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VEGETABLE ANTIOXIDANTS IN CANCER PREVENTION: A REVIEW

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ABSTRACT

Cancer is a leading global health challenge and accumulating evidence indicates the pivotal role of diet in its prevention. A hallmark of many cancers is nuclear DNA damage, which may be due to increased generation of oxidative and nitrative reactive species leading to genomic instability. Vegetables are a rich natural source of antioxidants that neutralize these harmful reactive species and help safeguard defense systems in the body. This review discusses the role of vegetable derived antioxidants such as carotenoids, flavonoids and polyphenols in cancer prevention. Experimental and observational studies have shown that these compounds can protect against oxidative damage, modulate inflammation, affect the progression of the cell cycle and influence apoptosis. Further population-based studies demonstrate a consistent inverse relationship between higher vegetable consumption and the risk of several cancers including lung, breast, colorectal and prostate cancers. In summary, the increased intake of antioxidant-rich vegetables is a simple, cost-effective and practical dietary measure to reduce risk of cancer.
Keywords: Antioxidants, cancer, flavonoids, oxidative stress, reactive oxygen species (ROS), reactive nitrogen species.

Introduction

Antioxidants are bioactive compounds that play a crucial role in protecting the body from oxidative stress by neutralizing free radicals, which are known to cause cellular damage and contribute to chronic diseases such as cancer and cardiovascular disorders (Paganga *et al.*, 1999). Antioxidants are broadly classified into enzymatic (superoxide dismutase, catalase and glutathione peroxidase) and non-enzymatic types, which include vitamins (A, C and E), carotenoids, flavonoids and phenolic compounds (Weisburger, 1999). Vegetables are among the most important dietary sources of non-enzymatic antioxidants. Key antioxidants present in vegetables include β-carotene, lycopene, lutein, quercetin, catechin, rutin, polyphenols and essential minerals such as selenium. Green leafy vegetables like spinach, kale and broccoli are rich in carotenoids and flavonoids; carrots and sweet potatoes contain high levels of β-carotene; tomatoes are abundant in lycopene; while onions, cabbage, okra and parsley provide quercetin, anthocyanins and other phenolic compounds (Prior *et al.*, 2000). These vegetable antioxidants have been shown to prevent types of free radical damage associated with cancer development (NCI, 2017).

Cancer

Cancer is a complex disease in which certain cells acquire the ability to grow uncontrollably, bypassing the normal regulatory mechanisms that govern cell division. These abnormal cells can accumulate to form tissue masses known as tumours. Tumours are classified as benign or malignant. Benign tumours are generally localized, do not invade surrounding tissues and rarely reoccur after removal. In contrast, malignant tumours are invasive, capable of penetrating adjacent tissues and can spread to distant organs through the bloodstream or lymphatic system-a process known as metastasis (Hanahan *et al*., 2011, Siegel *et al*., 2023 and Vogelstein *et al*., 2015)

Types of Cancer

Cancer is a group of diseases characterized by uncontrolled cell growth and the potential to invade or spread to other parts of the body. Carcinomas are the most common type of cancer and originate from epithelial cells, which form the lining of organs and tissues. Examples include lung, breast, prostate and colorectal cancers, which account for the majority of cancer-related cases globally (Siegel *et al*., 2023). Sarcomas arise from mesenchymal tissues, including bone, muscle, fat, blood vessels and fibrous connective tissues such as tendons and ligaments. Osteosarcoma, a type of bone sarcoma and liposarcoma, originating from fat cells, are notable examples (Hanahan *et al*., 2011). Leukaemia's are cancers of the blood-forming tissues in the bone marrow. Unlike solid tumours, leukemias lead to the accumulation of abnormal white blood cells, which interfere with normal blood function; common types include acute myeloid leukemia (AML) and chronic lymphocytic leukemia (CLL) (Kantarjian *et al*., 2012). Lymphomas originate from lymphocytes, a type of white blood cell involved in immune responses. These include Hodgkin lymphoma, characterized by Reed-Sternberg cells and non-Hodgkin lymphoma, which encompasses a diverse group of lymphoid cancers (Coiffier, 2008). Multiple myeloma is a malignancy of plasma cells, leading to excessive production of abnormal antibodies and bone lesions. This type often presents with anaemia, kidney dysfunction and skeletal damage (Rajkumar, 2020). Finally, melanoma arises from melanocytes, the pigment-producing cells of the skin and is the most aggressive form of skin cancer (Garbe *et al*., 2013).

Factors Causing Cancer

Cancer is a multifactorial disease influenced by a complex interplay of environmental, lifestyle and biological factors. Environmental factors contribute significantly to cancer risk through exposure to physical, chemical and biological agents. Ionizing radiation, such as X-rays and nuclear fallout, can directly damage DNA, while non-ionizing ultraviolet (UV) radiation induces mutagenesis and skin cancers (Rodriguez *et al*., 2021). Air and water pollution, including particulate matter (PM2.5), nitrogen oxides, arsenic and nitrates, introduce carcinogenic compounds that disrupt normal cellular functions (IARC, 2018 and Loomis *et al*., 2013). Occupational exposure to industrial chemicals such as asbestos, benzene and formaldehyde, as well as heavy metals like cadmium, chromium and arsenic, has been linked to lung, bladder and liver cancers (Smith *et al*., 2019)

Lifestyle factors also play a pivotal role in cancer development. Tobacco use remains the leading preventable cause of cancer worldwide, associated with lung, oral and pancreatic cancers. Diets high in processed and red meats, saturated fats and sugars, along with physical inactivity, contribute to obesity-related cancers, while excessive alcohol consumption increases the risk of liver, breast and colorectal cancers (WCRF/AICR, 2018). Viral infections, such as human papillomavirus (HPV), hepatitis B and C and Epstein-Barr virus, are recognized as oncogenic agents triggering abnormal cell proliferation (De Martel *et al*., 2020).

Biological and internal factors further influence cancer susceptibility. Genetic mutations, whether inherited or acquired, can impair tumour suppressor genes and activate oncogenes, initiating carcinogenesis. Hormonal imbalances, such as elevated estrogen levels, are linked to breast and endometrial cancers. A weakened immune system, chronic inflammation and cellular aging (senescence) create a microenvironment conducive to tumour progression (Hanahan *et al*., 2011 and Vogelstein *et al*., 2015). The risk of cancer thus emerges from a synergistic combination of these external exposures and internal vulnerabilities, emphasizing the need for preventive strategies targeting both environmental and lifestyle factors.

Generation of Free Radicals and Their Effects on the Body

Reactive oxygen species (ROS) are highly reactive molecules that are generated under both physiological and pathological conditions. Under normal cellular metabolism, ROS are primarily produced in the mitochondria during aerobic respiration. In the mitochondrial electron transport chain, electrons are transferred through a series of complexes and ultimately accepted by molecular oxygen. When oxygen receives the complete set of four electrons, it is reduced to harmless water. However, partial reduction of oxygen generates different ROS: the transfer of a single electron produces superoxide anion (O_2^-), two electrons produce hydrogen peroxide (H_2O_2) and three electrons generate the highly reactive hydroxyl radical (·OH). All of these ROS have the potential to damage cellular components if not properly neutralized (Halliwell *et al*., 2015).

Besides mitochondria, ROS are also produced endogenously via NADPH oxidase activity, xanthine oxidase and reactions involving transition metals such as iron and copper (Pham *et al*., 2008). Exogenous sources, including tobacco smoke, air pollution, ultraviolet and ionizing radiation, certain drugs and industrial chemicals, further contribute to ROS generation.

ROS are highly reactive because of their unpaired electrons, enabling them to attack biomolecules. They can induce lipid peroxidation, damaging cellular membranes; oxidize proteins, altering enzyme structure and function and induce DNA damage, leading to mutations and genetic instability. Accumulation of such damage can disrupt normal cell cycle regulation, promote uncontrolled cell proliferation and eventually contribute to tumour formation and cancer development (Valko *et al.*, 2007 and Klaunig *et al*., 2004). Therefore, maintaining a balance between ROS production and antioxidant defenses is critical for cellular homeostasis and cancer prevention.

What are Antioxidants?

Antioxidants are molecules that inhibit or significantly delay the oxidation of other molecules, thereby protecting cells from oxidative damage. They are often referred to as free radical scavengers because of their ability to neutralize highly reactive free radicals-unstable molecules containing unpaired electrons in their outer shell. Free radicals, generated during normal metabolic processes or through exposure to environmental stressors such as radiation, pollution and toxins, can damage DNA, proteins and lipids, contributing to aging and the development of chronic diseases including cancer, cardiovascular disorders and neurodegenerative conditions (Halliwell *et al*., 2015, Lobo *et al*., 2010). Antioxidants counteract these harmful effects by donating electrons to free radicals, stabilizing them without becoming reactive themselves. They can be enzymatic, produced naturally in the body (e.g., superoxide dismutase, catalase, glutathione peroxidase) or non-enzymatic, obtained through diet, particularly from fruits, vegetables, nuts and whole grains (Niki, 2014 and Surai, 2015). Regular intake of dietary antioxidants has been associated with reduced oxidative stress and lower risk of chronic diseases, highlighting their critical role in maintaining human health (Gulcin, 2020).

Types of Antioxidants:

Antioxidants are molecules that mitigate oxidative stress by neutralizing free radicals and reactive oxygen and nitrogen species, which are implicated in cellular damage, aging and chronic diseases including cancer and cardiovascular disorders. These compounds are broadly classified into enzymatic antioxidants, produced endogenously and non-enzymatic antioxidants, primarily derived from dietary sources. Enzymatic antioxidants such as Superoxide Dismutase (SOD), Catalase (CAT) and Glutathione Peroxidase (GPx) constitute the body's primary defense against oxidative stress. SOD catalyzes the conversion of superoxide radicals into hydrogen peroxide, which is further decomposed into water and oxygen by CAT. GPx reduces hydrogen peroxide and lipid peroxides using glutathione, thereby preventing membrane lipid peroxidation (Haida *et al*., 2019). These enzymes are essential for maintaining cellular redox homeostasis and protecting against oxidative damage.

Non-enzymatic antioxidants, largely obtained from vegetables, fruits and other plant-based foods, directly scavenge free radicals and include vitamins, carotenoids, polyphenols, organosulfur compounds and certain minerals. Water-soluble vitamin C protects plasma and cellular components, while fat-soluble vitamin E stabilizes lipid membranes. β-carotene, lycopene, lutein and zeaxanthin, present in carrots, tomatoes, spinach and kale, serve as carotenoids with potent antioxidant activity. Polyphenols, including flavonoids (quercetin, kaempferol, catechins) and phenolic acids (ferulic acid, caffeic acid), are abundant in cruciferous vegetables, onions and leafy greens and exhibit both radical-scavenging and anti-inflammatory properties. Organosulfur compounds such as glucosinolates in broccoli, cabbage and cauliflower and allicin in garlic and onions, enhance detoxification and antioxidant defenses. Additionally, minerals such as selenium, zinc, copper and manganese act as cofactors for enzymatic antioxidants, supporting their activity and reinforcing the body's oxidative defense system. The synergistic action of enzymatic and non-enzymatic antioxidants is crucial in protecting cells from oxidative damage, reducing the risk of chronic diseases, and maintaining overall physiological homeostasis (Rudenko *et al*., 2023).

Antioxidant-Rich Vegetables

Tomato

Tomatoes are among the most widely cultivated and consumed vegetables globally and are recognized for their exceptional nutritional and antioxidant profile. They are rich sources of vitamin C, β-carotene, folate, potassium, vitamin E, phenolic compounds, flavonoids, chlorogenic acid, rutin, xanthophylls, plastoquinones and, most notably, lycopene. Quantitative analyses of fresh tomato cultivars have revealed substantial antioxidant levels, including approximately 276 mg/100 g dry matter of ascorbic acid, 613 mg gallic acid equivalents/100 g dry matter of total phenolics and 38 mg/100 g dry matter of lycopene. Together, these compounds contribute significantly to the strong antioxidant capacity of tomatoes (Willcox *et al*., 2003, Sahlin *et al*., 2004., Friedman, 2002, George *et al*., 2004 and Kerkhofs *et al*., 2005).

Vitamin C acts as a powerful antioxidant by donating electrons to neutralize oxidative agents, while lycopene, the predominant carotenoid in tomatoes, plays a central role in protecting against oxidative stress despite lacking vitamin A activity (Giovannucci, 1999). Notably, lycopene exhibits high stability during storage and thermal processing, allowing it to remain abundant in commonly consumed cooked tomato products. This stability and bioavailability are believed to contribute to the observed associations between regular tomato consumption and reduced risks of cardiovascular diseases and several cancers, including breast, colorectal, lung and prostate cancers (Weisburger, 1998).

Processing methods can influence the antioxidant content of tomatoes in different ways. While prolonged drying and frying may reduce vitamin C, phenolics and overall antioxidant activity, certain cooking methods such as boiling and baking have relatively minimal effects. Interestingly, thermal processing can increase the extractability of lycopene, enhancing its bioaccessibility. Emerging technologies, such as high hydrostatic pressure treatment, further help preserve water-soluble antioxidants in tomato products. Overall, both fresh and appropriately processed tomatoes remain valuable dietary sources of health-promoting antioxidants (Arab *et al*., 2000, Rissanen *et al*., 2001, Munoz *et al*., 2009).

Chilli and Sweet Peppers

Chilli and sweet peppers are nutritionally rich vegetables and valuable sources of natural antioxidants in the human diet. They contain high levels of vitamin C, ranging from approximately 140-165 mg/100 g in chilli and 128-152 mg/100 g in sweet pepper, along with an array of carotenoids such as β-carotene and capsanthin (Daood *et al*., 1996, Krinsky, 1994, Krinsky, 2001 and Howard *et al*., 2000).Red sweet peppers, in particular, are notable for their high capsanthin content, while both pepper types provide substantial amounts of total phenolic compounds. These bioactive constituents collectively contribute to a strong antioxidant capacity, underscoring the role of peppers in protecting cells against oxidative stress.

Peppers are also excellent sources of vitamins A, C and E, as well as neutral and acidic phenolic antioxidants that play important roles in plant defense and human health. Distinct phenolic fractions, including flavonoids, phenolic acids and capsaicinoids-especially in chilli peppers-have been shown to exhibit significant antioxidant activity. The concentration and composition of these compounds vary widely depending on genotype, maturity stage and environmental growing conditions and they may be further influenced by post-harvest handling and processing (Kumar *et al*., 2009 and Martinez *et al*., 2005).

Fruit ripening and harvest timing strongly affect antioxidant accumulation in peppers. As peppers mature and develop colour, levels of carotenoids, provitamin A, flavonoids, phenolic acids and ascorbic acid generally increase, while lutein content tends to decline (Howard *et al*., 2000). Coloured and fully mature peppers, particularly red and brown varieties, show the highest antioxidant potential. However, vitamin C levels may decrease during drying and post-harvest storage, highlighting the importance of optimal harvest periods and handling practices to preserve the nutritional quality of chilli and sweet peppers.

Potato

Potato tubers are an important dietary source of ascorbic acid and contribute significantly to vitamin C intake in human nutrition. The concentration of ascorbic acid varies considerably among potato cultivars, with the Marabel variety showing particularly high levels, reaching up to 207.2 mg/kg and exceeding several other varieties by 15-49 per cent. Studies on North American potato varieties and breeding lines have similarly reported vitamin C contents ranging from 11 to 30 mg per 100 g fresh weight, highlighting the influence of genetic factors on nutritional quality (Hamouz *et al*., 2007 and Love *et al*., 2003).

Agronomic practices play a crucial role in determining ascorbic acid levels in potato tubers. Increased nitrogen fertilization has been shown to negatively affect vitamin C content, with higher nitrogen doses leading to measurable reductions. In contrast, elevated applications of potassium and magnesium have a positive effect, significantly enhancing ascorbic acid accumulation in tubers. These findings emphasize the importance of balanced nutrient management for improving the nutritional value of potatoes.

Post-harvest handling and processing further influence ascorbic acid retention in potatoes. Vitamin C levels gradually decline during storage and are further reduced by common cooking methods and industrial processing. Despite these losses, potatoes remain a valuable and widely consumed source of vitamin C, particularly when fresh tubers are stored properly and prepared using minimal processing techniques (Weber and Putz, 1999).

Cruciferous Vegetables

Vegetables of the Brassicaceae (Cruciferae) family are rich sources of bioactive compounds such as polyphenols, flavonoids and glucosinolates. Although glucosinolates themselves show limited antioxidant activity, their hydrolysis products exhibit strong antibacterial, antioxidant and anticancer effects. Brassica vegetables vary widely in their antioxidant profiles; red cabbage contains anthocyanins, while broccoli and Brussels sprouts are richer in carotenoids, tocopherols and vitamin C. Lutein and β-carotene are the dominant carotenoids in this group, contributing significantly to their antioxidant capacity (Jaiswal *et al*., 2011 and Plumb *et al*., 1997).

Broccoli is particularly notable for its high levels of polyphenols, glucosinolates especially glucoraphanin and vitamins C and E, which together enhance its ability to neutralize free radical (Heinonen *et al*., 1989). However, antioxidant content is influenced by growth stage, cultivation practices and cooking methods. While boiling can cause substantial losses due to leaching, microwaving better preserves or even enhances antioxidant availability. Therefore, both vegetable selection and preparation methods are crucial for maximizing the health benefits of Brassica vegetables.

Bulb Crops

The aerial parts of radish (*Raphanus sativus*), including the leaves and stems that are often discarded, possess remarkable antioxidant and free radical-scavenging activity. Analytical studies have identified a diverse range of polyphenolic compounds in these tissues, such as catechin, protocatechuic, syringic, vanillic, ferulic, sinapic and *o*-coumaric acids, along with flavonoids like myricetin and quercetin. Notably, radish leaves and stems exhibit high total polyphenolic contents, measuring approximately 86.16 and 78.77 mg/g dry extract, respectively. These findings highlight the significant nutritional value of these underutilized plant parts and support their potential use as natural antioxidant sources in health-promoting and functional food products (Beevi *et al.,* 2010).

Carrots are another antioxidant-rich vegetable, providing dietary fiber, carotenoids, vitamins C and E and a variety of phenolic acids, including chlorogenic, caffeic and coumaric acids (Potter *et al*., 2011 and Indrawati *et al*., 2004). In addition to these compounds, water-soluble anthocyanins present in certain carrot varieties contribute to their antioxidant potential. Regular consumption of carrot juice has been shown to enhance total antioxidant status and reduce lipid peroxidation, thereby offering protective effects for cardiovascular health. Processing techniques also influence antioxidant availability, with thermal treatment increasing water-soluble antioxidant capacity and high-pressure processing helping to preserve these beneficial compounds.

Bulb vegetables such as onion and garlic further enrich the diet with potent antioxidants, particularly in regions where they are consumed frequently. Among commonly eaten raw vegetables, red onion exhibits the highest antioxidant activity, followed by white and yellow onions, with garlic also contributing substantially. Together, these vegetables underscore the importance of diverse plant-based foods as accessible and effective sources of natural antioxidants that support overall health and disease prevention (Gorinstein *et al*., 2009).

Root crops contain antioxidants such as total phenolics (70-120 mg GAE/100 g), phenolic acids (catechin, protocatechuic, chlorogenic and caffeic acids), flavonoids (myricetin, quercetin), carotenoids or anthocyanins (5-10 mg/100 g) and vitamin C (10-25 mg/100 g). These phytochemicals provide strong free-radical-scavenging activity (Beevi *et al*., 2010).

Green Leafy Vegetables

Green leafy vegetables are excellent sources of antioxidant vitamins and bioactive compounds that contribute significantly to human health. Species such as *Amaranthus*, *Centella asiatica*, *Murraya koenigii* and *Trigonella foenum-graecum* contain substantial levels of ascorbic acid, total carotenoids, β-carotene and phenolic compounds. Among these, *Murraya koenigii* exhibits the highest antioxidant activity, while *Centella asiatica* shows comparatively lower activity. The wide variation in antioxidant content reflects differences in plant species and their biochemical composition (Gupta *et al*., 2005 and Gupta *et al*., 2009).

Lettuce is another leafy vegetable with notable antioxidant and health-promoting properties. Leaf-type lettuce varieties are particularly rich in phytochemicals, with red-leaf cultivars such as ‘Red Sails’ showing higher total phenolic content and antioxidant capacity than green types. This cultivar is especially abundant in chlorogenic acid, a major phenolic compound known for its antioxidant potential. Genetic factors, along with cultivation and management practices, strongly influence antioxidant composition, with open-field cultivation generally enhancing the phenolic content of lettuce compared to protected growing systems (Oh *et al*., 2011).

Spinach and kale are also recognized for their high antioxidant value, largely due to their richness in carotenoids and polyphenols. Spinach, in particular, contains exceptionally high levels of polyphenolic acids and flavonoids, which account for its strong antioxidant activity. Both spinach and kale are important dietary sources of lutein, a carotenoid with well-established antioxidant properties, further supporting the role of green leafy vegetables in reducing oxidative stress (Ligor *et al*., 2012).

Leguminous Vegetables

Leguminous vegetables such as cowpea (*Vigna unguiculata*) and African yam bean (*Sphenostylis sternocarpa*) are valuable sources of natural antioxidants. Their vitamin C, total phenol and phytate contents contribute to strong free radical scavenging activity and reducing power, suggesting that these beans can serve as functional foods. The high antioxidant potential of these legumes is largely attributed to their phenolic compounds, which play a key role in neutralizing oxidative stress and supporting overall health (Oboh, 2006 and Ismail *et al*., 2009).

Other commonly consumed legumes, including winged beans (*Psophocarpus tetragonolobus*), French beans (*Phaseolus vulgaris*), string beans (*Vigna sinensis*) and snow peas (*Pisum sativum*), also display significant antioxidant activity. Among these, string beans demonstrate the highest overall antioxidant capacity, while snow peas contain the richest levels of total phenolics, ascorbic acid and β-carotene. Detailed analyses of pea extracts reveal a diverse profile of phenolic compounds, including vanillic, caffeic, p-coumaric, ferulic and sinapic acids, as well as flavonoids like quercetin and kaempferol, all contributing to their strong antiradical and antioxidant properties (Tavani and Vecchia, 1995 and Block *et al*., 1992).

Beyond legumes, vegetables such as daikon sprouts, spinach and onions show high antioxidant activity against reactive oxygen and nitrogen species, while cruciferous vegetables like broccoli, cabbage and Chinese cabbage are particularly effective against hypochlorite ions. Epidemiological evidence highlights that consumption of raw and fresh vegetables consistently protects against cancer, with over 85 per cent of studies reporting an inverse association. Protective effects are especially notable for lettuce, leafy greens, cruciferous vegetables, allium species, tomatoes and carrots, while legumes and potatoes show more modest benefits. Key nutrients such as β-carotene, vitamin E and calcium have also been linked to reduced breast cancer risk (Negri *et al*., 1996).

Table 1: Antioxidants and their vegetable sources

Antioxidant	**Vegetables Rich in Antioxidants**
Lycopene	Tomato, Red Bell Pepper, Red Cabbage
Beta-Carotene	Carrot, Pumpkin, Sweet Potato, Spinach
Lutein & Zeaxanthin	Spinach, Broccoli, Green Peas
Anthocyanins	Red Cabbage, Purple Brinjal (Eggplant), Beetroot
Betalains	Beetroot
Vitamin C	Bell Pepper, Tomato, Broccoli, Green Peas
Vitamin E	Spinach, Pumpkin, Broccoli
Flavonoids	Okra, Broccoli, Beans, Onion
Phenolic Compounds	Okra, Brinjal, Tomato
Quercetin	Onion, Red Cabbage
Sulphur Compounds	Garlic, Onion, Radish, Turnip
Chlorophyll	Green Leafy Vegetables, Green Beans

Conclusion

Antioxidants are essential bioactive compounds that play a critical role in protecting the body against oxidative stress by neutralizing reactive oxygen species (ROS), thereby preventing cellular damage, DNA mutations and the development of cancer (Tajalli *et al*., 2020). They maintain redox homeostasis, support mitochondrial and metabolic functions, enhance immune responses and modulate inflammatory pathways, while also promoting detoxification and cellular repair mechanisms (Lucic *et al*., 2023). Regular consumption of natural antioxidants from vegetables, fruits and plant-based foods not only reduces the risk of chronic diseases such as cancer, cardiovascular disorders and diabetes, but also protects vision and skin health through carotenoids like lutein and zeaxanthin (EL feky *et al*., 2018). Overall, antioxidants represent a safe, effective and multifaceted strategy for disease prevention and health promotion, highlighting their importance in nutrition, therapeutic research and public health strategies.

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