Review Article

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Environmental modulation and genetic variation of quality traits in onion (*Allium cepa* L.): A review

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ABSTRACT

Onion (*Allium cepa* L.) stands among the most widely cultivated vegetable crops worldwide, valued for both its culinary uses and rich phytochemical composition and associated health benefits. Among the bioactive compounds, phenolics, flavonoids and anthocyanins play crucial roles in determining antioxidant capacity, nutritional quality and market preference. This review compiles recent findings on how environmental conditions and genotypes influence on onion quality traits. Evidence consistently demonstrates wide variability among cultivars, with red onions exhibiting the highest values of total phenolics, flavonoids, anthocyanins and antioxidants, followed by yellow and followed by white type cultivars. Antioxidant activity, assessed through diverse assays such as FRAP, DPPH showed variation across various parts of onion plant. Notably, onion skins, particularly from red varieties, contain substantially higher concentrations of flavonoids and anthocyanins than bulbs, showing their potential as valuable by-products. Environmental factors, including cultivation conditions, geographic location and harvest timing, further modulate phytochemical accumulation, highlighting the importance of genotype x environment interactions. Overall, the biochemical diversity observed across onion genotypes and ecotypes presents opportunities for breeding and selection strategies aimed at enhancing nutritional and functional quality, while also emphasizing the need for standardized analytical approaches.

Introduction

The onion (*Allium cepa* L.) has been used as a food, medicine, spice and condiment for centuries because of its numerous health benefits. It is consumed fresh in salads and also processed into products such as pickles, chutneys, sauces and dehydrated powders for flavouring (Teshika *et al.*, 2019). It is known as the "Queen of the kitchen" for its distinct flavour, onions offer a nutrient-rich profile, including protein, vitamins, minerals, fibers, sugars, micro and macro-nutrients (Gupta *et al.*, 2025a, Gupta and Lawande, 2010). It is the most important species of the Alliaceae family and cultivated as a hardy bulbous plant- grown annually for bulb harvest and biennially for seed production. The edible portion of onion is bulb which develops underground. Onion is the third most vegetable produced after tomato across 146 countries worldwide. In 2023, it was covered on an area of 58.42 lakh hectares producing 111.27 million tons (FAOSTAT, 2023). Recent statistics revealed that India as the leading producer of onions,

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with a production of 30.21 million tons across 17.40 lakh hectares. Other major onion-producing countries include China, Egypt, USA, Turkiye, Bangladesh, Indonesia, Pakistan and Mexico. The global average productivity of onion is 27.06 t/ha. In 2022–23, the Republic of Korea leading with 67.87 t/ha, followed by Guyana (64.36 t/ha) and the United States (61.28 t/ha), while India ranked 93rd by 17.36 t/ha. The principal onion-growing states in India include Maharashtra, Karnataka, Gujarat, Bihar, Madhya Pradesh, Rajasthan, Andhra Pradesh and Tamil Nadu. Among these, Maharashtra and Karnataka are the leading producers, contributing nearly half of the country's total production (Gupta *et al.*, 2025a).

According to Gupta *et al.* (2025b), onions are a great combination of numerous beneficial phytochemicals, including phenolic compounds, organosulphur compounds, flavonoids (quercetin, kaempferol and their glycosides), anthocyanins, pyruvic acids, antioxidants, thiosulfinates, saponins and fructooligosaccharides. These bioactive constituents of onions have been associated with a wide spectrum of health-promoting properties, including antioxidant, anticancer, antimicrobial, antimutagenic, antiproliferative, antiplatelet, antithrombotic and antibiotic activities (Suleria *et al.*, 2015). They lower the incidence of stomach ulcers by scavenging free oxygen radicals and preventing the growth of bacteria that cause ulcers. Additionally, it functions as an antibacterial and antiparasitic substance (Tabussam *et al.*, 2022).

The total phenolic content varies among cultivars with red and yellow onions typically possessing higher levels than white onions (Lee *et al.*, 2015). The onion's outer layers are known to contain a higher concentration of polyphenolic flavonoids and other phenolic chemicals than the inner and middle layers of the bulb. In general, peels exhibit the highest levels, ranging from about 80 to 1758 mg GAE/100 g DW across white, red and dark red varieties (Gorrepati *et al.*, 2024; Duan *et al.*, 2015), while bulbs contain lower concentrations, typically in the range of 6 to 22 mg GAE/g DW in both yellow and red onions (Cheng *et al.*, 2013). Traditional onion ecotypes fall within a comparable range, with reported values of about 6 to 11 mg GAE/g DW (Brahimi *et al.*, 2022). This variation reflects differences in onion colour, variety and tissue type, with outer layers and pigmented cultivars consistently showing higher phenolic contents. Climatic factors such as temperature, rainfall, humidity and wind speed further modulate onion quality. High maximum temperatures typically reduce total phenols (TPC) and total flavonoids (TFC), though moderate temperature may sometimes enhance flavonoid synthesis (Wang, 2006; Kumar *et al.*, 2017; Moreira *et al.*, 2020; Bibi *et al.*, 2022). Rainfall and relative humidity can have variable effects, sometimes negatively correlating with phenolic and flavonoid contents, but occasionally increasing antioxidant activities depending on the variety and environmental context (Bibi *et al.*, 2022; Boussaa *et al.*, 2020). Altitude also plays a role, with higher elevations often associated with reduced TPC and TFC, though some cultivars display increased antioxidant potential under these conditions (Liu *et al.*, 2016; Bernal *et al.*, 2013; Downey *et al.*, 2006). Despite the well-documented nutritional and functional value of onions, the considerable variation in their phytochemical profile arising from both genotypic diversity and environmental influences remains a critical challenge for breeders, producers, and food industries. While several studies have independently examined the role of onion genotype, cultivation practices and ecological conditions, there is a need for an integrated understanding of how these factors interact to shape quality traits. Addressing this gap is essential not only for improving breeding strategies and varietal selection but also for optimizing agronomic practices to enhance nutritional quality, antioxidant potential and industrial utility of onions and their by-products. This review therefore synthesizes current evidence on the combined influence of environmental factors and genotypic variation on onion quality traits, with the aim of providing awareness that can guide future research, cultivation and utilization strategies.

Environmental factors

The various environmental factors affecting levels of various quality parameters of onion have been listed in Table 1.

i. Temperature

This is a critical determinant of onion quality. High maxima (>25 °C) accelerate enzymatic degradation of TPC, TFC and antioxidant capacity, while low storage temperatures (4-10 °C) maintain phenolic content, antioxidant activity and pungency (Bibi *et al.*, 2022; Kumar *et al.*, 2017; Moreira *et al.*, 2020; Wang, 2006). Cold storage at 0-5°C markedly reduces metabolic degradation, preserving sugars, amino acids and peel color (Latt *et al.*, 2025; Demissew, 2018). In contrast, warm storage accelerates moisture loss, sprouting and deterioration, as shown in traditional ventilation systems compared with forced or natural ventilation (Hatem *et al.*, 2014). Optimal temperature control, including cold storage or controlled atmosphere at 2.5 °C (Ríos-González *et al.*, 2018) and short-term curing at 30°C in high humidity to improve skin integrity (Eshel *et al.*, 2014), can substantially extend shelf life and maintain marketable quality.

ii. Relative humidity (RH)

Relative humidity strongly influences onion quality by affecting moisture loss, microbial growth and biochemical stability. Moderate RH (65-75%) generally minimizes dehydration while avoiding conditions that promote rot (Bibi *et al.*, 2022; Sabaragamuwa *et al.*, 2011). Lower RH accelerates weight loss, whereas excessive RH (>90%) increases microbial spoilage risk. Controlled curing at 30-50 °C with 30-70% RH improves skin quality and reduces weight loss (Zewdie *et al.*, 2022). In long-term cold storage, 70% RH at 0 °C preserved firmness, sweetness and biochemical quality (Latt *et al.*, 2025). Natural ventilation with perforated pipes maintained moderate RH, limiting moisture loss and deterioration while reducing sprouting compared with traditional storage (Hatem *et al.*, 2014). Optimal RH control, particularly around 75%, therefore essential for balancing physical preservation, microbial safety and enhancing biochemical composition.

Fig. 1a. Onion plant

Fig. 1b. Onion bulbs

iii. Rainfall

Rainfall exhibits inconsistent relationships with onion phytochemicals. Liu *et al.* (2016) and Mditshwa *et al.* (2013) found mostly no significant correlation between rainfall and TPC & TFC, though occasional negative associations occur possibly due to excess moisture stress. Some studies noted positive correlations between rainfall and antioxidant activity, which may reflect stress-induced phenolic synthesis under moderate water availability (Moreira *et al.*, 2020). Overall, the timing and amount of rainfall appear to influence onion quality variably, often indirectly through effects on plant health and fungal pressure (Bibi *et al.*, 2022).

Table 1. Impact of environmental factors on level of onion of quality parameters

Environmental Factor	Phenols	Flavonoids	Antioxidants	Sugars	Pyruvic Acid
High Temperature	Low	Low	Low	Variable	Short-term
Low Temperature	High	High	High	High	Maintained
Nutrient deficiency	Low	Low	Low	Low	Low
Water Stress (Moderate)	High	High	High	Low	High
Low Light/Shading	Low	Low	Low	No Change	No Change
Long-Term Storage	Low	Low	Low	Low	Low
Salinity (Moderate)	High	High	High	Low	Low
High CO_2	Low	Low	Low	High	No Change
Soil pH	Low	Low	Low	Low	Low
Wind (mild stress)	High	High	High	No change	No change

iv. Soil pH

Soil pH influences nutrient availability, thereby affecting secondary metabolite accumulation in onions. Alkaline soils tend to correlate positively with antioxidant activity, enhancing free radical scavenging capacity (Bibi *et al.*, 2022; Khalsi Ahvazi *et al.*, 2016). Acidic soils, by contrast, have been linked to increased phenolic content, suggesting stress-induced biosynthesis under such conditions (Bibi *et al.*, 2022). These pH-dependent effects reflect varying nutrient interactions and stress responses that modulate onion phytochemicals, emphasizing the importance of soil management practices in quality optimization.

v. Soil salinity

Soil salinity, reflected in electrical conductivity (EC), imposes abiotic stress that alters onion biochemical pathways. Studies show EC can variably increase or decrease TPC, TFC, and antioxidant levels depending on the onion genotype and tissue type (Bibi *et al.*, 2022; Curcic *et al.*, 2012). Salinity stress often elevates antioxidant compounds as a protective response; however, excessive salt can degrade quality by impairing growth and metabolism (Khalsi Ahvazi *et al.*, 2016). Venâncio *et al.* (2022) reported that higher soil salinity have reduced sugars and total soluble solids in onions during storage and increased mass loss. Silicon fertilization (121.8-127.0 kg/ha) mitigated these effects by enhancing firmness and boosting pyruvic and ascorbic acid content. Thus, moderate control of soil salinity is critical for maintaining onion bulb nutritional and storability traits.

vi. Altitude

Altitude affects onion quality parameters mainly through environmental stressors such as UV radiation and temperature fluctuations. Higher elevations often correspond with reduced TPC and TFC, possibly due to lower temperatures and altered metabolic activity (Liu *et al.*, 2016; Bernal *et al.*, 2013). Interestingly, antioxidant capacity may increase in some varieties at higher altitudes, indicating adaptive responses to enhanced oxidative stress (Downey *et al.*, 2006). Shukla (2024) reported that onions cultivated at high altitude (3340 m) in Leh-Ladakh exhibited higher yield, crude protein, carbohydrates, total phenols, flavonoids, quercetin content and antioxidant activity compared to low-altitude (321 m). These findings suggest that altitude-mediated environmental variation can modulate onion phytochemical profiles in complex ways.

vii. Wind speed

Wind exposure can induce physical and oxidative stress impacting onion secondary metabolites. Bibi *et al.* (2022) observed that low inverse correlations between wind speed and TPC/TFC, while Maslennikov *et al.* (2020) reported occasional positive effects on antioxidant activity. Wind-induced stress likely triggers defense mechanisms, leading to variable modulation of quality parameters depending on intensity and duration of exposure. Such environmental dynamics highlight the multifactorial nature of onion quality regulation. Maude *et al.* (1984) found that drying topped onions at 30 °C with forced airflow within 48 h of harvest markedly reduced neck rot incidence compared to ambient drying at ~18°C, highlighting the role of elevated postharvest temperatures and rapid drying in maintaining onion health and storability.

Storage conditions

Effective control of temperature and humidity during postharvest storage is essential for preserving onion quality and extending shelf life. Storage conditions also have been reported to affect the quality of onion (Fig. 2). Cold storage (4-10 °C) maintains key parameters such as total phenolics, flavonoids, antioxidant capacity, sugars and pyruvic acid, minimizing metabolic degradation and sprouting (Sharma et al., 2025). Advanced non-thermal processing technologies-including irradiation and cold plasma-help retain onion phytochemicals more effectively than conventional heat treatments (Sharma et al., 2025), supporting nutritional and sensory quality. Both storage conditions and duration can influence the stability of bioactive compounds (Ren & Zhou, 2021), while temperature, humidity, and handling are key determinants of shelf life and nutritional value (Kiran et al., 2024). Controlled atmosphere storage offers further benefits, significantly improving preservation compared to traditional methods (RíosGonzález et al., 2018). Notably, high temperature and humidity exacerbate microbial spoilage, such as Fusarium-induced rotting, with losses of up to 50% (Suravi et al., 2024); however, practices like curing, improved ventilation, and elevated CO_2 can help reduce sprouting and decay.

The use of beneficial microbial inoculants appears to influence several physiological and biochemical aspects of onion bulbs. According to Islam *et al.* (2019), microbial inoculation seems to be associated with increases in total soluble solids and pyruvic acid, which might relate to enhanced bulb pungency and overall quality. Microorganisms could also contribute to nutrient uptake and stress resilience, possibly leading to changes in phenolic and antioxidant levels. The adoption of such biological inputs may therefore provide a potential avenue for modifying onion quality characteristics. Additionally, environmental stress and infection (Al-Khayri *et al.*, 2023; Suravi *et al.*, 2024) are known to provoke onion secondary metabolite accumulation-which may impact disease resistance-but postharvest losses can rise sharply under adverse conditions. Pellegrini *et al.* (2021) and Vojnović *et al.* (2024) indicated that microbial seed inoculation and application of biostimulants can improve crop yield, bulb quality, and other soil parameters; however, the effects on phenolics and antioxidants remain variable. Optimum planting density and variety selection, such as the use of the 'Nafis' variety under a 10 cm planting spacing, have been shown to enhance bulb yield and quality including biochemical constituents important for storability and nutritional value (Alemu *et al.*, 2022).

Fig. 2a. Onion storage boxes

Fig. 2b Onion storage structure

Genotypic variations

Onions display significant biochemical variation, especially in total phenolic content, total flavonoid contents and antioxidant activity, which influence their nutritional and functional value. Studies indicate that red and pink onion genotypes generally contain higher TPC and TFC, correlating with greater antioxidant activity compared to white varieties (Dalamu *et al.*, 2010; Singh *et al.*, 2009; Benítez *et al.*, 2011; Gupta *et al.*, 2025a). Quercetin and its derivatives are the primary flavonoids responsible for these effects, with concentrations varying among cultivars (Slimestad *et al.*, 2007; Lanzotti, 2006). Genetic and environmental factors contribute to this variability, suggesting the importance of comprehensive phytochemical profiling and bioactivity assessments to identify superior onion varieties for breeding programs aimed at enhancing health benefits (Paşazade and Hanci, 2025; Bibi *et al.*, 2022). The chemical structures of these phytochemicals are provided in Fig. 3.

i. Total phenolic content

Phenolic compounds, known for their antioxidant benefits, vary markedly with onion colour in Table 2. Red onions consistently show the highest total phenolic content (TPC), averaging 867.8mg gallic acid equivalents (GAE)/kg in red onion, compared to 702.0mg/kg in pink onions and just 165.0 mg/kg in white onions. High-performing red cultivars like Sel-397, Burgundy, and Sel-383 exceeded 1,000 mg/kg, while some pink varieties, Sel-20-411, Pusa Red and white types ranged from 60.1 to 512.8 mg/kg, reinforcing the trend of lower TPC in lighter bulbs (Dalamu *et al.*, 2010). Similarly, Elhassaneen (2006) reported red onions had 187.17 mg/100g fresh weight (FW) TPC versus 131.65 mg/100g FW in white onion. Onion genotypes displayed TPC levels ranging from 740.67 to 1,145.33 µg GAE/ml, with Hissar 2, Pusa Red, Arka Kalyan, L-28, Arka Pitamber, and JWO-1 among the top performers, though skin colour showed no consistent correlation (Kaur *et al.*, 2009). Studies investigating phenolic content across onion ecotypes reveal wide disparities. Using the Folin-Ciocalteu (F-C) method, TPC values among eleven ecotypes extended from 5.94-11.22 mg GAE/g dry weight (DW). Similarly, Italian cultivars showed TPC between 3.9 and 8.2 mg GAE/g, Czech cultivars recorded from 2.66 to 3.37 mg GAE/g DW (Mitrova, 2016) and Korean cultivars varied from 2.95 to 5.54 mg GAE/g DW (Sharma *et al.*, 2014).

Other research reported even higher phenolic concentrations, such as 25.96 mg GAE/g DW (Petropoulos *et al.*, 2015). Most studies indicated that white onions contain the lowest phenolic levels relative to red and yellow types (Lee *et al.*, 2015). In contrast, research in China reported that yellow cultivars had the highest TPC, followed by red and white (Zhang *et al.*, 2016). In 2004, TPC ranged from 42.22 mg/100 g in Pusa White Flat to 146.90 mg/100 g in Sel-383, whereas in 2005, it varied between 41.74 mg/100 g in Early Grano and 112.33 mg/100 g in Sel-383. Across both years, the average values spanned 42.95-129.62 mg/100 g, with Sel-383, Pusa Red, Sel-402 and N-53 grouped as high TPC genotypes and Pusa White Flat, Early Grano, and Pusa White Round classified as low. Red cultivars consistently exhibited significantly higher phenolic content than white ones. (Kaur *et al.*, 2009; Yang *et al.*, 2004). Indian genotypes confirmed this trend, with phenolic content highest in red onions (867.8 mg/kg FW), followed by pink (702.0 mg/kg) and lowest in white (165.0 mg/kg). In skins, dark red cultivars showed maximum levels (289.04 mg GAE/g DW), followed by pink (231.73 mg GAE/g DW) and white (19.74 mg GAE/g DW), confirming the association between bulb colour intensity and phenolic concentration (Gupta *et al.*, 2025b). Studies on onion skin powder also reflected significant variability. TPC ranged from 14.55 mg GAE/g DW in the white cultivar 'Bhima Shubhra' to 288.74 mg GAE/g DW in the red cultivar 'NHRDF Red' (Sagar *et al.*, 2020). Other investigations reported red onion skin TPC values between 63.62 and 208.42 mg GAE/g depending on extraction solvents, with ethanolic extracts yielding higher concentrations (Skerget *et al.*, 2009). Comparisons consistently show red onion skins containing substantially more phenolics than their edible parts or white skins (Nuutila *et al.*, 2003; Prakash *et al.*, 2007).

Further analyses of ten exotic onion cultivars identified 'Fireball' as having the highest TPC, whereas the yellow cultivar 'Starito' showed the lowest. Late varieties such as Kamal F_1 were rich in phenolics, while white and yellow cultivars like Diamant and Mundial had the lowest. Notably, TPC was also influenced by cultivation year, reflecting the combined effects of genetics, agronomy, climate and harvest maturity on phenolic composition and nutritional quality (Yang *et al.*, 2004; Lu *et al.*, 2011). Generally, TPC values span a wide range, from 1.17 to 2.10 g/kg, emphasizing the broad genetic and environmental influences shaping phenolic profiles in onions (Mlcek *et al.*, 2015). A meta-analysis confirmed that red and purple onions consistently have higher TPC than yellow or white onions, regardless of geographic origin. This pattern was observed in onions grown in Europe, Asia, and North America, with red onions often exhibiting TPC values up to three times higher than white onions (Benkeblia, 2005; Slimestad *et al.*, 2007). A comprehensive review by Griffiths *et al.* (2002) concluded that, while genetic factors (variety and colour) are the primary determinants of TPC, environmental and agronomic practices can modulate phenolic accumulation.

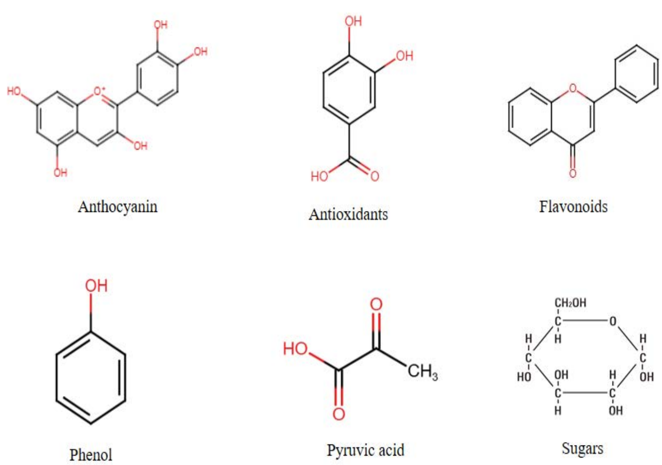

Fig. 3. Chemical structure of the major secondary metabolites found in onion

ii. Anthocyanins and flavonoids

Flavonols and anthocyanins are the primary subclasses of flavonoids present in onion. The flavonoid contents influenced by genotypes has been listed in Table 3. For Moroccan ecotypes, quercetin content ranged between 0.67 and 1.52 mg/g DW. Comparative studies have also reported values of 449.75 µg/g FW in other cultivars (Metrani *et al.*, 2020), while flavonol concentrations in red and yellow onions varied from 415–1917 mg/kg FW and 270-1187 mg/kg FW, respectively (Khandagale and Gawande, 2019). It is well documented that flavonoid concentration in onion bulbs tends to decrease from the outer to the inner layers (Cheng *et al.*, 2013). Several studies have also indicated that red-skinned onions generally exhibit higher flavonoid concentrations than yellow or white-skinned varieties (Cheng *et al.*, 2013; Zhang *et al.*, 2016). According to Pérez-Gregorio *et al.* (2010), red onion cultivars exhibited the greatest flavonol concentrations, with Vermelha da Povoa and Red Creole recording 280.24 ± 1.5 and 304.3 ± 81.2 mg quercetin/kg FW, respectively. Their studies concluded that red onions are distinguished not only by elevated flavonol levels but also by their anthocyanin content. In contrast, Zhang *et al.* (2016) observed a complete absence of flavonoids in Chinese white onion varieties. Consistently, subsequent analyses indicated that flavonoid concentrations in white onion ecotypes were significantly lower than those in red or yellow bulbs (Brahimi *et al.*, 2022).

Historical data also support considerable variability in flavonoid content among onion cultivars. Marotti and Piccaglia (2002) reported that golden and red onions contained relatively high flavonoid levels, averaging 765.1 and 610.5 mg/kg, respectively, whereas white onions had only trace amounts (1.8 mg/kg). These results are consistent with earlier reports, which reported flavonoid levels in the range of 37.8-55.78 mg/100 g FW (Ewald *et al.*, 1999). Overall, red cultivars consistently demonstrated higher average flavonoid contents than white cultivars (Bilyk *et al.*, 1984). Comparative studies revealed that red onions possessed higher flavonoid content (70.38 mg/100 g FW) relative to white onions (32.49 mg/100 g FW). A similar trend was observed for anthocyanins, with red onions recording 7.56 mg/100 g FW compared to 4.90 mg/100 g FW in white types (Elhassaneen, 2006; Kaur *et al.*, 2009).

Onion genotypes are categorized into six colour groups-white, yellowish brown, light brown, dark brown, brown and purplish brown-with the purplish brown, yellowish brown and dark brown types exhibiting the greatest flavonoid concentrations. Flavonoid levels varied widely among genotypes, ranging from 0.15 to 2.56 QE/g, with *MKS8823GO* recording the maximum (Tabussam *et al.*, 2022). A study on ten onion varieties and shallots demonstrated strong genotype effects on flavonoid content, with values ranging from 69.2 mg catechin equiv/100 g in Western Yellow to only 5.8 mg/100 g in Western White, representing an 11-fold difference (Nuutila *et al.*, 2003). The lowest flavonoid concentration was recorded in Pusa White Flat (31.67 µg QE/ml), while Arka Pitamber, a yellow cultivar, showed the highest (465.00 µg QE/ml). Genotypes were accordingly classified as low (<200 µg/ml), medium (200-300 µg/ml), and high (>300 µg/ml) and nine cultivars-including Hissar-2, Pusa Red, Arka Pitamber, and the white JWO-1-were grouped as high, surpassing several red types (Islam *et al.*, 2019). Furthermore, anthocyanin and flavonoid levels were strongly linked to bulb colour, with anthocyanin contents arranged as red > yellow > white and flavonoid levels similarly higher in red (111.10 mg/100 g FW) and yellow (36.64 mg/100 g FW) onions, while white onions showed negligible flavonols (Zhang *et al.*, 2016).

A comparative study of white (Branca da Póvoa, hybrid SK409) and red onions (Vermelha da Póvoa, its selected line and Red Creole) revealed clear differences in flavonoid and anthocyanin composition. The dominant flavonols identified included quercetin and isorhamnetin glycosides in red onions, particularly Vermelha da Póvoa (selected line) and Red Creole, displaying much higher levels (280.2-304.3 mg/kg FW) while white onions showing the lowest concentrations (89.3-101.0 mg quercetin/kg FW). Red onions also contained significant anthocyanins, namely cyanidin derivatives, with Red Creole reaching 28.6 mg/kg FW (Pérez-Gregorio *et al.*, 2010). Recent findings further confirm strong varietal differences in onion flavonoid content. In one study, AC-2, AC-3 and AC-10 exhibited the highest total flavonoids (219.00-220.90 mg QE/g), while AC-8 and AC-11 also stood out for their high dry matter content (up to 42.37%), underscoring the potential for selecting nutritionally rich and commercially valuable varieties (Paşazade & Hanci, 2025). Similarly, another evaluation reported 'NHRDF Red' with the highest flavonoid content (168.77 mg QE/g DW) and 'Bhima Shubhra' with the lowest (1.31 mg QE/g DW), with most cultivars showing significant differences (Sagar *et al.*, 2020).

Flavonoid content in onions is strongly influenced by tissue type, with the skin consistently showing much higher levels than the bulb. For example, red onion skin contained the highest flavonoid concentrations (20.22 mg QE/g DW) compared to yellow skin (10.69 mg QE/g DW) (Albishi *et al.*, 2013), and other studies reported even greater values, such as 165.20 mg QE/g in red onion skin (Singh *et al.*, 2009) and 163.14 mg QE/g in skin *vs* only 13.76 mg QE/g in the bulb (Skerget *et al.*, 2009). Similar findings were noted by Duan *et al.* (2015), who measured 49.69 mg QE/g in onion peel. In contrast, bulb flavonoid levels were generally much lower, ranging from 7.48 to 9.92 mg/100 g FW across six cultivars (Rodríguez *et al.*, 2008) and 1.85-2.13 mg QE/g FW in 18 Korean varieties (Sharma *et al.*, 2014).

iii. Antioxidant activity

Onions are rich in antioxidant compounds such as flavonoids, quercetin, kaempferol, and their derivatives (Liguori *et al.*, 2017). The comparative antioxidant activity as influenced by various genotype groups has been listed in Table 4. Assessment of antioxidant capacity using FRAP showed that red onions possess the highest antioxidant activity, with values ranging from 1.97 to 5.45 mmol Trolox/g and reducing power up to 345 mmol ascorbic acid equivalents/g; notable genotypes include I-80, I-33, Sel-383, and Sel-397, while white genotypes exhibited the lowest antioxidant and phenolic content (Dalamu *et al.*, 2010). Similar trends were reported in antioxidant assays, with FRAP values ranging from 1.60 to 4.63 µmol Trolox/g FW and CUPRAC values from 2.23 to 5.14 µmol Trolox/g FW. Among the genotypes, Pusa White Flat (white) recorded the lowest activity, whereas L-28 (dark red) showed the highest (Islam *et al.*, 2019). Comparable findings were observed in the USA, where FRAP ranged from 2.48 µmol Trolox/g in sweet onions to 5.76 µmol Trolox/g in red cultivars (Lu *et al.*, 2011). Another FRAP and CUPRAC analyses confirmed red and yellow onion cultivars (e.g., Sel-383, N-53, Pusa Red) consistently exhibited superior antioxidant activities compared to white varieties, with rank orders largely stable across years and methods (Kaur *et al.*, 2009). In a research of 15 short-day onion varieties, antioxidant activity (AOA) measured by the Folin-Ciocalteu assay ranged from 440–785µg/mL and by DPPH from 19.1-79.8 µg/mL, with white onions generally showing lower AOA and red onions higher values, albeit with exceptions (Lee *et al.*, 2015). While some studies found bulbs to contain higher flavonoid content and antioxidant capacity than leaf blades, others highlight strong genotype-dependent differences (Arena *et al.*, 2024). Across ecotypes, antioxidant capacity generally follows the trend white < yellow < red, although exceptions exist, such as Moroccan yellow ecotypes displaying antioxidant levels comparable to red ones. Moroccan onions overall showed strong antioxidant activity (0.0989-1.15 mg ascorbic acid equiv/g DW), exceeding that of Czech varieties (Brahimi *et al.*, 2022). Similarly, Chinese onions demonstrated a clear color-dependent pattern, with red cultivars consistently exhibiting the highest antioxidant activity compared to yellow and white types (Zhang *et al.*, 2016). The FRAP from 0.31-27.22 µmol Trolox/g, with red onions often showing peaks such as 82.04mg/100g FW for DPPH, 175.2 mg/100g FW for ABTS and 143.37mg/100g FW for FRAP, illustrated the significant influence of genotype, pigment and agronomic practices on antioxidant potential (Gupta *et al.*, 2025a).

Red onions demonstrated the highest antioxidant activities, recording 82.04 mg/100 g FW (DPPH), 175.2 mg/100 g FW (ABTS), and 143.37 mg/100 g FW (FRAP). In contrast, white onions, despite lacking flavonoids and anthocyanins, still exhibited moderate values of 33.38, 66.48, and 54.36 mg/100 g FW, respectively (Zhang *et al.*, 2016). Similarly, antioxidant assays on onion skin powder from fifteen Indian cultivars revealed wide variability, with DPPH scavenging ranging from 5.71% in the white cultivar 'Bhima Shubhra' to 94.17% in the red cultivar 'NHRDF Red', confirming significant differences ($P < 0.05$) in antioxidant potential across genotypes (Sagar *et al.*, 2020). Studies have shown that red onion skins exhibit the highest antioxidant activity (84.1%), followed by violet (73.9%) and white (23.4%) (Prakash *et al.*, 2007). Similarly, Nuutila *et al.* (2003) reported higher DPPH activity in red skins (74.7%) compared to yellow (40.8%). Additional studies found similar trends: Singh *et al.* (2009) measured DPPH activity at 75.3 ± 4.5% for red onion peel, Skerget *et al.*

(2009) at 47.17 ± 1.85%, and Duan *et al.* (2015) observed a remarkable 93.45 ± 0.42%. ABTS assays further confirmed wide variation, with values ranging from 6.97% in 'Bhima Shubhra' to 96.04% in 'NHRDF Red', and consistently higher inhibition in darker cultivars (Manohar *et al.*, 2017; Burri *et al.*, 2017).

Conclusions

Onions hold both nutritional and functional importance, with their health advantages largely linked to their high levels of phenolic compounds, antioxidants and flavonoids. The significant variations in total phenols, total flavonoids and antioxidant activity among different onion genotypes and colour categories, especially the elevated concentrations in red and yellow onions have been reported in various studies which highlights the opportunity for selecting and breeding improved varieties that provide enhanced health benefits. Elements such as environmental conditions, agricultural practices, postharvest techniques and storage conditions also influence these quality traits, underscoring the necessity for integrated management approaches to maximize the preservation of phytochemicals. There is a need for thorough phytochemical profiling and bioactivity assessments of Indian onion varieties, which are presently inadequately researched. By tackling this gap through targeted breeding and refined cultivation practices, we can significantly improve the nutritional value of onions and further their contribution to public health.

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Contributions

Amar Jeet Gupta and Volaguthala Sairam-*Literature Review*; Amar Jeet Gupta, Volaguthala Sairam and Priyanka Kotapati-*First Draft Preparation*; Amar Jeet Gupta and Supriya Kaldate-*Review and Editing*; Amar Jeet Gupta and Vijay Mahajan-*Conceptualization, Supervision and Final Review*.

Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

This review article did not generate any supplementary data.

Informed Consent

All the authors agree with the content of this review article.

Table 2. Comparative analysis of total phenolic content (TPC) in onion

Category	Range of TPC	High TPC varieties	Reasons	References
Red, Pink and White Onions	Mean values of Red onion :867.8 mg/kg; Pink onion: 702.0 mg/kg; and White onion: 165.0 mg/kg	Sel-397, Burgundy, Sel-383; Sel-20-411 and Pusa Red	Red onions are characterized by a predominance of quercetin derivatives, with quercetin-3, 4-diglycoside being the major compound.	Dalamu *et al*., 2010
Red, Pink, White, Yellow and Purple Onions	Yellow: 741.84 mg/100 g FW; Red: 622.27 mg/100 g FW; White: 389.69 mg/100 g FW; Skin: DR: 289.04, Pink: 231.73, White: 19.74 mg / 100 g FW	The onion genotypes of Yellow, Red (bulb and skins); Dark Red (skin) had both anthocyanin and flavonol contents more compared to white onion	Phenolic content correlates with colour intensity; skins have notably higher TPC; Yellow > red > pink > white.	Gupta *et al*., 2025a
Red and White Onions (India, USA)	Total phenolics was highest in red genotypes (867.8 mg GAE/kg), followed by pink (702.0 mg GAE/kg), and lowest in white onions (165.0 mg GAE/kg)	Sel-383, Pusa Red, Sel-402 and N-53	Red colour is associated with higher levels of flavonoids, particularly quercetin glycosides which contributed the colour intensity and the higher antioxidant potential.	Kaur *et al*., 2009
Red, White Onions (Turkey/ Iran)	Red: 6.4-13.8 mg GAE/g DW; White: 2.2-4.7 mg GAE/g DW	Turkish Red Onions	Red onions are rich in flavonoids which contribute to both the red pigmentation and the higher antioxidant/phenolic levels.	Guner *et al*., 2021

Red, White Onions (Iran)	Red onions contain 1.5-2x times and more phenolics than white varieties	Red Onions	Due to the presence of anthocyanins and higher levels of other polyphenolic compounds in red onion varieties.	Mardani *et al*., 2023
Ecotypes and Cultivars (Czech)	Czech: 2.66-3.37 g GAE/Kg DW	Elenka (brown-skinned, Italian cultivar)	Due to their genetic background and reflecting inherent genetic variation rather than environmental effects	Mitrova *et al*., 2016
Korean cultivars	All Cultivars: 2.39 ± 0.05 mg GAE/g DW to 6.63 ± 0.66 mg GAE/g DW	Korean cultivars: 2.39 ± 0.05 mg GAE/g DW	Genetic variation of onion cultivars is the major factor influencing phenolic and flavonoid levels.	Sharma *et al*., 2014
Multiple cultivars and year-wise	Highest in Fireball; lowest in Starito; late varieties richer than early	Fireball, Kamal F_1 (late maturing)	The type of Cultivar, colour, and year (environment) shown impact on TPC; late-maturing and red varieties had higher phenolics contents.	Yang *et al*., 2004; Lu *et al*., 2011
Various genotypes	TPC: 740.67 to 1145.33 µg GAE/ml	Among the tested varieties, Hissar 2, Pusa Red, Arka Kalyan, L-28, Arka Pitamber & JWO-1 have ranked among the top for TPC	The genotypic differences played a major role in the accumulation of bioactive compounds.	Islam *et al*., 2019
Onion skin powder	14.55-289.04 mg GAE/g DW	Red type: NHRDF Red	Significant variation in TPC of onion skin powder depending on cultivar; red skin richest in phenolics.	Sagar *et al*., 2020

Table 3. Comparative analysis of flavonoid Content in onion

Category	Range of flavonoids content	High flavonoid sample	Reasons	References
Red, yellow, white onions	Total flavonoid content was 111.10 ± 5.98 mg/100 g in red onions, 36.64 ± 3.59 mg/100 g in yellow onions & absent in white onions	Red onions	The presence of quercetin and its glycosides was more in red and yellow cultivars due to their high pigment concentration and genetic ability to synthesize flavonoids.	Zhang *et al*., 2016
Red & Yellow onions	Red: 415-1917 mg/kg FW Yellow: 270-1187 mg/kg FW	Red onions	Variations in bulb colour arise from mutations in structural and regulatory genes such as *dihydroflavonol 4-reductase*, *chalcone isomerase* and *anthocyanidin synthase*.	Khandagale and Gawande, 2019
White vs. Red onions	Among the tested cultivars, Vermelha da Povoa and Red Creole red onions contained the greatest quercetin concentrations, with 280.2 ± 41.5 and 304.3 ± 81.2 mg/kg FW, respectively	Red onions	Due to their richness in flavonols (e.g., quercetin derivatives like quercetin 7,4-diglucoside and quercetin 3,4-diglucoside) and the presence of anthocyanins (e.g., cyanidin derivatives).	Pérez-Gregorio *et al*., 2010
Red and Yellow onion ecotypes (Morrocan)	The flavonoid content ranged from 0.67 to 1.52 mg equivalent of quercetin/g DW respectively	Red onions	Due to inherent genetic differences that determine their biochemical expression and antioxidant profiles.	Brahimi *et al*., 2022
Various onion cultivars (India)	Ranged from 7.26–49.29 mg/100 g FW	Pusa Red, N-53, Sel-402, H-44 (>40 mg/100 g FW)	Major onion flavonoids include quercetin and kaempferol, along with derivatives such as quercetin-3,4′-O-diglucoside, quercetin-4′-O-monoglucoside, and isorhamnetin glucosides.	Ewald *et al*., 1999; Marotti and Piccaglia, 2002
Onion genotypes by colour groups	Total flavonoids range from 0.15-2.56 QE/g FW	Purplish brown, yellowish brown, dark brown genotypes (e.g., MKS8823GO)	The interaction between genotype and environment causes phenotypic plasticity, resulting in fluctuations in flavonoid content even within the same cultivar.	Tabussam *et al*., 2022

Ten onion varieties and shallots	Flavonoids: 5.8–69.2 mg catechin equiv/100 g FW.	Western Yellow (69.2 ± 3.7), New York Bold (55.2 ± 5.8) were on the top	Varieties with darker skin pigmentation, such as red onions, possess higher flavonoid contents due to their enhanced phenolic compound profiles, which contribute to greater antioxidant capacity.	Nuutila *et al*., 2003
Onion bulb varieties AC series	Total flavonoid content: AC-2 (219.00 mg QE/g), AC-3 (219.952 mg QE/g), AC-10 (220.904 mg QE/g).	AC-2, AC-3 and AC-10	Among onion varieties and between bulbs & leaves, indicated that the genetic background of each ecotype strongly influences flavonoid biosynthesis.	Paşazade and Hanci, 2025
Varietal flavonoid differences in Indian cultivars	Total flavonoids ranged from 1.31 ± 0.32 (Bhima Shubhra) to 168.77 ± 0.87 mg QE/g DW (NHRDF Red)	NHRDF Red	The elevated flavonoid content in onion cultivars like NHRDF Red and Hissar-2 is primarily explained by their genetic makeup, pigment intensity and the protective function of onion skins as flavonoid reservoirs.	Sagar *et al*., 2020
Onion skin *vs.* bulb flavonoid content	Red skin: 20.22–165.20 mg/g DW Peel: 49.69 mg/g DW; Bulbs (6 cultivars): 7.48–9.92 mg/100g FW; Korean cultivars: 1.85–2.13 mg/g FW	Red onion skin	Onion skin-especially from red cultivars-is a concentrated reservoir of flavonoids and a valuable source of natural antioxidants while bulb has lower metabolic activity and thus lower flavonoid levels.	Albishi *et al*., 2013; Singh *et al*., 2009; Skerget *et al*., 2009; Sharma *et al*., 2014

Table 4. Comparative analysis of antioxidant activity/ content in onion genotypes

Variety/ colour category	Range of total antioxidant activity	High antioxidant sample	Assessed via	Reasons	References
Red and White onions	Highest antioxidant levels; FRAP: 1.97–5.45 mmol Trolox/g; Reducing power up to 345 mmol ascorbic acid equiv./g	I-80, I-33, Sel-383, Sel-397	FRAP, CUPRAC, Reducing power	The specific onion cultivars reflect the combined effects of pigment-associated biochemical pathways and inherent genotypic potential.	Dalamu *et al*., 2010
White, Yellow, Red Onions	FRAP: 1.60–4.63 µmol Trolox/g; CUPRAC: 2.23–5.14 µmol Trolox/g	Dark red genotype L-28	FRAP, CUPRAC	This attributed to their phenolic composition and genetic variation among coloured cultivars.	Lu *et al*., 2011; Islam *et al*., 2019
Short-day onions (white, yellow, red)	AOA (Folin-Ciocalteu): 440–785 µg/mL; DPPH: 19.1–79.8 µg/mL	Onions with higher anthocyanin and quercetin	Folin-Ciocalteu, DPPH	The onions richer in anthocyanins and quercetin consistently exhibited higher AOA levels.	Lee *et al*., 2015
Bulbs vs. leaf blades of various genotypes	Bulbs higher antioxidant capacity and flavonoid content	Red onion bulbs	FRAP, DPPH, ORAC	High antioxidant contents in certain cultivars, particularly red and traditional landraces, reflect their pigment-rich biochemical, genetic makeup and organ-specific metabolic allocation.	Arena *et al*., 2024
Moroccan onion ecotypes (white, yellow and red)	Antioxidant potential: 0.0989 to 1.15 mg ascorbic acid equiv./g DW	Red and some yellow ecotypes	Assay not specified	The higher flavonoid and antioxidant contents in some Moroccan onion varieties are directly attributed to their intrinsic genetic differences among ecotypes in their capacity to biosynthesize and accumulate secondary metabolites.	Brahimi *et al*., 2022
Red vs Yellow Onions (Red Cross F_1, Vatikiotiko, Sivan F_1, Creamgold)	DPPH radical scavenging capacity lower in red varieties compared to red-yellow and yellow	Sivan F_1 (red-yellow), Creamgold (yellow)	DPPH	The low antioxidant content in "Vatikiotiko" was due to its genetic and biochemical characteristics, distinguishing it from the flavonoid-rich red commercial varieties.	Petropoulos *et al*., 2015
Onion skins of different colours	Red skins highest AOA 84.1%, violet 73.9%, white 23.40%; DPPH in red peel 75.3 ± 4.5%, up to 93.45 ± 0.42%	Red onion skins	DPPH, AOA	Darker skins have significantly greater antioxidant activity.	Duan *et al*., 2015; Nuutila *et al*., 2003; Skerget *et al*., 2009

FRAP values in onion cultivars	The range of 0.12 ± 0.03 to 37.12 ± 0.49 µmol gallic acid/g; 'NHRDF Red' highest, 'Bhima Shubhra' lowest; 'Donna' 43.6 ± 4.4; 'Barito' 28.2 ± 1.8 µmol gallic acid/g	NHRDF Red, Donna	FRAP	The cultivars with darker pigmented outer skins contained higher levels of quercetin, which is strongly linked to both anthocyanin presence and overall antioxidant activity.	Burri *et al*., 2017
Red vs White Cultivars (Korean onions)	Red cultivars FRAP: 33.18 ± 0.43 µmol TE/g dw; White cultivars FRAP: 12.58 ± 1.14 µmol TE/g dw; Range 11.59 ± 0.99 to 27.22 ± 1.34 µmol TE/g dw across 18 cultivars	Red cultivars	FRAP	Higher antioxidant activity in certain genotypes was associated with increased accumulation of quercetin and its glycosides, such as quercetin-3,4′-O-diglucoside and quercetin-4′-O-monoglucoside.	Sharma *et al*., 2015
10 Onion Cultivars (Total Antioxidant Capacity, TAC)	Significant variation in TAC; Fireball highest TAC; yellow Starito lowest; among late onions, Kamal F_1 & Rolex highest; Hamlet & Mundial low	Fireball, Kamal F_1, Rolex	TAC	The cultivars pigmentation (linked to flavonoid and anthocyanin content) plays a significant role in determining antioxidant potential	Mlcek *et al*., 2015

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