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Unlocking the Healing Power of Beetroot: Nutritional Profile & Evidence-Based Health Benefits

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ABSTRACT

***Background**: Beetroot (Beta vulgaris L.) is a nitrate- and betalain-rich root vegetable increasingly recognized as a functional food with potential benefits for cardiovascular, metabolic, and oxidative stress–related disorders. However, translational gaps remain between experimental evidence and its routine clinical or dietary use. **Objective**: To synthesize current evidence on the nutritional profile, phytochemical composition, and evidence-based health effects of beetroot, with emphasis on its cardiometabolic, antioxidant, and potential chemopreventive roles, as well as limitations and safety concerns. **Methods**: A narrative review of peer-reviewed literature was conducted, focusing on human, animal, and in vitro studies evaluating beetroot's nutrient composition, bioactive compounds (notably nitrates and betalains), functional food applications, and associated health outcomes. Key data on cardiovascular function, exercise performance, metabolic regulation, liver health, and cancer-related endpoints were summarized. **Results**: Beetroot and its derivatives provide substantial dietary nitrate, folate, potassium, vitamin C, fiber, and betalain pigments. Clinical and experimental studies indicate improvements in blood pressure, endothelial function, exercise efficiency, antioxidant status, and selected metabolic parameters. Preclinical data suggest antiproliferative and cytotoxic effects against several cancer cell lines, alongside hepatoprotective and antimicrobial activities. Processing method and cultivar markedly influence nitrate and betalain retention. Excessive nitrate intake raises potential concerns regarding N-nitroso compound formation, though adverse effects in humans remain insufficiently characterized. **Conclusion**: Beetroot is a nutrient-dense functional food with promising cardiometabolic, antioxidant, and emerging chemopreventive properties. Standardized formulations and high-quality clinical trials are needed to define optimal doses, long-term safety, and targeted therapeutic applications.*

Keywords
Beetroot; Beta vulgaris; Nitrate; Betalains; Functional foods; Cardiovascular health; Antioxidants; Chemoprevention.

INTRODUCTION

Beetroot (*Beta vulgaris L.*), a cross-pollinated root crop from the family Chenopodiaceae, is widely cultivated for its nutritional, economic, and industrial importance. It is considered one of the most valuable vegetable crops due to its resilience, yield potential, and functional applications in the food and health sectors *(1)*. In Pakistan, beetroot production has increased in recent years, with approximately 6,426 hectares under cultivation and an annual yield exceeding 480,000 tons, highlighting its growing agricultural and commercial relevance *(2)*.

Nutritionally, beetroot is rich in essential micronutrients, including vitamins A and C, folate, potassium, and dietary fiber, along with diverse antioxidant compounds *(3)*. Its physiological significance is strongly linked to its naturally occurring inorganic nitrate content, which undergoes reduction to nitric oxide (NO), a key mediator of vasodilation and endothelial function. Clinical and experimental studies demonstrate that dietary nitrate from beetroot can lower systolic and diastolic blood pressure in both healthy and hypertensive adults *(4–6)*. Beetroot contains characteristic betalain pigments—betacyanins and betaxanthins—which contribute to its red–yellow coloration and exhibit strong antioxidant and anti-inflammatory activities *(7)*. These pigments, together with polyphenols and organic acids, contribute to beetroot's functional capacity in oxidative stress modulation and cellular protection *(8)*. Its vibrant color also enables its use as a natural food dye in processed foods *(9)*. Historically cultivated for over two millennia, beetroot adapts well to cool climates and fertile, well-drained soils *(10,11)*. Its betalain pigments may temporarily discolor urine and stools, a benign condition known as beeturia *(12)*. Recent studies suggest that fractionated beetroot juice may offer neuroprotective and geriatric benefits, including support for muscle function, cognition, and vascular integrity, although evidence remains preliminary *(13)*.

Emerging findings also indicate potential benefits of beetroot-derived nitrate supplementation in clinical populations. For example, in obstructive sleep apnea patients, acute beetroot juice intake blunted morning systolic blood pressure elevation and improved ventilatory responses under hypoxic conditions *(14)*. Preclinical evidence further suggests that betanin—one of beetroot's principal betacyanin pigments—may alleviate neuropathic pain through attenuation of microglial activation and oxidative stress pathways *(15)*. During periods of reduced physical activity, such as pandemic-related confinement, nitrate-rich foods like beetroot may also support vascular function by sustaining NO bioavailability *(16,17)*. Collectively, these findings highlight beetroot as a nutrient-dense functional food with diverse physiological effects. However, while mechanistic and preclinical studies provide promising insights, further controlled human trials are essential to validate its therapeutic applications.

NUTRITIONAL COMPOSITION SECTION

Beetroot juice and whole beetroot products are valued for their substantial nitrate concentration and diverse bioactive compounds, including betalains, phenolic acids, and organic acids, which collectively contribute to cardiovascular, antioxidant, and metabolic benefits *(6,7)*. Although nitrate is considered the primary active constituent, emerging evidence suggests synergistic interactions among these compounds, enhancing the overall health effects of beetroot-based formulations *(18)*.

Table 1. Nutrient Composition of Raw Beetroot (per 100 g edible portion)

Constituent	Amount	Source
Water	87.5%	(19,20)
Energy	43 kcal	(19)
Fat	0.17 g	(19)
Protein	1.61 g	(19)
Carbohydrates	9.56 g	(19)
Dietary fiber	2.8 g	(19)
Potassium	325 mg	(19)
Sodium	78 mg	(19)
Phosphorus	40 mg	(19)
Calcium	16 mg	(19)
Magnesium	23 mg	(19)
Iron	0.80 mg	(19)
Zinc	0.35 mg	(19)
Vitamin A	36 IU	(19)
Vitamin E	0.30 mg	(19)
Vitamin C	4.9 mg	(19)
Vitamin B2 (riboflavin)	0.04 mg	(19)
Vitamin B6	0.067 mg	(19)
Folate	109 mcg	(19)
Niacin	0.334 mg	(19)

Beetroot's antioxidant activity is driven largely by its betalain pigments, which function as effective radical scavengers and contribute to reduced oxidative stress and inflammation in experimental models *(21,22)*. Additionally, beetroot ingestion has been associated with enhanced exercise performance, potentially through improved mitochondrial efficiency and oxygen utilization *(23)*.

Table 2. Proximate Composition of Beetroot Flour (per 100 g dry weight)

Nutrient	Amount (mean ± SD)	Source
Moisture	6.30 ± 0.20 g	(20,24)
Ash	7.89 ± 0.10 g	(24)
Fat	1.53 ± 0.15 g	(24)
Crude fiber	5.08 ± 0.16 g	(24)
Carbohydrates	77.74 ± 1.07 g	(24)
Protein	1.61 ± 0.33 g	(24)
Iron	4.14 ± 0.28 mg	(24)
Calcium	160.32 ± 2.00 mg	(24)
Vitamin C	4.20 ± 0.28 mg	(24)

These variations reflect the concentration effects of dehydration and the influence of processing methods on nutrient retention. Beetroot flour is particularly rich in minerals, suggesting potential applications in value-added food products targeting nutritional enhancement.

PHYTOCHEMICALS AND BIOACTIVE COMPOUNDS

Beetroot contains a diverse array of bioactive phytonutrients that contribute to its antioxidant, anti-inflammatory, and metabolic effects. Although numerous studies have explored these compounds, most evidence arises from *in vitro* and *animal models*, highlighting the need for more robust human trials to validate therapeutic applications *(25)*. The major classes of bioactive constituents in beetroot include betalains, polyphenols, flavonoids, saponins, vitamins, and inorganic nitrate, each contributing uniquely to its functional properties.

Betalains, the signature pigments of beetroot, are divided into two subclasses—**betacyanins** (red–violet pigments) and **betaxanthins** (yellow–orange pigments). These compounds demonstrate strong radical-scavenging ability, modulate inflammatory pathways, and protect cellular components from oxidative damage *(7,26)*. Among these, **betanin** and **isobetanin** are the most abundant betacyanins, while **vulgaxanthin I**, **vulgaxanthin II**, and **indicaxanthin** represent key betaxanthins.

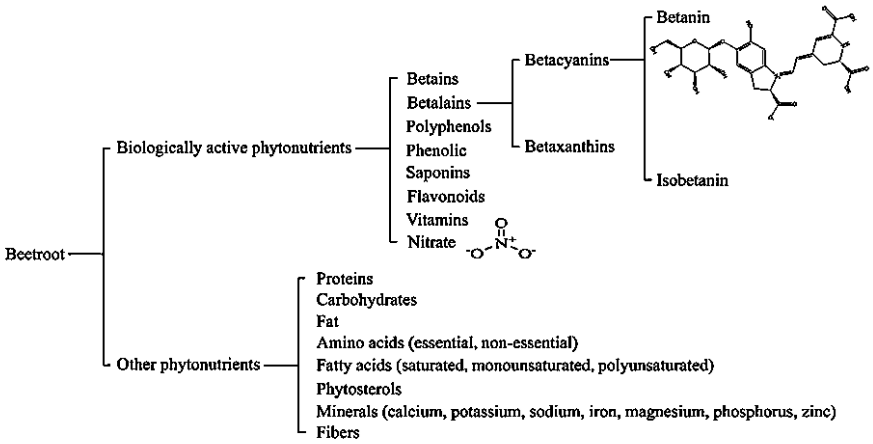

Figure 1. Schematic representation of major phytonutrients present in beetroot, including biologically active constituents (betalains, polyphenols, saponins, flavonoids, vitamins, and nitrate) and other nutritive components such as proteins, amino acids, fatty acids, minerals, and dietary fibers (adapted from Chen et al. (25) and KC et al. (27)).

The broad spectrum of beetroot's physiological benefits is largely attributed to these compounds. For example, beetroot juice exhibits antioxidant, anti-inflammatory, anti-anemic, and anti-ischemic properties, while fractionated beetroot preparations have shown potential roles in mitigating age-associated cognitive decline, sarcopenia, and gastrointestinal dysfunction *(13,23)*. These effects arise through the synergistic actions of nitrate-mediated nitric oxide production and betalain-mediated oxidative stress reduction *(7,18)*. The characteristic earthy flavor of beetroot, caused by volatile compounds such as **geosmin** and **pyrazines**, along with its high nitrate content, may limit its use in some food applications despite its value as a natural dye *(28)*. Nonetheless, beetroot's unique phytochemical profile continues to position it as a promising functional ingredient for nutraceutical and therapeutic product development.

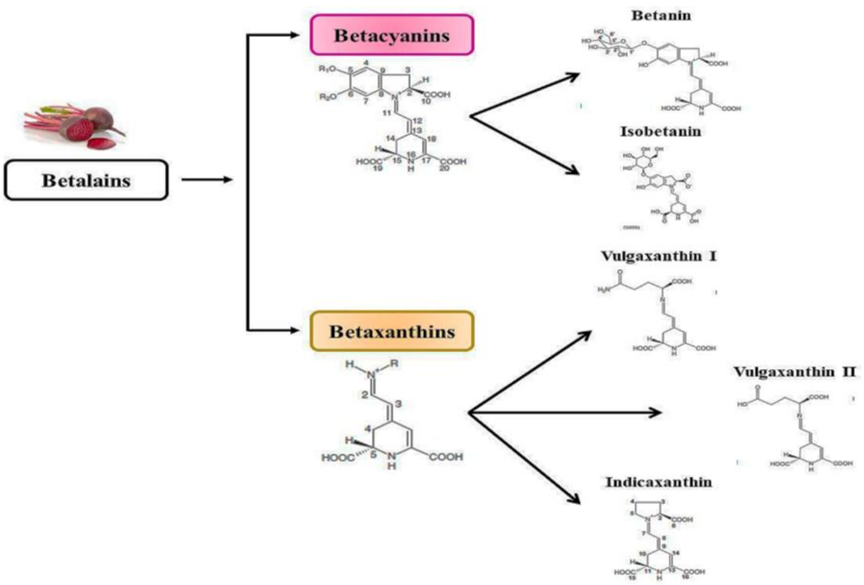

Figure 1 Classification of beetroot betalains into betacyanins and betaxanthins with representative chemical structures, including betanin and isobetanin (betacyanins) and vulgaxanthin I, vulgaxanthin II, and indicaxanthin (betaxanthins). Structures adapted from Khan et al. (29) and Czapski et al. (22).

In addition to antioxidative benefits, beetroot phytochemicals demonstrate biological activities relevant to chronic disease modulation. Betanin, for instance, inhibits cancer cell proliferation, regulates key signaling pathways, and reduces inflammatory mediators *(15,30)*. Methanolic extracts of *Beta vulgaris* roots show cytotoxicity against carcinoma cell lines including PANC-1, HepG2, A549, and PC-3, and exert antimicrobial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa (30)*. Dietary nitrates in beetroot also contribute to cardiovascular protection by improving endothelial function, reducing arterial stiffness, and lowering systemic inflammation *(6,31)*. Comparative botanical analyses further demonstrate that different beet cultivars—sugar beet, fodder beet, leaf beet, and garden beet—possess varying nutrient and phytochemical compositions, including significant differences in chlorophyll content, root mineral levels, and amino nitrogen distribution *(32)*. These variations underscore the importance of cultivar selection for targeted nutritional or industrial applications.

VITAMINS IN BEETROOT

Beetroot contains a variety of vitamins and micronutrients that contribute to its nutritional functionality and health-promoting properties. Recent compositional analyses reveal significant variation in vitamin and mineral distribution across different anatomical parts of the beetroot. Peel tissues consistently exhibit higher concentrations of iron, calcium, magnesium, and manganese, whereas the top and basal regions are particularly enriched in calcium and magnesium *(33)*. These patterns reflect physiological accumulation processes that may inform processing strategies for maximizing nutritional yield.

Beetroot also contains essential vitamins in moderate amounts, including vitamin A (2 µg), thiamine (0.031 mg), riboflavin (0.027 mg), niacin (0.331 mg), pantothenic acid (0.145 mg), vitamin B6 (0.067 mg), ascorbic acid (3.6 mg), and folate (80 µg) per 100 g fresh weight *(33,34)*. Although present in smaller quantities than in leafy vegetables, these micronutrients contribute to beetroot's antioxidant capacity and metabolic relevance. Processing methods significantly influence the stability and retention of these bioactive compounds. Lyophilization, for instance, preserves betalains and phenolic compounds more effectively than sun drying or high-temperature tray drying, yielding higher antioxidant activity and mineral retention *(35)*. Beetroot powder obtained through gentle dehydration methods shows substantial phenolic (11.49–15.50 mg GAE/g) and betalain (3.10–4.89 mg/g) content, alongside notable iron concentrations ranging from 1.16 to 1.56 g per 100 g dry weight *(35,36)*. Functional food applications—such as beetroot-enriched biscuits and hard candies—demonstrate considerable improvements in nutritional quality, including increased protein, fiber, minerals, vitamin C, betalain content, and antioxidant capacity *(37–39)*. These enhancements highlight beetroot's potential as a versatile ingredient in nutrient-fortified food products aimed at promoting health and preventing oxidative stress–related conditions.

NUTRITIONAL BENEFITS OF BEETROOT

Beetroot is recognized as a nutrient-dense vegetable that contributes meaningfully to human health due to its rich profile of vitamins, minerals, antioxidants, and nitric oxide–enhancing compounds. The naturally occurring inorganic nitrate in beetroot plays a central physiological role by undergoing stepwise reduction to nitric oxide (NO), which supports endothelial function, vasodilation, and oxygen delivery to tissues *(4,6)*. This nitrate–nitrite–NO pathway has been associated with improvements in blood pressure, vascular stiffness, and exercise performance, where reduced oxygen cost during submaximal activity has been documented in both healthy and clinical populations *(6,23)*. Beetroot is also a reliable dietary source of folate, manganese, potassium, vitamin C, and dietary fiber, supporting metabolic activity, antioxidant defense, and gastrointestinal health *(19)*. Its betalain pigments—betacyanins and betaxanthins—exhibit strong radical-scavenging capacity and modulate oxidative and inflammatory pathways *(7,22)*. These effects contribute to the potential reduction of chronic disease risk, including cardiovascular disorders, metabolic dysfunction, and oxidative stress–related conditions *(7,25)*.

Additional nutritional benefits include anti-inflammatory activity mediated by betalains and polyphenols, which have been shown to reduce inflammatory markers in experimental models *(25)*. The fiber content of beetroot supports digestive health by promoting bowel regularity and gut microbial activity, while its micronutrients contribute to hematologic status and immune function *(19,33)*. Preliminary experimental evidence also suggests that beetroot extracts may exert antiproliferative or cytotoxic effects against cancer cell lines; however, these findings remain limited to *in vitro* settings and require controlled clinical verification *(30,31,40)*. Studies such as those by Varshney and Mishra *(41)* and Clifford et al. *(7)* highlight the potential of beetroot in supporting cardiometabolic health, lipid regulation, and antioxidant defenses. Beetroot's versatility in food systems—including its use in juices, powders, baked products, and confections—further enhances its potential as a functional food ingredient. However, the stability of betalains is sensitive to heat and pH conditions, necessitating optimized processing to preserve bioactive integrity *(28,35)*.

While beetroot is generally safe, excessive consumption of high-nitrate beetroot juice may contribute to the formation of N-nitroso compounds under specific conditions, prompting ongoing evaluation of intake thresholds and long-term safety *(42)*. Despite these considerations, the balance of evidence supports beetroot as a valuable component of a health-promoting diet, warranting further investigation through well-designed human trials.

MEDICINAL BENEFITS OF BEETROOT

Beetroot possesses a broad spectrum of bioactive phytochemicals that contribute to its medicinal potential, including betalains, polyphenols, phenolic acids, flavonoids, and amino-acid derivatives. These compounds exhibit antioxidant, anti-inflammatory, antimicrobial, antiviral, and antiapoptotic activities, several of which have been validated in preclinical models *(25,43)*. The high nitrate content of beetroot further enhances its therapeutic value by supporting nitric oxide–mediated improvements in vascular function, platelet activity, and arterial stiffness *(4,6,31)*.

Beetroot extracts have demonstrated the capacity to inhibit cancer cell proliferation, migration, and oxidative damage by modulating signaling pathways and enhancing cellular antioxidant enzymes. Betanin, in particular, has been shown to reduce oxidative stress and apoptosis markers and to induce cytotoxicity in carcinoma cell lines including PANC-1, HepG2, A549, and PC-3, although these effects remain limited to laboratory studies *(30,40)*. Such findings indicate potential chemopreventive applications but require extensive clinical validation. Emerging evidence also demonstrates metabolic benefits. Beetroot-derived compounds may improve glucose regulation and insulin sensitivity in experimental models, suggesting a possible role in type II diabetes management *(43)*. Likewise, betaine, a methyl donor found in beetroot, exhibits hepatoprotective activity by reducing liver inflammation and lipid accumulation *(43)*. Anti-inflammatory and antimicrobial effects against pathogens such as *Staphylococcus aureus* and *Pseudomonas aeruginosa* further support beetroot's potential inclusion in therapeutic and nutraceutical formulations *(30)*.

Cardiovascular benefits remain the most extensively studied clinical domain. Nitrate-rich beetroot products have been shown to reduce blood pressure, improve endothelial function, and support oxygen utilization during physical exertion *(6,23)*. Bioactive compounds such as saponins, phenolics, and organic acids may also contribute to these effects by reducing oxidative stress and modulating gene expression relevant to vascular homeostasis *(31)*. Processing and product formulation significantly influence the medicinal profile of beetroot. The stability of betalains, for instance, is reduced by heat and light exposure, requiring careful control of processing conditions to preserve therapeutic potential *(28,35)*. Novel beetroot formulations, including gels, concentrated juices, and fortified powders, have demonstrated improved adherence and measurable physiological benefits in clinical practice *(31)*. Overall, beetroot's medicinal value arises from its synergistic composition of nitrate, betalains, and phenolic compounds, supporting its potential as a complementary intervention for cardiometabolic disorders, oxidative stress, inflammation, and selected metabolic dysfunctions.

CONCLUSION

Beetroot (*Beta vulgaris L.*) is a nutrient-rich vegetable with a diverse profile of bioactive compounds that collectively contribute to its nutritional and medicinal potential. Its high nitrate content supports nitric oxide production, leading to improvements in vascular function, blood pressure regulation, and exercise performance. Betalains and phenolic compounds provide potent antioxidant and anti-inflammatory effects, while experimental studies suggest additional benefits related to metabolic regulation, hepatoprotection, antimicrobial activity, and potential chemopreventive action.

Table 3. Proximate Composition and Bioactive Compound Content of Different Beetroot Formulations

Compound	Cereal Bar	Gel	Chips	Juice
Ash (%)	1.30 ± 0.06[b]	2.01 ± 0.13[a]	1.00 ± 0.05[c]	0.80 ± 0.06[d]
Moisture (%)	12.90 ± 0.50[b]	76.14 ± 0.48[a]	4.66 ± 0.57[c]	85.50 ± 0.50[a]
Energy (kcal)	325.58 ± 2.5[b]	148.50 ± 0.01[c]	365.05 ± 2.10[a]	94.90 ± 1.70[d]
Carbohydrates (g)	62.97 ± 0.97[b]	42.62 ± 0.31[c]	89.96 ± 0.52[a]	22.67 ± 0.40[d]
Protein (g)	16.20 ± 0.39[a]	3.02 ± 0.09[b]	0.97 ± 0.01[c]	0.70 ± 0.07[c]
Lipids (g)	0.97 ± 1.00[a]	0.61 ± 0.01[b]	0.14 ± 0.01[c]	0.16 ± 0.01[c]
Total dietary fiber (g)	4.07 ± 0.14[a]	3.71 ± 0.10[b]	3.22 ± 0.63[b]	0.91 ± 0.31[c]
Total sugars (g)	37.72 ± 0.70[a]	19.14 ± 0.23[c]	18.79 ± 0.13[b]	12.11 ± 0.35[d]
Fructose (g)	2.79 ± 0.15[a]	1.21 ± 0.15[b]	1.47 ± 0.11[c]	0.86 ± 0.19[c]
Glucose (g)	4.71 ± 0.16[a]	2.61 ± 0.12[b]	2.70 ± 0.11[b]	2.45 ± 0.21[b]
Sucrose (g)	26.59 ± 0.80[a]	11.60 ± 0.13[b]	14.62 ± 0.17[b]	8.80 ± 0.65[c]
Maltose (g)	3.63 ± 0.19[a]	0.00[b]	0.00[b]	0.00[b]
NO_3^- (mmol)	14.00 ± 0.05[a]	6.30 ± 0.01[b]	6.90 ± 0.02[b]	4.10 ± 0.01[c]
NO_2^- (mmol)	0.20 ± 0.01[a]	0.11 ± 0.02[b]	0.13 ± 0.02[b]	0.10 ± 0.02[b]
Betanin ($mg \cdot g^{-1}$)	173 ± 0.12[c]	246 ± 0.07[b]	1274 ± 0.01[d]	298.5 ± 0.03[b]

Processing methods, cultivar differences, and product formulations significantly influence the stability and concentration of these bioactives, shaping the nutritional and therapeutic value of beetroot-derived products. Although preclinical and emerging clinical data highlight promising health effects, further rigorously designed human trials are essential to clarify efficacy, optimal dosing, safety concerns—such as nitrate-related N-nitroso compound formation—and long-term applications. Overall, beetroot represents a versatile functional food with significant potential to support dietary, metabolic, and cardiovascular health. Its integration into nutrition and food product development offers valuable opportunities for enhancing public health and expanding functional food innovation.

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