

Diverse applications of beta vulgaris in biological sciences

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Abstract :

Beetroot (*Beta vulgaris*) is an edible root vegetable valued for its nutritional content and rich phytochemical profile. In recent years, beetroot has gained increasing scientific attention due to the presence of biologically active compounds such as betalains, phenolics, flavonoids, vitamins, etc. These bioactive constituents make beetroot a promising natural resource in various biological fields. This review summarizes the published literature and patents related to biological applications of beetroot. The review provides an overview of botanical characteristics, phytochemical composition, use in food sciences, health related application, application in biotechnology and microbiology and much more.

Introduction :

Beta vulgaris beetroot is increasingly recognized as a multifunctional biological resource beyond its conventional nutritional role. Research in betalain, phenolics, organic acids, sugars and micronutrients, beetroot exhibits diverse physicochemical and bioactive properties that support its application across multiple biological disciplines. The unique pigment system of beetroot, characterized by strong coloration, antioxidant activity, and pH sensitivity, forms the basis for any of its emerging non-food applications.

Recent research has explored beetroot derived extracts and pigments in microbiology, analytical biology and histology, including their use as natural pH indicators and components of alternative culture media. Parallel studies have highlighted pharmacological, antimicrobial, antioxidant, and cosmetic relevant properties, reinforcing beetroot's biocompatibility and suitability as a sustainable substitute for synthetic compounds. These experimental validations have been complemented by transitional effects and patents focused on pigment, stabilization, formulation, development, and commercialization.

Despite promising outcomes, challenges such as pigment instability, compositional variability, and lack of standardized protocols limit widespread adaptation. This review synthesizes published research addressing beetroot's biological applications, mechanistic insights, limitations and future potential positioning beetroot as an eco-friendly interdisciplinary bioresource.

Context :**1. Botanical origin and taxonomic position of *Beta vulgaris*.**

Beta vulgaris L is a herbaceous biennial species belonging to the family of Amaranthaceae subfamily Betoideae and genus *Beta*. Earlier classifications placed the genus within the family Chenopodiaceae; however, molecular phylogenetic analysis based on chloroplast and nuclear DNA sequences have confirmed the inclusion of Chenopodiaceae within Amaranthaceae, leading to its current taxonomic placement (Kadereit et al., 2003) The species *B. vulgaris* represents a taxonomically complex and polymorphic group comprising several cultivated forms such as beetroot (garden beet), sugar beet, fodder beet and leaf beat (Swiss chard), all classified under *Beta vulgaris*. subsp *vulgaris* (Biancardi et al., 2012). The wild progenitor of these cultivated forms is widely accepted to be *Beta vulgaris* subsp. *maritima*, a halophytic sea beet distributed along Mediterranean and Atlantic coastal regions (Hanelt, 2001). Genetic and archaeological evidence indicate that domestication involved selection from this wild gene pool, with diversification driven by human selection for storage, root enlargement, leaf biomass or sucrose accumulation (McGrath et al., 2019).

2. Chemical Composition and phytochemical profiling

Beetroot (*Beta vulgaris*) is characterized by a distinctive phytochemical profile dominated by betalain pigments, phenolic compounds, dietary nitrates and essential micronutrients. Betalains are water soluble nitrogen containing pigments exclusive to plants of the order Caryophyllales and are classified into Betacyanins (red-violet pigments, primarily betanin and isobetanin) and Betaxanthins (yellow-orange pigments, such as vulgaxanthin I), with Betanin counting up to 75-95% of total betacyanins in red beetroot (Stintzing & Carle, 2004 ; Azeredo, 2009). In addition to pigments, Beetroot contains significant quantities of phenolic acids, (including ferulic, caffeic and p-coumaric acids) and flavonoids, which contribute to its antioxidant capacity (Kujala et al., 2000; Clifford et al., 2015).

Beetroot is also recognized as one of the richest dietary sources of inorganic nitrate, with concentrations influenced by cultivar, agronomic conditions and post harvest processing. Nitrate levels reported in fresh beetroot typically range from 1100 to 2500 mg kg⁻¹ fresh weight (Lidder & Webb, 2013). Furthermore, beetroot provides essential vitamins, notably, Folate and Vitamin C and minerals such as potassium, magnesium and iron supporting its nutritional relevance (Eruss et al., 2015). Several analytical studies using HPLC-DAD, LC-MS and spectrophotometric techniques have demonstrated substantial variation in

phytochemical composition across beetroot cultivars and its processed forms (juice, powder, pomace), underscoring the need for standardized profiling when correlating composition with biological activity (Sawicki et al., 2016; Wruss et al., 2015)

3. Beetroot as a Source of Natural Pigments: Applications in Food and Industry

Beetroot is a primary commercial source of betalain pigments, particularly Betanin which is widely used as a natural red colorant in food systems under the designation E162. Multiple food chemistry studies have documented the application of beetroot derived betalains in beverages, dairy products, confectionery and processed food due to their high tinctorial strength and water solubility (Stintzing & Carle, 2004; Azeredo, 2009). However, betalains exhibit limited stability when exposed to heat, light, oxygen, and extreme pH, which constrains their broader industrial utilization compared to anthocyanins and synthetic dyes (Azeredo, 2009; Gandía-Herrero et al., 2010). To address these limitations, research has focused on stabilization strategies such as encapsulation, formulation with antioxidants and controlled pH environments, all of which have demonstrated improved pigment retention during processing and storage (Gandía-Herrero et al., 2010; Sawicki et al., 2016).

From an industrial and intellectual property perspective, several patents disclose beetroot based colourant compositions with enhanced stability and standardisation betalain profiles for food and beverage applications reflecting translational efforts to overcome technological bottlenecks identified in academic studies (von Elbe & Schwartz, 2013). Collectively, published evidence positions beetroot betalains as safe, consumer-acceptable natural colorants, while also highlighting the need for formulation- driven innovation to ensure industrial robustness.

4. Antioxidant and Redox Modulating properties of beetroot extracts.

Beetroot (*Beta vulgaris L.*) exhibits significant antioxidant activity, largely attributed to its high contents of betalains and phenolic compounds, which function as efficient electron and hydrogen donors (Stintzing & Carle, 2004). *In vitro* studies using standard radical scavenging assays such as DPPH, ABTS and FRAP have consistently demonstrated strong antioxidant capacity of beetroot extracts, with betalin identified as the principal contributor to free radical neutralization (Kujala et al., 2000, Escribano et al., 1998). Beyond direct radical scavenging, betalains have been shown to inhibit lipid peroxidation and protect low

density lipoproteins from oxidative modification, indicating a broader role in redox regulation (Tesoriere et al., 2004).

At the cellular level Beetroot derived betalains modulate oxidative stress by reducing intracellular reactive oxygen species and enhancing endogenous antioxidant differences. Experimental studies have demonstrated cryoprotective effects of beetroot pigments against oxidative damage induced by hydrogen peroxide and other pro oxidant systems in cell culture models, suggesting their involvement in redox homeostasis (Kanner et al., 2001; Tesoriere et al., 2004). Collectively, these findings provide mechanistic evidence supporting beetroot as a biologically relevant source of redox active compounds.

5. Explored Cardiovascular and Metabolic Effects; Supported by Clinical and Experimental Studies

Beetroot has been extensively studied for its cardiovascular and metabolic benefits, primarily attributed to its high content of inorganic nitrate, which serves as a precursor for nitric oxide (NO) via the nitrate-nitrite-NO pathway (Lidder & Webb, 2013). Controlled human intervention studies have demonstrated that beetroot juice supplementation significantly increases plasma nitrite levels, leading to improved endothelial functions and vasodilation (Webb et al., 2008). Acute and chronic consumption of beetroot-derived nitrate has been shown to reduce systolic and diastolic blood pressure in both healthy individuals and hypertensive populations with effects observed within hours of intake and sustained with regular consumption (Kapil et al., 2015).

In addition to vascular effects, beetroot supplementation has been associated with improvements in metabolic efficiency and exercise performance, which are indirectly linked to enhanced mitochondrial efficiency and reduced oxygen expenditure during physical activity (Larsen et al., 2011). Experimental and clinical data further suggests that beetroot-derived nitrates may contribute to improved glucose homeostasis and insulin sensitivity, although these effects appear to be context-dependent and require further clinical validation (Clifford et al., 2015). Overall, published evidence supports a mechanistic link between beetroot nitrate intake and cardiovascular health outcomes mediated through NO bioavailability.

6. Anti- Inflammatory, Cryoprotective, and Enzyme-Modulating Activities

Beetroot (*Beta vulgaris*) and its betalain rich extracts have demonstrated anti-inflammatory and cryoprotective effects. In several experimental models, *in vitro* and *in vivo* studies have shown that betalains, particularly betanin, significantly suppress pro inflammatory mediators such as tumor necrosis factor- α (TNF- α), interleukin-6 (IL-6), and cyclooxygenase-2 (COX-2), indicating modulation of key inflammatory signaling pathways (El Gamal et al., 2014). These effects are closely linked to the antioxidant properties of betalains, which reduce oxidative stress, induce cellular damage and preserve membrane integrity under inflammatory conditions (Kanner et al., 2001).

Beyond inflammation control, beetroot extracts have been reported to exhibit enzyme modulating activities relevant to metabolic and neuroprotective processes. Experimental evidence indicates inhibitory effects of beetroot phenolics and betalains on carbohydrate metabolising enzymes such as α -amylase and α -glucosidase, suggesting a potential role in postprandial glucose regulation (Wootton-Beard & Ryan, 2011). Additionally, *in vitro* enzyme inhibition and molecular docking studies have shown suppression of acetylcholinesterase activity, supporting preliminary neuroprotective implications of beetroot bioactives (Lechner et al., 2010). Collectively, these published findings support beetroot's role in modulating inflammatory response and enzyme mediated biological pathways.

7. Anticancer and Antiproliferative Evidence from Cell-Based and Preclinical Studies

Beetroot has been investigated for its anti cancer and anti proliferative properties with evidence primarily derived from *in vitro* cell culture studies and preclinical models. Betalain pigments, particularly betanin, have been shown to inhibit proliferation and induce apoptosis in several human cancer cell lines, including colon, breast and leukemia models, through mechanisms involving mitochondrial dysfunction and activation of caspase- dependent pathways (Reddy et al., 2005). These effects are often associated with the ability of betalain to modulate oxidative stress and suppress DNA damage, thereby interfering with cancer cells survival and progression (Kanner et al., 2001).

Animal studies further support the chemopreventive potential of beetroot derived compounds. Dietary administration of beetroot extracts has been reported to reduce tumour incidence and delay tumour development in chemically induced carcinogenesis models, suggesting a protective role during early stages of cancer development (Kapadia et al.,

2011). Mechanistically, these effects have been linked to inhibition of lipid peroxidation, downregulation of pro-inflammatory mediators and enhancement of endogenous antioxidant defenses (Kapadia et al., 2011). While clinical evidence remains limited, the consistency of cell based and animal data supports continued investigation of beetroot bioactives as adjuncts in cancer prevention research.

8. Microbiological and Analytical Applications of Beetroot in Biological Sciences

Beetroot (*Beta vulgaris*) has been explored beyond nutritional context for analytical microbiological and histological applications primarily due to the chromatic and pH responsive properties of its betalain pigments. A recent peer reviewed study demonstrated that beetroot extract can function as a natural biological stain for microorganisms, particularly fungi and yeast, where betalain pigments enabled visualization of cellular morphology compared to conventional stains, though with limitations for differential bacterial staining (Gauda et al., 2025). This study provided experimental validation of beetroot pigments as an eco-friendly alternative to synthetic dyes in microbiology (Gauda et al., 2025).

The pH sensitive color transitions of beta linens have also been exploited for analytical purposes. Several experimental studies have reported the use of beetroot extract as a natural acid base indicator in titrimetric analysis, showing distinct and reproducible colour changes across acidic to alkaline pH ranges. Making it suitable for laboratory titrations and educational use (Patil et al., 2009; Bhagat et al., 2018). These findings highlight the structural sensitivity of betalains to proton concentration supporting their application as low-cost biodegradable pH indicators.

In microbiological cultivation, beetroot juice and beetroot derived substrates have been evaluated as nutrient sources in culture media, supporting the growth of bacteria and fungi due to their carbohydrate mineral and micronutrient content. Studies have demonstrated that beetroot based media can sustain microbial growth comparable to standard laboratory media for certain organisms, particularly in low resource or experimental settings (Singh & Sharma, 2016).

Additionally, beetroot pigments have been investigated as histological stains where betalain extract successfully stained plant and animal tissue sections.

9. Use of Beetroot in Cosmetics and Cosmeceutical Applications

Beetroot (*Beta vulgaris L.*) has been explored in cosmetic science primarily as a source of natural antioxidants and bio active pigments with skin protecting potential. Betalains, especially betacyanins, exhibit strong radical scavenging capacity and have been shown to inhibit oxidative damage to biomolecules, a key mechanism underlying skin aging and photo-induced damage (Ravichandran et al., 2013). *In vitro* studies demonstrate that betalain rich extracts can effectively neutralize reactive oxygen species, supporting their inclusion in anti aging and protective cosmetic formulations.

Beyond antioxidative activity, beetroot extracts contain phenolic compounds and bioavailable micronutrients that contribute to anti-inflammatory and skin conditioning effects. These properties are relevant for cosmetic products aimed at soothing irritated skin and maintaining epidermal barrier integrity (Kanner et al., 2001). Additionally, the intense red violet coloration of betalains enables beetroot to function as a natural colorant in cosmetics such as lip products, blushes and tinted greens, offering a plant based alternative to synthetic dyes with added biological functionality (Stintzing & Carle, 2007).

From a formulation perspective published studies highlight challenges related to pigment instability under exposure to light, oxygen, and elevated temperatures, which can limit shelf life and color consistency in cosmetic products (Ravichandran et al., 2013). Nevertheless, research indicates that appropriate formulation strategies such as controlled pH environments and protective matrices can partially mitigate degradation. Collectively, existing scientific evidence supports beetroot derived pigments as multifunctional cosmetic ingredients combining aesthetic value with antioxidant and skin beneficial properties.

10. Patents, Translational Potential, and Commercialization of Beetroot derived Biomolecules

The translational exploration of *Beta vulgaris* derived pigments and extracts has been supported by a growing patent landscape, particularly in the domains of natural colorants, pH responsive indicators, nutraceuticals, and bio active formulations. Several patents disclose stabilized betalain composition intended for use as natural dyes and analytical indicators addressing inherent instability issues through encapsulation, antioxidant supplementation, or controlled pH matrices (Kujala et al., 2001; Azeredo, 2009). These inventions form the technological basis for extending beetroot pigments beyond food systems into biomedical and analytical applications.

In the pharmaceutical and nutraceutical sectors, beetroot extract rich in betalains and nitrates have been patented for antioxidant, anti-inflammatory and cardioprotective applications, reflecting strong alignment between experimental pharmacology and commercial interests (Clifford et al., 2015). Importantly, patents emphasize standardized extraction processes and define betalain profiles, highlighting the necessity of reproducibility for regulatory and market acceptance.

From a diagnostic and laboratory perspective, emerging intellectual property has focused on the use of plant derived pigments, including beetroot betalains as eco-friendly alternatives to synthetic dyes and staining, sensing and educational laboratory kits. These disclosures resonate with recent experimental validation of beetroot extracts as microbial and histological stains, suggesting a clear pathway from proof of concept research to low-cost commercial products, particularly for teaching laboratories and resource limited settings (Gauda et al., 2025).

Despite this process, commercialization remains constrained by scalability challenges, regulatory classification ambiguities (food additive vs. diagnostic reagent), and absence of harmonized quality standards for long food biological use. Future patent activity is expected to increasingly converge on formulation, engineering, shelf-life enhancement and multi-functional platforms combining staining, sensing and antimicrobial properties, thereby strengthening the position of beetroot derived molecules as sustainable bio-based alternatives in applied biological Sciences.

11. Limitations, Challenges and Future Research Directions of Beetroot- Based Biological Applications

Despite the growing interest in *Beta vulgaris* derived pigments and extracts for microbiological, analytical and histological applications, several scientific and transitional limitations remain. Betalain, the principal chromophores in beetroot, are inherently sensitive to pH, temperature, oxygen and light, leading to instability during storage, sterilization, and prolonged experimental procedures, which restricts their routine laboratory adoption (Azeredo, 2009; Delgado-Vargas et al., 2000). This instability is particularly relevant in microbiological staining and media formulation, where autoclaving and variable incubation conditions are unavoidable.

Another major challenge is batch to batch variability in pigment composition and concentration due to cultivar differences, agronomic conditions, and extraction protocols,

resulting in inconsistent staining intensity and reproducibility across laboratories (Clifford et al., 2015). In microbial staining applications, beetroot extracts demonstrate stronger affinity for fungal cell walls than for bacterial envelopes, indicating limited universality compared to synthetic dyes and necessitating organism specific optimization.

From a methodological standpoint, the lack of standardized extraction, purification, and fixation protocols hampers regulatory acceptance and comparative validation against established dyes such as saffron in crystal violet or eosin in histology and microbiology (Azeredo, 2009).

Discussion :

The authors of this review contribute practical insights based on their ongoing experimental work. The authors have actively investigated the use of beetroot extracts in microbial staining and are currently extending this work to explore beetroot based microbial media and cosmeceutical formulations. A major technical challenge encountered during these studies is achieving effective pigment concentration while maintaining stability without exposing the extracts to high temperatures, which are known to accelerate betalain degradation. Addressing this limitation is crucial for translating laboratory success into reproducible protocols and scalable products.

Future research should focus on stabilization strategies such as encapsulation, co-pigmentation, or chemical modification of betalains to enhance thermal and pH resilience. Systematic structure-function studies correlating betalain chemistry with microbial cell wall composition could improve staining specificity and broaden acceptability. Furthermore, integrating beetroot based indicators and stains into low cost eco friendly diagnostic kits may offer significant advantages in resource limited settings provided rigorous validation and standardization are achieved through multi centric studies.

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