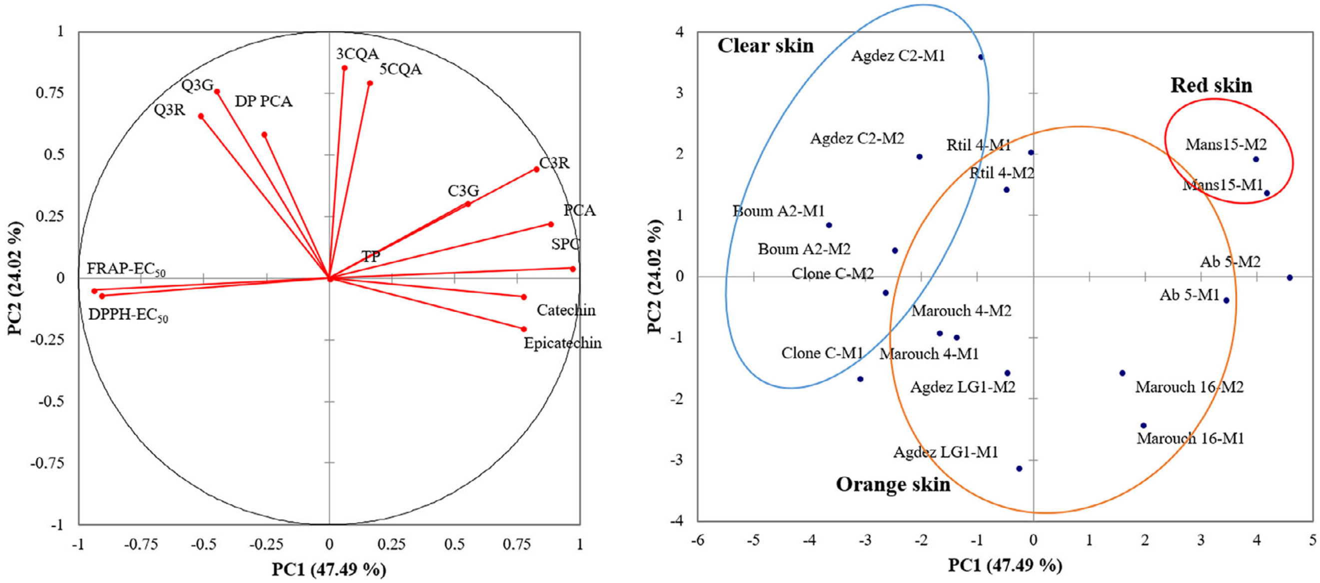

FIGURE 1 | Principal component analysis of polyphenol and antioxidant variables of 10 apricot clones at commercial (M1) and consumption (M2) stages. TP: total phenolic content; SPC: sum of quantified phenolic compounds; PCA: procyanidins; DP: degree of polymerization; 3CQA: 3-O-caffeoylquinic acid; 5CQA: 5-O-caffeoylquinic acid; Q3R: quercetin-3-O-rutinoside; Q3G: quercetin-3-O-glucoside; C3G: Cyanidin-3-O-glucoside; C3R: Cyanidin-3-O-rutinoside [11].

anthocyanins, and these include tannins, phenolic acids, and flavonoids. Overall, these compounds interact synergistically in the enhancement of the antioxidant capacity and promotion of health benefits of the fruit. Of particular interest are the phenolic acids, more particularly chlorogenic acid, for their powerful antioxidant activities contributing to both the pigmentation and bioactivity of apricot skin [11, 15]. It is generally noted that chlorogenic acid can stabilize free radicals, hence enhancing the antioxidant properties of anthocyanins and carotenoids in apricot skin [16].

Tannins constitute the other class of polyphenolic compounds in apricot skin, improving the bioavailability and protective potential of other pigments. The complexation capability of tannins with anthocyanins and carotenoids results not only in the stabilization of these compounds but also enhances the absorption and bio efficacy of such bioactive molecules in the human system. More importantly, flavonoids exhibit anti-inflammatory and antioxidant activities that act in synergy with tannins and phenolic acids to provide a wide-ranging defense against oxidative damage [17].

3 | Evolution of Fruit Skin Coloring in Apricot

3.1 | Biosynthesis and Regulation of Pigments

Biosynthesis of the pigments in apricot skin is strictly regulated by multiple enzymatic pathways. Anthocyanin synthesis involves the phenylpropanoid pathway, and the participating enzymes are phenylalanine ammonia-lyase, chalcone synthase, and anthocyanidin synthase. The process is highly regulated at the transcriptional level by MYB, bHLH, and WD40 proteins that form a complex to activate structural genes [18]. Moreover, anthocyanin biosynthesis is also being modulated by the action of light-responsive elements and hormonal signals during fruit ripening, like abscisic acid.

Carotenoids synthesis is completely dependent on the methylerythritol phosphate (MEP) pathway, wherein the basic block isopentenyl pyrophosphate is derived from pyruvate and glyceraldehyde-3-phosphate. Phytoene synthase (PSY), phytoene desaturase (PDS), and lycopene β-cyclase (LCYB) are some of the key regulators in carotenoid biosynthesis, and other forms of biosynthesis are controlled by different enzymes or precursor molecules. There are temporal and spatial variations in carotenoid synthesis because of environmental factors like temperature and light exposure through changes in gene expression levels and/or enzymatic activity [19]. Despite general agreement on the biochemical pathways of carotenoid and anthocyanin formation, substantial variability exists among apricot cultivars regarding regulatory gene expression. Differential activation of MYB-, bHLH- and WD-repeat transcription factors under specific environmental stimuli (e.g., high light, cold nights) contributes to inconsistent pigment accumulation across genotypes. These discrepancies help explain why colorimetric values do not always correlate uniformly with phytochemical data. These pathways emphasize the interaction of genetic, biochemical, and environmental factors in the regulation of apricot pigmentation. Such genotype-specific regulatory behaviors highlight the necessity of interpreting skin color not as a fixed indicator but as the outcome of complex gene–environment interactions.

3.2 | Assessment of Fruit Skin Coloring in Apricot

Besides the sensory analysis, advanced techniques for the determination of skin color in apricots include spectrophotometry, colorimetry, and high-performance liquid chromatography. In

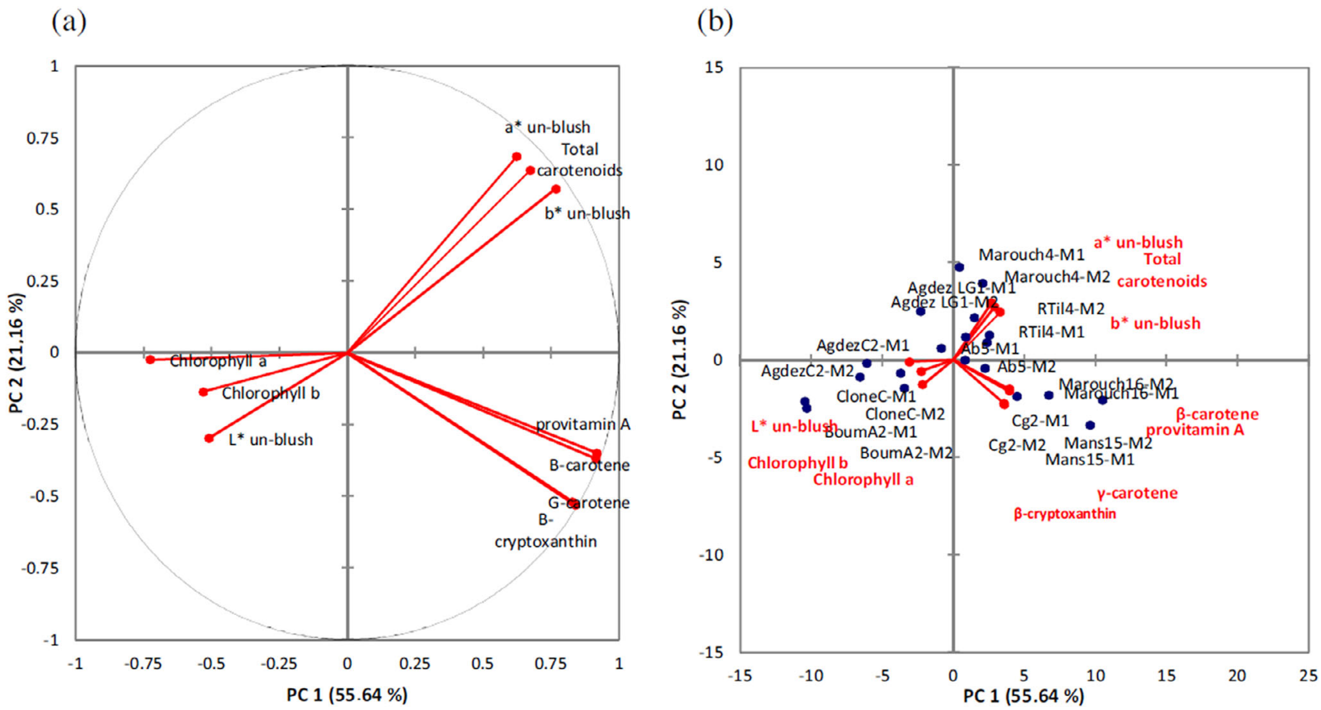

FIGURE 2 | Biplots of the studied variables and apricot genotypes. (a) Correlation circle of variables according to PCA; (b) Segregation of 10 apricot clones according to maturity and quality color parameters [20].

spectrophotometry, light absorbance or reflectance by the fruit skin is measured and provides very accurate data regarding pigment concentration. Colorimetry, often in combination with digital imaging, provides quantitative descriptions of color attributes, including hue, saturation, and brightness, which relate to pigment composition. HPLC is still the gold standard in the analysis of pigments that can identify and quantify specific anthocyanins and carotenoids, among other bioactive compounds [11, 20]. Using UV–vis HPLC to identify carotenoid compounds, *β*-carotene was the main pigment quantified in the analyzed apricot fruits. Changes in pigment composition in apricot fruit were found to occur in parallel: chlorophyll degradation occurs simultaneously with carotenoid synthesis during fruit ripening. Using CIELAB chromatic spectrometric parameters (a*, b*, and C*), a strong correlation of this pigmentation evolution was revealed that could be used as a reliable tool to predict the phytochemical composition especially apricot pigments [20] (Figure 2). Differences in L, a*, and b* values among cultivars can result from distinct pigment profiles, cuticle thickness, or light absorption properties. Regression analyses in multiple studies demonstrate moderate to strong correlations between a* values and anthocyanin content, yet these correlations weaken when comparing diverse genotypes or environments.

Recent developments include hyperspectral imaging, mapping of pigment distribution through the combination of imaging and spectroscopy and LC-MS, which offers improved sensitivity and accuracy in the detection of minor pigments. These methodologies enable deep insight into the relation among skin pigmentation, antioxidant activity, and health-promoting properties for the development of improved apricot cultivars and post-harvest practices [21].

4 | Health-Promoting Properties of Fruit Pigments

4.1 | Antioxidant Activity

Health benefits associated with apricot pigments remain largely genotype-dependent. Variability in bioaccessibility, influenced by cultivar, matrix composition, and ripening stage, makes it difficult to generalize functional effects across all apricot varieties. The pigments in apricot skin are effective antioxidants that effectively neutralize ROS and prevent the oxidative damage of critical biomolecules like DNA, lipids, and proteins. Anthocyanins are a class of flavonoids with the ability to act as electron and hydrogen donors, thereby stabilizing harmful free radicals and reducing oxidative stress. Besides, anthocyanins chelate metal ions catalyzing the production of ROS, which enhances their antioxidant efficacy. Carotenoids, with their polyene chains, effectively quench singlet oxygen and scavenge lipid peroxyl radicals, helping protect cellular membranes from oxidative degradation [22, 23]. Assays like DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)) have been consistently used in studies to show that apricot extracts rich in these pigments exhibit high radical-scavenging activities [11]. The synergy between anthocyanins and carotenoids enhances the overall antioxidant capacity, making these pigments highly important in the prevention of oxidative stress that may be linked to aging and various chronic diseases [24, 25].

4.2 | Anti-Inflammatory Effects

Apricot pigments may create significant anti-inflammatory effects by modulating the expression of pro-inflammatory mediators and signaling pathways. Flavonoids, such as quercetin and kaempferol, inhibit the synthesis of pro-inflammatory cytokines including tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6). These compounds also downregulate the activity of COX and LOX, enzymes involved in the biosynthesis of pro-inflammatory eicosanoids [26]. Anthocyanins and carotenoids in apricot skins undergo extensive metabolism during digestion, and their absorption depends on interactions with dietary fats, fiber, and the food matrix. This underscores the need for studies integrating compositional data with human bioavailability assessments.

Carotenoids, such as beta-carotene and lutein, reduce inflammation through suppression of the nuclear factor kappa-light-chain-enhancer of activated B-cells pathway. NF-κB is regarded as a major regulator of inflammatory processes. The inhibition of this pathway suppresses the transactivation of a number of inflammatory genes. In addition, carotenoids in combination with flavonoids increase their bio-efficiency and modulate inflammation in chronic diseases such as arthritis and cardiovascular diseases [27, 28].

4.3 | Potential Role in Disease Prevention

Regular consumption of apricots has been associated with reduced risk for many chronic diseases. Anthocyanins and carotenoids in apricot skins undergo extensive metabolism during digestion, and their absorption depends on interactions with dietary fats, fiber, and the food matrix. This underscores the need for studies integrating compositional data with human bioavailability assessments. The additive effect of anthocyanins and flavonoids improves vascular health through enhancement of endothelial function, reduction of arterial stiffness, and reduction of blood pressure. These effects are critical in preventing atherosclerosis and other cardiovascular diseases [29, 30].

Carotenoids in apricots reduce the risk of age-related macular degeneration, which is one of the leading causes of blindness among elderly individuals. In addition, carotenoids have shown chemopreventive properties, especially against lung, prostate, and skin cancers through inhibiting oxidative stress and modulating gene expression involved in apoptosis and cell proliferation [31]. Hence, whole fruits are recommended over supplementation with isolated pigments, since there is a synergy among the pigments and other phytochemicals like polyphenols and vitamins that together enhance their bioavailability and therapeutic potential [32, 33].

5 | Factors Influencing Bioactive Compound Accumulation

5.1 | Genetic Variation

Genetic diversity among apricot cultivars has brought considerable variation in pigment composition. Biosynthetic genes responsible for anthocyanin and carotenoid synthesis were chalcone synthase and phytoene synthase, respectively. These enzymes have been used as selection criteria in selective breeding activities to enhance the concentration of bioactive compounds in certain cultivars, considering their color intensity and antioxidant capacity. Besides, progress in genetic engineering, such as CRISPR/Cas9-mediated genome editing has so far allowed for precise manipulation of key biosynthetic genes that enhance pigment accumulation without affecting other qualities of fruits [34, 35].

5.2 | Environmental Conditions

Environmental factors like light intensity, temperature, and soil composition all play a critical role in pigment biosynthesis. For instance, high light exposure initiates various photoreceptors to strongly induce the biosynthesis of anthocyanin due to increased expression of light-induced transcription factors like MYB10. High solar radiation has been shown to induce anthocyanin accumulation in cultivars such as ‘Pinkcot’, whereas other genotypes exhibit minimal response, underscoring the need for cultivar-tailored orchard management. Similarly, carotenoid biosynthesis is favored by moderate temperatures due to enhancement of enzymatic activity in the methylerythritol phosphate pathway responsible for carotenoid production. Cool nighttime temperatures (<15°C) enhance red pigmentation in some cultivars but may reduce carotenoid stability, illustrating complex trade-offs between pigment classes. Nutrient availability in the soil, particularly nitrogen and potassium, controls the metabolic pathways of biosynthesis of these pigments. Nitrogen imbalance has been implicated in reduced anthocyanin biosynthesis, suggesting controlled fertilization may optimize skin color and bioactive content [36, 37]. Overall, environmental drivers influence pigment accumulation in a highly cultivar-dependent manner, emphasizing that color-based nutritional predictions must be contextualized within orchard management practices.

5.3 | Agricultural Practices

The agricultural practices are very important for the accumulation of bioactive compounds in apricots. Organic farming methods are associated with higher concentrations of phenolic compounds, inducing increased stress responses in plants due to the use of reduced pesticide application and dependence on natural fertilizers. Regulated irrigation methods, like deficit irrigation, would provoke a mild water stress inducing secondary metabolite production, which includes pigments. Moderate deficit irrigation (40%–60% ETc) can increase carotenoid concentration without negatively affecting yield, making it a viable strategy for enhancing color quality. In addition, pruning practices that increase light penetration into the canopy further stimulate anthocyanin and carotenoid synthesis, improving fruit quality and nutritional value [38, 39].

5.4 | Post-Harvest Handling, Preservation, and Processing

Handling after harvesting and methods of preservation and processing have a great impact on pigment stability and bioavailability. The adequate storage conditions, especially with low temperatures and controlled atmosphere, are highly important to maintain anthocyanins and carotenoids. Freeze-drying and

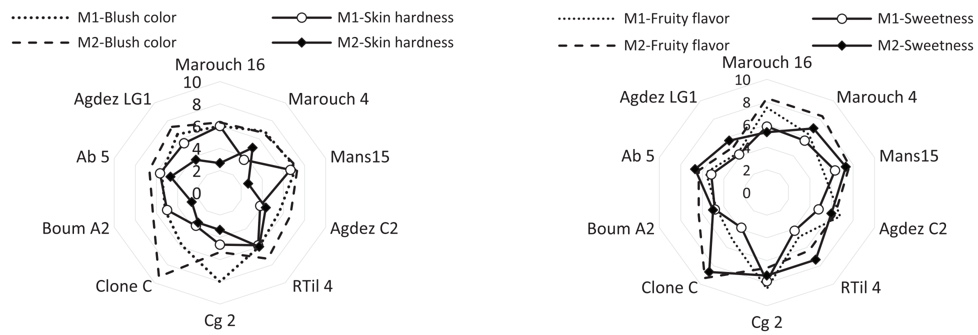

FIGURE 3 | Main sensory attributes including color of ten apricot cultivars at the commercial (M1) and consumption (M2) ripe stages [42].

vacuum sealing reduce the occurrence of oxidative degradation, maintaining bioactive compounds during storage. Furthermore, heat-sensitive pigments are broken down under high temperatures during processing in such cases as canning or traditional drying. Various innovative techniques, including HPP and microwave-assisted drying, have been developed to retain pigment integrity with microbial safety and extended shelf life [40, 41].

In the context of use for the fresh fruit market or for the industrial processing market, it was highlighted the implication of skin color in the fate of apricot fruits. In fact, it was reported a strong correlation between biochemical criteria, aromatic compounds, and sensory profiles of 10 studied cultivars of apricots of different colors: light, orange, and red [42] according to the performed quantitative descriptive sensory analysis (Figure 3). GC-MS HS-SPME (Head space-Solid phase microextraction) highlighted a rich and very varied aromatic composition between the studied cultivars with a very significant genotype effect, especially skin color. Red apricot cultivars were suggested for fresh consumption as fruits thanks to a nutritional and sensory balance. While orange-skinned cultivars have been recommended for the processing industry due to their texture and firmness that resist handling and therefore heat treatments in processing (Table 1) [42]. This finding further confirms the importance of apricot skin color as a tool to predict fruit quality and facilitate post-harvest management, which is a major issue for the apricot sector.

6 | Applications and Future Prospects

Recent studies [43–45] demonstrate that apricot peel extracts possess promising stability under moderate processing conditions and retain antioxidant activity after encapsulation. These findings support the potential use of apricot pigment fractions in functional beverages, natural colorants, and antioxidant-enriched formulations, although further validation in real food matrices is required. However, large-scale industrial applications are still constrained by limited data on pigment stability during storage and digestion.

6.1 | Natural Food Colorings

Carotenoids and anthocyanins are two great potential sources of natural food coloring derivatives from apricot skin. Both biomolecules give a color range from orange to red and hence can be used as alternatives to artificial dyes like FD&C Red No. 40 and Yellow No. 5, which have negative health impacts. The increasing demand of consumers for clean-label products has directed interest in natural colorants that, besides enhancing visual appearance, provide health benefits [43].

Apricot pigments have been incorporated into beverages, confectioneries, and dairy products. Studies have indicated good stability over a wide range of pH and temperature conditions. Microencapsulation and liposome incorporation are some of the modern encapsulation technologies under study to improve pigment stability and extend shelf life in processed foods [44].

6.2 | Nutraceuticals and Functional Foods

Antioxidant and anti-inflammatory properties of apricot pigments are powerful and place them as one of the valuable ingredients in nutraceuticals and functional foods. Formulations containing anthocyanins and carotenoids address conditions related to oxidative stress, including cardiovascular diseases, diabetes, and neurodegenerative disorders. For example, carotenoids such as beta-carotene and lutein are already applied in supplements for the prevention of age-related macular degeneration [45].

Apricot-derived functional beverages, energy bars, and yogurt added with these pigments enable increased consumer acceptance due to dual benefits related to taste and health. Moreover, the formulation of synergistic formulations combining apricot pigments with other bioactives, such as omega-3 fatty acids or polyphenols, is a fresh area of research in functional food innovation [46, 47].

6.3 | Potential for Biofortification

Biofortification is a sustainable strategy against micronutrient deficiencies through the enhancement of the nutritional value of crops. Regarding apricots, there is a need for biofortification strategies aimed at improving anthocyanin and carotenoid contents, among other important nutrients, through appropriate genetic and agronomic interventions [48]. Success has also been achieved with advances in genetic engineering, such as the overexpression of key biosynthetic genes like PSY for carotenoids

TABLE 1 | Descriptive sensory analysis means scores of ten apricot cultivars at commercial (M1) and consumption (M2) ripe stages [42].

Ripe stage	Cultivar	Unblush color	Blush color	Hardness	Persistence	Skin hardness	Flesh cohesion	Flesh color
M1	Marouch 16	4.17[bc]	6.00[c]	5.33[ab]	2.31[abc]	6.00[ab]	7.65[ab]	7.17[a]
	Marouch 4	3.57[cd]	6.83[bc]	6.00[a]	2.58[abcd]	3.58[d]	8.37[a]	6.67[ab]
	Mans15	3.67[cd]	7.17[b]	7.00[a]	1.30[bcd]	6.69[a]	5.61[d]	5.70[c]
	Agdez C2	4.80[abc]	5.60[d]	5.60[ab]	2.81[ab]	3.80[d]	7.80[ab]	6.40[ab]
	RTil 4	4.67[bc]	6.00[c]	6.67[a]	2.85[ab]	5.83[ab]	8.27[a]	6.83[ab]
	Cg 2	2.33[d]	8.00[a]	5.00[ab]	0.60[d]	4.67[cd]	6.44[cd]	7.00[a]
	Clone C	5.50[ab]	5.83[d]	5.83[a]	3.16[a]	3.68[d]	6.61[bcd]	5.50[c]
	Boum A2	6.33[a]	5.17[d]	6.00[a]	1.00[cd]	5.00[c]	7.17[abc]	3.71[d]
	Ab 5	4.50[bc]	5.50[d]	5.33[ab]	1.00[cd]	5.60[ab]	6.51[cd]	5.83[c]
	Agdez LG1	3.50[cd]	6.50[bc]	3.50[b]	2.00[abcd]	5.50[ab]	7.83[a]	6.67[ab]
	Pooled SD	2.4	3.6	3.2	1.4	3.7	2.3	3.1
M2	Marouch 16	3.66[bcd]	6.61[bc]	3.33[bc]	1.46[ab]	5.00[ab]	7.33[ab]	7.58[ab]
	Marouch 4	2.67[cde]	7.33[b]	4.00[bc]	1.06[ab]	2.47[d]	7.60[a]	7.01[abc]
	Mans15	3.00[bcd]	7.23[b]	6.61[a]	0.42[b]	6.00[a]	5.63[b]	6.39[bc]
	Agdez C2	3.56[bcd]	6.22[bc]	4.43[b]	2.23[a]	2.71[d]	8.00[a]	6.45[bc]
	RTil 4	4.00[bc]	6.62[bc]	4.67[b]	1.69[ab]	4.39[bc]	7.67[a]	7.69[ab]
	Cg 2	1.33[e]	9.33[a]	3.77[bc]	0.31[b]	3.31[cd]	6.23[ab]	7.61[ab]
	Clone C	4.33[ab]	6.31[bc]	4.24[b]	1.67[ab]	2.57[d]	6.27[ab]	6.47[bc]
	Boum A2	5.61[a]	5.43[c]	4.63[b]	0.65[b]	3.29[cd]	7.30[ab]	3.60[d]
	Ab 5	3.70[bcd]	6.67[bc]	3.30[bc]	0.40[b]	4.617[abc]	6.19[ab]	6.33[c]
	Agdez LG1	2.34[de]	7.30[b]	2.55[c]	0.41[b]	3.44[bcd]	7.67[a]	8.00[a]
	Pooled SD	2.7	2.6	1.8	1.1	2.2	1.7	3.2

Each value is the mean of 40 replicates for fresh apricot. Means with same letters within the same column do not differ significantly according to Fisher's LSD test at $p < 0.05$. Pooled SD: pooled standard deviation.

and MYB transcription factors for anthocyanins, in improving pigment content in fruits. Agronomic practices, including optimized fertilization and irrigation regimes, further complement these genetic efforts by enhancing the bioavailability of nutrients [49]. On a global scale, biofortified apricots could contribute to reducing micronutrient malnutrition, especially in regions with low dietary diversity.

7 | Conclusion and Futures Perspectives

By critically integrating the biochemical, genetic, environmental, and functional dimensions of apricot pigmentation, this review provides a comprehensive framework that supports the use of skin color as a practical indicator of phytochemical richness and nutritional potential. The skin color of apricots is not only a display for appearance, ripeness, and quality but also a reflection of their nutritional and functional value. This is the result of a complex interaction between bioactive compounds like anthocyanins, carotenoids, and flavonoids that are important contributors to the health-promoting properties of the fruit. These pigments play important roles in mitigating oxidative stress, reducing inflammation, and preventing chronic diseases, hence enhancing functional attributes in apricots.

Genetic factors, environmental conditions, and agricultural practices have thus been shown to control the biosynthesis of those pigments and could give opportunities for the optimization of their content in apricots. These would involve methods like selection and genetic engineering, which enhance the concentration of desirable bioactive compounds. Further, sustainable farming methods improve pigment stability and quality [50, 51].

From the consumer point of view, these pigments offer not only aesthetic appearance but also meet the modern trend for natural products with a focus on health. Such interest has motivated the attentiveness in the application of apricot pigments in functional foods, nutraceuticals, and natural food colorings, where their nutritional value and vibrant colors can be used effectively. Besides, new biofortification techniques open a new opportunity toward reducing micronutrient deficiencies and may contribute to the fulfillment of global nutritional needs by the use of apricot pigments [52, 53].

Future research on apricot pigmentation should prioritize the optimization of cultivation practices and post-harvest technologies to maximize pigment retention, stability, and bioavailability. Integrating advanced analytical tools, including multi-omics approaches, hyperspectral imaging, and controlled genotype

× environment experiments will provide deeper insight into the regulatory mechanisms governing pigment accumulation. Equally important is the need for well-designed human studies to evaluate the bioavailability and functional impacts of apricot skin compounds, thereby validating their proposed nutritional relevance. Finally, innovative applications of apricot pigments in the food, nutraceutical, and healthcare industries will be crucial for fully valorizing the functional potential of these bioactive biomolecules.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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