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Nutritional and Bioactive Profile of Beetroot (*Beta vulgaris*) and Its Impact on Human Health

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ABSTRACT

Beta vulgaris L., commonly known as beetroot, is an important dietary plant recognized for its high nutritional value and diverse bioactive compounds. It has gained increasing scientific attention for its potential therapeutic effects on cardiovascular, hepatic, renal, and metabolic disorders. This review highlights the nutritional composition, bioactive constituents, and associated health benefits of B. vulgaris. The root and leaves are rich in carbohydrates, dietary fiber, vitamins, minerals, and phytochemicals such as betalains, polyphenols, flavonoids, and nitrates. These compounds exhibit antioxidant, anti-inflammatory, hepatoprotective, and anticancer activities. The review also emphasizes the mechanisms through which beetroot-derived compounds exert their physiological effects, including modulation of oxidative stress, enhancement of nitric oxide bioavailability, and regulation of cellular signaling pathways. Overall, B. vulgaris serves as a functional food with considerable potential in disease prevention and health promotion.

Keywords: Phytochemicals, diabetes, antioxidant, infections

INTRODUCTION

Over the past decade, there has been a growing global interest in plant-based nutrition and functional foods due to their role in preventing chronic diseases and improving overall health outcomes (Pandey & Rizvi, 2019). Among these, *Beta vulgaris* L., commonly known as beetroot, has emerged as a significant vegetable crop valued not only for its culinary applications but also for its therapeutic properties (Clifford et al., 2015). Belonging to the family Amaranthaceae, B. vulgaris encompasses several varieties, including sugar beet, chard, and table beet, which differ in chemical composition and use (Kujala et al., 2017). Beetroot has long been utilized in traditional medicine for treating ailments such as anemia, hypertension, and liver dysfunction (Vulić et al., 2014). Recent studies have confirmed that its health-promoting effects are primarily attributed to the presence of bioactive compounds such as betalains, phenolic acids, flavonoids, and inorganic nitrates (Kujawska et al., 2021). These constituents exhibit a broad spectrum of pharmacological actions, including antioxidant, anti-inflammatory, antimicrobial, and anticancer properties (Georgiev et al., 2010). Furthermore, the increasing popularity of beetroot juice as a natural ergogenic aid for athletes highlights its ability to enhance exercise performance and cardiovascular efficiency through improved nitric oxide (NO) synthesis (Jones et al., 2018). Consequently, B. vulgaris is being increasingly recognized as a functional food with significant implications for human health and disease prevention.

This review provides an updated overview of the nutritional composition, phytochemical profile, and biological effects of *Beta vulgaris*, emphasizing its potential role in promoting health and preventing disease.

2. Nutritional Composition of *Beta vulgaris*

The nutritional profile of *Beta vulgaris* is characterized by its abundance in carbohydrates, dietary fiber, essential vitamins, and minerals. The root is composed primarily of water (approximately 85–88%) and carbohydrates (about 8–10%), mainly in the form of sucrose, glucose, and fructose (Guldiken

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et al., 2016). The protein and fat contents are relatively low, typically ranging from 1–2% and <0.1%, respectively (Wruss et al., 2015). Nevertheless, the high concentration of dietary fiber contributes significantly to digestive health and glycemic control.

Beetroot is also a valuable source of micronutrients such as folate, potassium, magnesium, iron, and vitamin C (Clifford et al., 2015). Folate, in particular, is essential for DNA synthesis and repair, making beetroot beneficial during periods of rapid growth or pregnancy (Wootton-Beard & Ryan, 2011). Potassium supports cardiovascular health by regulating blood pressure, while magnesium contributes to enzymatic and metabolic processes. The leaves of B. vulgaris are nutritionally rich, containing higher levels of calcium, iron, and vitamin A compared to the root (Lee et al., 2020).

Another distinctive feature of B. vulgaris is its high nitrate (NO_3^-) content, which has been associated with improved vascular function and reduced hypertension (Lidder & Webb, 2013). Upon ingestion, dietary nitrates are converted to nitrites (NO_2^-) and subsequently to nitric oxide (NO), a potent vasodilator that enhances endothelial function and oxygen delivery (Kapil et al., 2015). This property underpins many of the cardioprotective effects attributed to beetroot consumption.

Additionally, beetroot provides various organic acids such as oxalic, citric, and malic acids, which contribute to its flavor and potential health benefits (Guldiken et al., 2016). The combination of macro- and micronutrients in B. vulgaris not only supports general nutrition but also provides a foundation for its therapeutic applications in cardiovascular and metabolic health.

3. Bioactive Compounds in *Beta vulgaris*

The diverse pharmacological activities of *Beta vulgaris* are largely attributed to its wide array of bioactive compounds, including betalains, phenolic acids, flavonoids, and nitrates. These constituents not only provide beetroot's distinctive red-violet color but also play critical roles in antioxidant defense, inflammation modulation, and cellular protection.

3.1 Betalains

Betalains are nitrogen-containing, water-soluble pigments unique to the order Caryophyllales and are classified into two groups: betacyanins (red–violet) and betaxanthins (yellow–orange) (Stintzing & Carle, 2004). Betacyanins such as betanin and isobetanin are predominant in beetroot, constituting up to 95% of total pigment content (Esatbeyoglu et al., 2015). These pigments exhibit potent free-radical scavenging activity and are more stable across a range of pH values compared to anthocyanins (Kujala et al., 2017). The antioxidant mechanism involves the donation of electrons to neutralize reactive oxygen species (ROS), thereby preventing oxidative stress-induced cellular damage.

3.2 Phenolic Compounds and Flavonoids

Beetroot contains various phenolic acids, including ferulic, caffeic, and p-coumaric acids, which contribute to its overall antioxidant capacity (Clifford et al., 2015). Flavonoids such as quercetin, rutin, and kaempferol are also present in significant amounts, particularly in the leaves (Lee et al., 2020). These compounds inhibit lipid peroxidation, chelate transition metals, and regulate inflammatory signaling pathways such as NF-κB and MAPK (Pavlov et al., 2013). Regular consumption of flavonoid-rich beetroot extracts has been associated with improved vascular function and reduced oxidative stress in vivo (Kujawska et al., 2021).

3.3 Dietary Nitrates

Beetroot is one of the richest dietary sources of inorganic nitrates (NO_3^-), which are metabolized into nitric oxide (NO) through the nitrate–nitrite–NO pathway (Lidder & Webb, 2013). Nitric oxide acts as a key vasodilator, improving blood flow and oxygen delivery to tissues while reducing blood pressure (Kapil et al., 2015). Additionally, nitrate-derived NO enhances mitochondrial efficiency, thereby improving exercise endurance and performance (Jones et al., 2018).

3.4 Other Bioactives

Minor compounds such as saponins, carotenoids, and betaine also contribute to the overall bioactivity of B.

vulgaris (Chhikara et al., 2019). Betaine functions as an osmolyte and methyl donor, playing a vital role in liver function and homocysteine metabolism. These diverse bioactive compounds collectively account for the therapeutic efficacy of beetroot in maintaining health and preventing disease.

4. Pharmacological and Therapeutic Properties

4.1 Antioxidant Activity

Numerous studies have confirmed that *Beta vulgaris* exhibits strong antioxidant potential due to its betalain and polyphenol content. Betanin, in particular, scavenges free radicals such as superoxide and hydroxyl radicals and prevents lipid peroxidation (Esatbeyoglu et al., 2015). Animal studies have shown that beetroot extract enhances the activities of endogenous antioxidant enzymes, including superoxide dismutase (SOD), catalase, and glutathione peroxidase (Kujawska et al., 2021). These properties help counteract oxidative damage associated with chronic diseases like atherosclerosis, diabetes, and cancer.

4.2 Anti-inflammatory Effects

Beetroot extract downregulates pro-inflammatory mediators such as interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and cyclooxygenase-2 (COX-2), reducing systemic inflammation (Pavlov et al., 2013). Betalains also inhibit the expression of inducible nitric oxide synthase (iNOS), thereby modulating the inflammatory response (Vulić et al., 2014). These effects make B. vulgaris beneficial in the management of inflammatory and autoimmune conditions.

4.3 Anticancer Potential

Betanin and other betalains have been reported to suppress cancer cell proliferation and induce apoptosis through mitochondrial and caspase-dependent pathways (Kapadia et al., 2018). In vitro studies have demonstrated that beetroot extract inhibits the growth of colon, lung, and breast cancer cells, while in vivo models show reduced tumor formation (Zielinska-Przyjemska & Ignatowicz, 2008). The anticancer activity is attributed to the modulation of oxidative stress, cell cycle arrest, and upregulation of pro-apoptotic genes.

4.4 Cardiovascular and Metabolic Benefits

Beetroot's nitrate content promotes vasodilation, endothelial repair, and blood pressure regulation (Kapil et al., 2015). Regular consumption of beetroot juice has been linked to reductions in systolic and diastolic blood pressure, improved lipid profiles, and enhanced exercise tolerance (Jones et al., 2018). Additionally, beetroot supplementation has shown beneficial effects in metabolic syndrome by improving insulin sensitivity and reducing oxidative lipid damage (Clifford et al., 2015).

4.5 Hepatoprotective and Renal Effects

Experimental evidence suggests that B. vulgaris protects hepatic and renal tissues from oxidative injury induced by toxins or heavy metals. Kujawska et al. (2021) reported that beetroot juice administration in cadmium-exposed rats significantly reduced markers of hepatic damage and lipid peroxidation. The hepatoprotective mechanism involves activation of antioxidant defense systems and inhibition of inflammatory signaling pathways.

5. Impact on Human Health

The inclusion of *Beta vulgaris* in the human diet provides multifaceted health benefits. The synergistic effects of its bioactive compounds support cardiovascular, metabolic, neurological, and gastrointestinal health.

5.1 Cardiovascular Health

Dietary nitrate supplementation through beetroot enhances endothelial function by increasing nitric oxide availability, leading to improved vascular relaxation and lower blood pressure (Lidder & Webb, 2013). Clinical studies have shown that daily intake of beetroot juice significantly reduces systolic blood pressure in hypertensive individuals (Kapil et al., 2015).

5.2 Athletic Performance

Beetroot supplementation is widely recognized for enhancing exercise performance. The nitrate–nitrite

(NO) pathway improves muscle oxygenation, reduces oxygen cost during submaximal exercise, and delays fatigue (Jones et al., 2018). Athletes consuming beetroot juice demonstrate increased endurance, power output, and recovery efficiency.

5.3 Neurological and Cognitive Effects

Recent studies indicate that beetroot-derived nitrates improve cerebral blood flow, which may enhance cognitive function and reduce the risk of neurodegenerative disorders (Wightman et al., 2015). The antioxidant and anti-inflammatory effects of betalains further contribute to neuronal protection against oxidative stress.

5.4 Gut Health and Microbiota

Beetroot fiber supports gut microbiome diversity by promoting the growth of beneficial bacteria such as Lactobacillus and Bifidobacterium (Chhikara et al., 2019). Moreover, betalains may possess prebiotic-like properties, enhancing short-chain fatty acid (SCFA) production and intestinal barrier integrity.

6. Mechanisms of Action

The diverse biological effects of *Beta vulgaris* are primarily mediated through several molecular and biochemical pathways involving nitric oxide (NO) production, antioxidant defense mechanisms, and modulation of cellular signaling networks.

6.1 Nitric Oxide Pathway

Dietary nitrates from beetroot are converted into nitrites via oral bacteria and subsequently reduced to nitric oxide (NO) in the systemic circulation (Lidder & Webb, 2013). NO acts as a vasodilator by activating guanylyl cyclase, which increases cyclic guanosine monophosphate (cGMP) levels in vascular smooth muscle cells, leading to relaxation and improved blood flow (Kapil et al., 2015). Additionally, NO enhances mitochondrial efficiency and glucose uptake, contributing to improved energy metabolism and exercise tolerance (Jones et al., 2018).

6.2 Antioxidant Mechanisms

Betalains and phenolic compounds exert their antioxidant activity by scavenging reactive oxygen species (ROS), chelating metal ions, and upregulating antioxidant enzymes such as catalase, superoxide dismutase, and glutathione peroxidase (Esatbeyoglu et al., 2015). These compounds also inhibit lipid peroxidation and protect cellular components from oxidative stress-induced apoptosis (Georgiev et al., 2010). Betanin, the major betalain pigment, acts as a chain-breaking antioxidant, stabilizing free radicals through hydrogen atom transfer.

6.3 Modulation of Cellular Signaling

Beetroot bioactives regulate various intracellular pathways, including NF-κB, Nrf2, and MAPK (Pavlov et al., 2013). Activation of Nrf2 (nuclear factor erythroid 2-related factor 2) promotes the transcription of antioxidant response elements, enhancing cellular resistance to oxidative damage. Meanwhile, inhibition of NF-κB signaling results in decreased expression of pro-inflammatory mediators, providing anti-inflammatory benefits (Kujawska et al., 2021).

6.4 Anti-apoptotic and Cytoprotective Effects

Experimental models demonstrate that beetroot extract modulates apoptotic pathways by upregulating Bcl-2 (anti-apoptotic) and downregulating Bax and caspase-3 (pro-apoptotic) proteins (Kapadia et al., 2018). These actions contribute to its cytoprotective effects against oxidative and chemical insults in hepatic and renal tissues.

7. Processing and Bioavailability

The health-promoting properties of B. vulgaris are influenced by food processing methods, storage conditions, and digestive bioavailability.

7.1 Effect of Processing

Processing techniques such as boiling, baking, and fermentation can alter the stability and concentration of beetroot's bioactive compounds. Betalains are sensitive to high temperatures, prolonged cooking, and light exposure, which can lead to pigment degradation and reduced antioxidant capacity (Guldiken et al., 2016). However, mild thermal treatments and vacuum concentration can preserve or

even enhance phenolic content due to the release of bound compounds (Clifford et al., 2015).

7.2 Bioavailability of Betalains and Nitrates

Betalains exhibit moderate bioavailability, with plasma concentrations peaking within 2–3 hours post-consumption (Tesoriere et al., 2013). Despite limited absorption, they are biologically active at low concentrations and contribute significantly to systemic antioxidant defense. Dietary nitrates, in contrast, display high bioavailability and efficiently convert into bioactive nitric oxide in the body (Lidder & Webb, 2013).

7.3 Influence of Food Matrix

The bioaccessibility of beetroot compounds depends on the food matrix and co-ingested nutrients. For example, co-consumption with vitamin C-rich foods can enhance nitrate conversion to NO, while polyphenol interactions may affect betalain absorption (Wootton-Beard & Ryan, 2011). Beetroot juice and powders are thus considered optimal formulations for maximizing physiological benefits.

8. Safety, Toxicity, and Contraindications

8.1 General Safety

Beetroot and its derived products are generally recognized as safe (GRAS) for human consumption. Most studies report no adverse effects even with regular intake of beetroot juice or supplements (Clifford et al., 2015).

8.2 Potential Risks

Excessive consumption may lead to beeturia, a harmless condition characterized by red-colored urine due to betalain excretion (Guldiken et al., 2016). However, individuals with kidney stones or oxalate sensitivity should limit intake because beetroot contains moderate levels of oxalates (Wruss et al., 2015). Furthermore, individuals with hypotension or those taking antihypertensive medications should exercise caution due to beetroot's blood pressure–lowering effects (Kapil et al., 2015).

8.3 Toxicological Evidence

Animal studies have shown no genotoxic or mutagenic effects associated with beetroot extracts, confirming their high safety margin (Kujawska et al., 2021). Nevertheless, further long-term clinical studies are needed to assess chronic exposure and potential drug–nutrient interactions.

9. Future Prospects and Research Gaps

1. Although extensive research supports the nutritional and therapeutic potential of B. vulgaris, several gaps remain. Future studies should focus on:

2. Conducting large-scale, randomized clinical trials to validate preclinical findings.

3. Elucidating molecular targets of betalains and their metabolites in human physiology.

4. Improving stability and bioavailability through encapsulation or nano-formulation technologies.

5. Exploring synergistic effects of beetroot with other functional foods or nutraceuticals.

6. Investigating genetic and environmental factors influencing phytochemical composition.

Emerging research in metabolomics, nutrigenomics, and personalized nutrition could further clarify the mechanisms through which beetroot exerts health-promoting effects (Chhikara et al., 2019).

10. CONCLUSION

Beta vulgaris L. represents a nutritionally and pharmacologically valuable plant with multifaceted health benefits. Its rich composition of betalains, phenolics, flavonoids, and dietary nitrates contributes to potent antioxidant, anti-inflammatory, cardioprotective, and anticancer properties. The mechanisms underlying these effects involve modulation of nitric oxide signaling, oxidative stress defense, and cellular homeostasis. Despite its recognized safety, further clinical validation and formulation optimization are warranted to maximize its bioefficacy. As an emerging functional food, B. vulgaris holds great promise for integration into dietary strategies aimed at preventing chronic diseases and enhancing human health.

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