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Phyto-nutraceuticals importance of beet root: A review

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Abstract
Beetroot (*Beta vulgaris*) is a nutrient-dense vegetable increasingly recognized for its significant phyto-nutraceutical properties and health benefits. It is rich in bioactive compounds, including betalains, dietary nitrates, polyphenols, and flavonoids, which contribute to its potent antioxidant, anti-inflammatory, and cardioprotective effects. The high nitrate content, which converts to nitric oxide in the body, enhances vasodilation, improves blood flow, and helps regulate blood pressure. Clinical studies support its role in improving cardiovascular health, endothelial function, and athletic performance by increasing oxygen utilization and endurance. Additionally, beetroot consumption has been linked to enhanced cognitive function due to improved cerebral blood flow, as well as digestive health benefits from its dietary fiber content. Its anti-inflammatory and potential anti-cancer properties further underscore its therapeutic value. Economically, beetroot is a versatile and sustainable crop with growing applications in the food industry as a natural colorant and functional ingredient, as well as in the cosmetic and nutraceutical sectors. Despite its benefits, considerations regarding oxalate content and interactions with medications necessitate moderated consumption. Overall, beetroot represents a promising functional food with substantial health-promoting potential and economic relevance, supporting its integration into balanced diets and sustainable agricultural systems.

Keywords: Beetroot, phyto-nutraceuticals, antioxidants, cardiovascular health, functional food, nitric oxide, sustainable agriculture

Introduction
Beetroot (*Beta vulgaris*) has garnered significant scientific and commercial attention in recent years, due to its notable nutritional profile and diverse health benefits. Historically valued in ancient civilizations such as the Egyptians, Greeks, and Romans, beetroots were initially cultivated for their medicinal properties before becoming a staple in various culinary traditions (Mirmiran *et al*., 2020) [46]. Contemporary research has substantiated many of these historical claims, elucidating the rich composition of bioactive compounds, including betalains, nitrates, polyphenols, and flavonoids, which contribute to their antioxidant, anti-inflammatory, and cardioprotective effects (Fu *et al*., 2020 [16, 17, 18, 19]; Velmurugan *et al*., 2016) [59]. This has positioned beetroot as a functional food with promising applications in both preventive healthcare and disease management (Clifford *et al*. 2015) [11].

One of the most extensively studied benefits of beetroot is its positive effect on cardiovascular health. Beetroots are abundant in dietary nitrates and facilitate the production of nitric oxide in the body, which enhances vasodilation, improves blood flow, and regulates blood pressure (Kapil *et al*., 2015 [30]; Hobbs *et al*., 2013) [27]. Clinical studies have demonstrated that regular consumption of beetroot juice significantly lowers systolic and diastolic blood pressure, particularly in hypertensive individuals (Wylie *et al*., 2013 [63]; Jones, 2014) [29]. Furthermore, the potent antioxidant capacity of beetroot helps mitigate oxidative stress and inflammation, which are two key contributors to chronic diseases such as diabetes, neurodegenerative disorders, and metabolic syndromes (Clifford *et al*., 2015) [11]. Recent evidence also suggests that beetroot supplementation enhances oxygen utilization and endurance in athletes, thereby improving performance and post-exercise recovery (Baum *et al*., 2016) [8].

Beetroot possesses significant economic value beyond its physiological benefits. The increasing global demand for natural and plant-based health products has driven an upsurge in beetroot-based functional foods, dietary supplements, and nutraceuticals (Mirmiran *et al*. 2020) [43, 44, 45, 46].

Compositional analysis of commercial beetroot products has revealed variations in betalain content, nitrate levels, and antioxidant activity, emphasizing the need for standardization in the food and pharmaceutical industries. The increasing commercialization of beetroot-derived products, including natural food colorants and functional beverages, underscores their potential as lucrative crops for agricultural economies worldwide (Fu *et al*., 2020) [15]. Given its extensive health-promoting properties and economic relevance, beetroot remains a critical subject for further research in nutritional science, functional food development, and sustainable agriculture.

Nutritional Profile of Beetroot

Beetroot (Beta vulgaris) is recognized for its exceptional nutritional profile, offering a rich composition of macronutrients, micronutrients, and bioactive compounds that contribute to a broad spectrum of health benefits. As a functional food, beetroot has garnered significant attention in the field of clinical nutrition due to its potential role in modulating metabolic processes, improving cardiovascular health, and enhancing exercise performance.

Macronutrients

Beetroot is predominantly composed of carbohydrates with a lower proportion of proteins and fats, rendering it a vital energy source in the human diet. On average, a 100 g serving of raw beetroot provides approximately 9.6 g of carbohydrates, including naturally occurring sugars such as sucrose, fructose, and glucose, which serve as readily available energy substrates (Mirmiran *et al*., 2020). Additionally, beetroot contains 2.8 g of dietary fiber, which plays a crucial role in maintaining gut health, regulating blood glucose levels, and supporting lipid metabolism (Kapil *et al*., 2015) [30]. Although the protein content is relatively low (1.6 g per 100 g), it provides the essential amino acids required for cellular function and tissue repair (Jones, 2014) [29]. The lipid content is minimal (0.1 g per 100 g), reinforcing its classification as a low-fat dietary component suitable for cardiovascular health.

Micronutrients

Beetroots are a rich source of essential vitamins and minerals, which contribute to multiple physiological functions. It is particularly abundant in folate (vitamin B9), an essential cofactor for DNA synthesis, cellular division, and erythropoiesis, with an average concentration of 109
µg per 100 g (Hobbs *et al*., 2012) [28]. Potassium, another key constituent (325 mg per 100 g), is critical for maintaining electrolyte balance, muscle contraction, and cardiovascular function (Velmurugan *et al*., 2016) [59]. Magnesium (23 mg per 100 g) supports neuromuscular transmission and enzymatic activities, while iron (0.8 mg per 100 g) plays a vital role in oxygen transport and hemoglobin synthesis (Gilchrist, Winyard, & Benjamin, 2010) [25]. Furthermore, beetroot contains moderate levels of vitamin C (4.9 mg per 100 g), an essential antioxidant involved in collagen synthesis and immune function (Clifford *et al*., 2015) [11].

Phytochemicals and Bioactive Compounds

In addition to their fundamental macronutrient and micronutrient composition, beetroots are a potent source of bioactive compounds that exhibit significant pharmacological potential. The presence of betalains, which are nitrogen-containing pigments responsible for red violet coloration, contributes to their strong antioxidant and anti-inflammatory properties (Pietrzkowski *et al*., 2010) [48, 49]. These compounds have been reported to reduce oxidative stress by scavenging free radicals and modulating inflammatory pathways (Mirmiran *et al*. 2020) [43, 44, 45, 46].

Dietary nitrates, another key bioactive component of beetroot (250-400 mg per 100 g), have been extensively studied for their role in enhancing nitric oxide (NO) bioavailability (Jones, 2014 [29]; Wylie *et al*., 2013) [63]. NO-mediated vasodilation has been demonstrated to improve endothelial function, reduce arterial stiffness, and lower systolic and diastolic blood pressures, thereby mitigating cardiovascular risk factors (Kapil *et al*., 2015; Velmurugan *et al*., 2016) [59, 30]. Furthermore, nitrate-derived NO enhances mitochondrial efficiency and reduces oxygen consumption during exercise, thereby contributing to improved endurance and physical performance (Wylie *et al*., 2013) [63].

Beetroot also contains a variety of polyphenolic compounds, including flavonoids and phenolic acids, which further augments its antioxidant potential (Baum, Kim, & Wolfe, 2016) [8]. These phytochemicals have demonstrated protective effects against oxidative damage, lipid peroxidation, and neuroinflammation, highlighting their therapeutic potential for the prevention of neurodegenerative and metabolic disorders (Clifford *et al*., 2015) [11].

The combined presence of macronutrients, micronutrients, and bioactive compounds underscores beetroot's classification as a functional food, with significant implications for human health. Its growing prominence in dietary interventions and clinical applications further reinforces the need for continued research on its mechanistic benefits and therapeutic potential.

Health Benefits

Cardiovascular Health

Beetroot (Beta vulgaris) has garnered considerable attention due to its beneficial effects on cardiovascular health, primarily attributed to its high nitrate content. Nitrates are metabolized into nitric oxide in the body, which plays a critical role in vasodilation, thereby improving blood flow and reducing vascular resistance. The antihypertensive effects of beetroot, particularly its ability to regulate blood pressure, have been well-documented in both clinical and preclinical studies (Kavitha *et al*., 2013 [35]; PMC, 2015). Furthermore, beetroot consumption has been demonstrated to enhance endothelial function, a key factor in maintaining vascular health and preventing cardiovascular disease (Székely & Máté, 2023 [55, 56]; Bangar *et al*., 2022) [6].

Blood Pressure Regulation

The blood pressure-lowering effect of beetroot is largely attributed to its high nitrate content, which is converted into nitric oxide (NO) in the body. NO induces vasodilation by relaxing smooth muscle cells in the blood vessels, thus improving blood flow and reducing systolic and diastolic blood pressures. Clinical trials have consistently demonstrated that beetroot supplementation significantly lowers both systolic and diastolic blood pressures, providing an effective natural strategy for managing hypertension (Wylie *et al*., 2013; PMC, 2015) [63]. These findings highlight the potential of beetroot as a functional food for improving cardiovascular health.

Improved Endothelial Function

In addition to its effects on blood pressure, beetroot has been demonstrated to enhance endothelial function, which is crucial for maintaining vascular integrity. Endothelial cells regulate vasodilation and platelet aggregation, and their dysfunction is a

precursor to atherosclerosis and other cardiovascular diseases. Studies have indicated that beetroot consumption enhances NO bioavailability, thereby improving endothelial responsiveness and vascular function (Székely & Máté, 2023 [55, 56]; Fu *et al*., 2020) [18, 19].

Athletic Performance

The potential of beetroot to enhance athletic performance has garnered significant interest, particularly for its effects on endurance and post-exercise recovery. The primary mechanism underlying these benefits is the improvement in oxygen delivery to the muscles facilitated by the conversion of dietary nitrates into nitric oxide. This results in enhanced muscle oxygenation, which leads to improved endurance and reduced fatigue during exercise.

Enhanced Endurance

Numerous studies have demonstrated that beetroot supplementation significantly improves endurance performance, particularly during prolonged aerobic exercise. Nitrate-derived NO enhances the efficiency of oxygen utilization in muscles, enabling athletes to sustain exercise for extended periods. This effect is particularly pronounced in exercises that require sustained cardiovascular output, such as running and cycling (Wylie *et al*. 2013) [63]. The ergogenic potential of beetroot renders it a valuable dietary supplement for athletes seeking to optimize their performance.

Improved Recovery

Beetroot supplementation also facilitates post-exercise recovery. Research has demonstrated that the antioxidant properties of beetroot help mitigate exercise-induced oxidative stress, reduce muscle soreness, and improve recovery time. Moreover, the enhanced blood flow resulting from increased nitric oxide availability accelerates nutrient and oxygen delivery to the muscles, contributing to faster repair and recovery post-exercise (Wylie *et al*., 2013) [63].

Cognitive Function

The cognitive benefits of beetroots have been increasingly recognized, particularly in aging populations. The high nitrate content of beetroot has been associated with improved cerebral blood flow, which is essential for optimal brain function. Increased NO production facilitates vasodilation, improves blood supply to the brain, and potentially enhances cognitive performance, especially in individuals at risk for age-related cognitive decline.

Increased Blood Flow to the Brain

Increased blood flow to the brain is crucial for the maintenance of cognitive health. Beetroot nitrate-derived nitric oxide has been shown to enhance cerebral blood flow, which may contribute to improved cognitive function, particularly in older adults. This effect is especially relevant in individuals with early signs of cognitive decline, as improved cerebral circulation can support brain function and delay neurodegeneration (Gilchrist *et al*. 2014) [25].

Potential Neuroprotective Effects

In addition to improving blood flow, the antioxidant properties of beetroots are hypothesized to exert neuroprotective effects. Betalains and other bioactive compounds found in beetroot have been shown to exhibit strong antioxidant activity, which helps mitigate oxidative stress, an underlying factor in many neurodegenerative diseases, including Alzheimer's and Parkinson's diseases (Gilchrist *et al*., 2010) [25]. By reducing oxidative damage, beetroots may offer protection against neurodegenerative conditions.

Digestive Health

Beetroot is a rich source of dietary fiber that plays a crucial role in maintaining digestive health. Fibers support gastrointestinal motility, prevent constipation, and promote regular bowel movement. Furthermore, beetroots with high fiber content contribute to gut health by fostering the growth of beneficial bacteria, which is essential for maintaining a balanced microbiome and overall digestive function (Healthline, 2016).

Anti-inflammatory Properties

Chronic inflammation is a significant factor in the pathogenesis of metabolic and cardiovascular diseases. Beetroot has demonstrated potent anti-inflammatory properties owing to its high concentration of bioactive compounds, such as betalains. These compounds contribute to the reduction of pro-inflammatory cytokine levels, thus mitigating chronic inflammation. Regular consumption of beetroot has been associated with lower levels of inflammatory markers, which may reduce the risk of diseases, such as rheumatoid arthritis, cardiovascular disease, and diabetes (Self, 2023; BBC Good Food, 2023).

Potential Anti-cancer Effects

Emerging evidence suggests that beetroot may possess anti-cancer properties, which are attributed to its antioxidant-rich composition. Betalains and other polyphenolic compounds in beetroot exhibit strong antioxidant and anti-inflammatory effects, which may help to prevent oxidative DNA damage and inhibit cancer cell proliferation. Preclinical studies have shown that beetroot extracts can induce apoptosis (programmed cell death) in various cancer cell lines, suggesting their potential therapeutic role in cancer prevention and treatment (Jones *et al*., 2014; Journal of Clinical Pharmacy and Therapeutics, 2021) [25].

Economic Benefits

Agricultural Perspective

Beetroot (Beta vulgaris) is an economically important crop due to its high yield and adaptability to diverse climatic conditions. Studies have demonstrated that beetroots can thrive in various soil types and environmental conditions, making them a viable crop across different geographic regions (Kujala *et al*., 2002; Gasztonyi *et al*., 2001) [21, 22, 23]. Their ability to grow in both temperate and subtropical climates enhances their potential for global cultivation (Adhikari *et al*., 2017; Adhikari *et al*., 2020) [1, 2]. Furthermore, the robust crop yield and sustainability of beetroots make them an essential crop for sustainable agricultural systems, providing economic stability for farmers (Singh *et al*., 2021) [54].

Food Industry Applications

Beetroot has garnered substantial attention in the food industry, primarily due to its natural pigments (betalains), which serve as effective and non-toxic food colorants. These pigments not only provide vibrant hues but also exhibit antioxidant properties, making them a desirable alternative to synthetic dyes (Fu *et al*., 2020 [18, 19]; Georgiev *et al*., 2010) [24]. Additionally, the nutritional composition of beetroot, including dietary fiber and bioactive compounds, supports its use as a functional ingredient in processed foods, enhancing both flavor and health benefits

(Székely & Máté, 2023 [55, 56]; Gasztonyi *et al*., 2001) [21, 22, 23]. Its application in fortified foods such as juices and smoothies has further accelerated its demand in the health-conscious consumer market (Basile *et al*., 2016 [7]; Sienkiewicz *et al*., 2017) [52].

Beetroot-based Products Market

In recent years, the market for beetroot-based products has expanded significantly. Beetroot juices, which are recognized for their cardiovascular health benefits and role in improving exercise performance, have become popular consumer products (Kapil *et al*., 2015 [30]; Wylie *et al*., 2013) [63]. Moreover, the antioxidant and anti-aging properties of beetroot have facilitated its incorporation into the cosmetic industry, with applications in skincare and beauty products (Fu *et al*. 2020; Mirmiran *et al*. 2020) [43, 44, 45, 46]. The increasing consumer preference for natural and plant- based ingredients has further propelled the demand for beetroot-based products in both the wellness and cosmetic sectors (López-Delgado *et al*., 2019 [40]; Gao *et al*., 2018) [20].

Employment Opportunities in Farming and Processing

Beetroot cultivation and processing play crucial roles in job creation in rural and urban economies. The expanding market for beetroot-based products has led to an increased demand for labor in the farming, harvesting, and food processing industries (Hobbs *et al*., 2013) [27]. The rise in beetroot-based supplements and processed food products has generated employment opportunities in the research, product development, and distribution sectors (Liu *et al*., 2020 [38, 39]; Wang *et al*., 2021) [61]. This growth fosters economic development by providing stable livelihoods in both agricultural and industrial sectors.

Cultivation and Processing

Farming Techniques

Beetroot cultivation is highly influenced by the soil type, climatic conditions, and agricultural practices. Optimal growth is achieved in loamy, well-drained soils with a pH range of 6.0-7.0. Sustainable farming practices, such as crop rotation with legumes and incorporation of organic amendments, enhance soil health and increase the nutrient content of the soil (Karami *et al*., 2021) [33]. Furthermore, modern techniques such as precision agriculture, utilizing GPS-guided machinery and soil sensors, have proven effective in optimizing water and nutrient use, reducing waste, and enhancing yield (Alva *et al*., 2022) [4]. The integration of biocontrol agents for pest management, along with minimal chemical inputs, significantly reduces environmental impacts and enhances the sustainability of beetroot farming (Fathima *et al*., 2020) [13]. Additionally, the use of nitrogen-fixing cover crops improves soil fertility and reduces reliance on synthetic fertilizers (Möller *et al*., 2019) [47].

Harvesting Methods

Beetroot harvesting is a critical process that directly influences the quality and nutritional content of the crop. Beetroots are typically ready for harvest 3-4 months after planting, depending on the cultivar and climatic conditions (Kendall *et al*., 2020) [36]. Mechanical harvesting is commonly employed in large-scale production, where soil conditions and beetroot size allow efficient root extraction. However, manual harvesting remains predominant on smaller farms, and high-quality roots are required for niche markets (Zhang *et al*., 2021) [64]. The timing of harvest is crucial, as over-mature roots can lead to a loss in marketability due to size and texture deterioration, with beetroot roots exceeding 12 cm in diameter exhibiting a decline in sweetness and nutritional content (Sarker *et al*., 2019) [51]. Proper timing ensures that the roots retain optimal levels of bioactive compounds, particularly betalains, which are susceptible to post-harvest degradation (Gao *et al*., 2020) [20].

Processing and Preservation

Post-harvest processing techniques play a significant role in preserving the nutritional and bioactive properties of beetroot. Standard processing involves washing, peeling, and cutting, followed by boiling, juicing, or fermentation. To maintain the integrity of betalains, which are sensitive to heat, cold storage and minimal processing techniques are recommended (Turhan *et al*. 2022) [57]. For beetroot juice, pasteurization and vacuum sealing are commonly employed to inhibit microbial growth and extend the shelf life (Gao *et al*., 2020) [20]. Fermentation is also gaining popularity, not only as a preservation method but also as a means to enhance probiotic content and functional benefits (Gürbüz *et al*., 2021) [26]. Additionally, freeze-drying and spray-drying are effective in maintaining nutritional content, particularly polyphenolic compounds, while providing a longer shelf life for powdered beetroot supplements (Vasanthan *et al*., 2020) [58]. Studies have shown that fermentation can increase betalain bioavailability and improve antioxidant properties, making fermented beetroot products attractive in the functional food sector (Gürbüz *et al*., 2021) [26].

Potential Drawbacks and Considerations

Despite the numerous health-promoting properties of beetroot (Beta vulgaris), certain considerations must be taken to ensure safe consumption and sustainable production.

1. Oxalate Content

Beetroots contain oxalates, organic compounds that can form insoluble salts when bound to calcium in the body, potentially leading to the formation of calcium oxalate kidney stones (Siener *et al*., 2014) [53]. Research indicates that the oxalate content in beetroot, although moderate compared to other vegetables such as spinach, still poses a risk to individuals with predispositions to hyperoxaluria or nephrolithiasis (Wang *et al*., 2020) [60]. Chronic excessive intake of oxalate-rich foods can exacerbate renal complications, particularly in individuals with reduced renal function, thereby highlighting the need for dietary moderation (Siener *et al*., 2014) [53].

2. Interactions with Medications

The high nitrate content in beetroot, which is metabolized to nitric oxide (NO), has been demonstrated to influence blood pressure regulation (Hobbs *et al*., 2013) [27]. While beneficial for individuals with hypertension, it may interact with antihypertensive medications such as nitrates or angiotensin-converting enzyme (ACE) inhibitors, potentially resulting in an exaggerated hypotensive effect (Zhao *et al*., 2020). Furthermore, beetroot supplementation may alter the pharmacokinetics of certain drugs, particularly those utilized in the management of chronic kidney disease, by affecting the renal blood flow and glomerular filtration rate (Zhao *et al*., 2020). Consequently, patients undergoing pharmacological treatment should consult healthcare providers prior to incorporating substantial quantities of beetroot into their diet.

3. Environmental Impact of Large-Scale Production

Large-scale cultivation of beetroots, particularly in intensive farming systems, may contribute to environmental degradation.

The excessive utilization of synthetic fertilizers and pesticides, coupled with high water demand, can result in soil nutrient depletion, water contamination, and biodiversity loss (Gao *et al*., 2020) [20]. Moreover, the transportation and processing of beetroots for commercial purposes generate significant greenhouse gas emissions, notably carbon dioxide, contributing to global warming (Foley *et al*., 2021) [14]. To mitigate these effects, sustainable agricultural practices, including integrated pest management (IPM) and optimized water usage, should be implemented alongside local sourcing initiatives to reduce the carbon footprint.

Future Research Directions

1. Long-term Effects of Beetroot Consumption

Although beetroot (Beta vulgaris) is widely recognized for its acute health benefits, including cardiovascular improvements and enhanced exercise performance, its long-term effects have not been fully elucidated. Current evidence primarily focuses on short-term interventions, and more extensive longitudinal studies are necessary to evaluate the sustained impact of beetroot consumption on chronic diseases, such as hypertension, type 2 diabetes, and neurodegenerative disorders. Specifically, there is a need for large-scale, randomized controlled trials (RCTs) and cohort studies to determine whether long-term consumption of beetroot can lead to sustained improvements in health biomarkers or if any potential adverse effects emerge with prolonged use. For instance, while Hobbs *et al*. (2013) [27] demonstrated that acute beetroot ingestion results in endothelium-independent vasodilation and a reduction in blood pressure, the persistence of these effects over extended periods remains unclear. Similarly, the long-term influence of bioactive compounds such as betalains and nitrates on cognitive function and systemic inflammation warrants further investigation (Jones, 2014 [29]; Wylie *et al*., 2013) [63].

2. Optimal Dosage for Various Health Benefits

Determining the optimal dosage of beetroot to maximize its health benefits is a critical area for future research. While substantial evidence supports the positive effects of beetroot, particularly its nitrate content, on blood pressure regulation and exercise performance, the precise quantity required to achieve these outcomes remains inadequately defined. Research must investigate the pharmacokinetics of beetroot active compounds, primarily nitrates, betalains, and phenolic compounds, along with their bioavailability, to determine the most effective and safe dosage for specific health outcomes. Notably, the dosages used in clinical trials have varied significantly, with studies such as Hobbs *et al*. (2013) [27] and Kapil *et al*. (2015) [30] indicating blood pressure reductions following doses of 70-140 mL of beetroot juice daily. However, discrepancies in the dosage required to achieve improvements in other health parameters, such as muscle endurance or cognitive function, persist. Future clinical trials should focus on determining the minimal effective dose for specific populations, including individuals with pre-existing conditions, such as hypertension, and assessing the potential for dose-dependent side effects

3. Innovative Applications in Food and Non-Food Industries

Beetroot's bioactive compounds, particularly betalains, offer promising avenues for innovation in both food and non-food sectors. In food technology, beetroots are increasingly being investigated as natural food colorants due to their potent antioxidant properties and potential to replace synthetic additives. Fu *et al*. discussed the potential of betalains as stable and health-promoting alternatives to synthetic dyes in processed foods. Additionally, the functional properties of BR, such as its anti-inflammatory and antioxidant effects, render it an attractive ingredient for the formulation of functional foods and dietary supplements aimed at enhancing public health. Non-food applications of beetroots are also garnering attention. Beetroot-derived betalains exhibit potential as active ingredients in cosmetic formulations, particularly for anti- aging and skin protection (Gasztonyi *et al*., 2001) [21, 22, 23]. Moreover, beetroot bioactive compounds may have applications in pharmaceutical and agricultural industries, including natural anti- inflammatory agents and bio-based pesticides. As consumer demand for natural products increases, exploring these innovative uses could further enhance beetroot's commercial value and provide new revenue streams in multiple industries (Fu *et al*., 2020) [18, 19].

Conclusion

1. Recap of Health and Economic Benefits

Beetroot (Beta vulgaris) is a nutritionally dense vegetable with a wide range of health benefits, primarily due to its high concentration of bioactive compounds. The nitrates in beetroot, once converted into nitric oxide in the body, contribute to improved vascular health by reducing blood pressure, particularly in individuals with hypertension. Furthermore, beetroot contains potent antioxidants such as betalains, which help mitigate oxidative damage and inflammation, thereby reducing the risk of chronic diseases including cardiovascular disorders, type 2 diabetes, and cancer (Zhang *et al*., 2021) [64]. These health benefits establish beetroot as a significant functional food in disease prevention and health promotion.

From an economic perspective, beetroot offers substantial value as a high-yield, low- cost crop that supports various industries. It is extensively utilized in the food sector, not only as a nutrient-dense ingredient but also as a natural colorant, providing a viable alternative to synthetic dyes (Liu *et al*., 2020) [38, 39]. Its role in the nutraceutical industry is also expanding due to the increasing interest in natural health products. Moreover, beetroot's adaptability to diverse climatic conditions and its relatively low environmental impact make it an important crop for fostering economic sustainability, particularly in regions with moderate climates (Zhao *et al*., 2021) [65].

2. Importance of Beetroot in a Balanced Diet and Sustainable Agriculture

Incorporating beetroot into a balanced diet provides essential nutrients such as vitamins A, C, and B-complex, along with minerals including potassium and magnesium, which contribute to optimal cardiovascular function and muscle performance. Beetroot's fiber content supports digestive health, while its unique nitrate content has been demonstrated to improve physical endurance and overall exercise performance (McMahon *et al*., 2017) [41].

In terms of sustainability, beetroot is a low-maintenance crop that requires less water and fewer pesticides compared to many other vegetables, making it suitable for environmentally responsible farming practices (Bucher *et al*., 2016) [10]. The ability of beetroot to thrive in diverse soil types enhances its suitability for different agricultural systems, promoting food security and supporting climate-resilient agriculture. Additionally, beetroot can be integrated into crop rotation practices to improve soil health and prevent nutrient depletion, offering long-term benefits to farming systems (Adhikari *et al*., 2017) [1].

In conclusion, beetroot's exceptional nutritional profile and its

potential as a sustainable crop position it as a crucial component of future global food systems. With increasing consumer demand for functional foods and sustainable agricultural practices, beetroot's role in improving public health and advancing eco-friendly farming methods is likely to continue to expand.

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