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Broccoli sprouts as an underrated functional food: a rich source of bioactive compounds with prominent anticancer properties

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ABSTRACT

Introduction: Broccoli sprouts, the young shoots of *Brassica oleracea*, are rich in sulforaphane (SFN), a bioactive compound with strong antioxidant and chemopreventive properties. SFN helps reduce oxidative stress, detoxify carcinogens, and regulate cellular pathways linked to cancer development. Other compounds present, such as polyphenols and glucosinolates, further enhance their health benefits. Due to their accessibility and high SFN content, broccoli sprouts are gaining attention as a complementary strategy in cancer prevention.

Aim: This study aims to review current evidence on the anticancer properties of broccoli sprouts, focusing on SFN's mechanisms in cancer prevention and therapy, including its role in cellular defense, apoptosis, and epigenetic regulation.

Materials and Methods: A literature review was conducted using PubMed, Scopus, and Google Scholar, covering studies from 2015 to 2025. Research on the effects of SFN in preclinical models, human trials, and epidemiological studies was analyzed. Both in vitro and in vivo studies were evaluated to assess SFN's relevance to human cancer prevention and treatment.

Results: SFN shows anticancer activity through activation of the Nrf2 pathway, induction of apoptosis, and modulation of the cell cycle. Preclinical and in vitro studies report reduced tumor growth, suppressed proliferation, and enhanced detoxification. SFN also influences gene expression through epigenetic mechanisms. While clinical data are limited, early evidence supports a role for broccoli sprouts in reducing cancer risk.

Conclusions: Broccoli sprouts offer strong potential as a functional food in cancer prevention, thanks to their SFN content and multifaceted biological effects. Further clinical research is needed to confirm efficacy, dosage, and safety in humans. Their affordability and availability make them a promising tool for public health.

Key words: broccoli sprouts, cancer, superfood, sulforaphane

Introduction

Broccoli sprouts, the young shoots of *Brassica oleracea*, have gained recognition as a potent and affordable superfood. While mature broccoli has long been acknowledged for its health benefits, the sprouted form contains significantly higher concentrations of bioactive compounds, particularly sulforaphane (SFN). This isothiocyanate has demonstrated strong anticancer properties, making it a promising candidate for preventing and treating various health conditions. Additionally, broccoli sprouts are rich in polyphenols, glucosinolates, and antioxidants, all of which contribute to their health-promoting effects. Notably, broccoli sprouts contain 20-50 times higher SFN levels than mature broccoli, making them an exceptionally rich dietary source. Their ease of incorporation into daily diets and availability in supplement form further enhance their potential as a cost-effective alternative to traditional chemopreventive drugs [1,2,3,4].

Sulforaphane is derived from the hydrolysis of glucoraphanin, a compound found in cruciferous vegetables, particularly broccoli sprouts. It has been extensively studied for its potential role in disease prevention and treatment. Research indicates that SFN exhibits significant anticancer activity by inhibiting tumor proliferation and inducing apoptosis, leading to a reduction in tumor size and improved survival rates in animal models [5].

The mechanisms underlying SFN's protective effects are largely attributed to its ability to activate nuclear factor erythroid 2-related factor 2 (Nrf2), a transcription factor that regulates oxidative stress and inflammation. By modulating these cellular pathways, SFN plays a crucial role in combating various chronic diseases [5].

Beyond SFN, sprouting itself has emerged as an effective strategy to manipulate phytochemical composition in seeds, enhancing their overall health benefits. This has spurred interest in exploring novel applications of sprouted seed flours in processed products, as well as utilizing sprouts as a biological template for synthesizing nanoparticles. Additionally, the

relationship between sprouts and gut health dynamics presents another promising avenue for future clinical research, emphasizing the need to fully understand the broader health implications of sprouted foods [2].

The growing recognition of SFN's broad therapeutic potential has fueled interest in its use as both a dietary supplement and an adjunct to conventional treatments. However, despite its promising preclinical benefits, there is still a need for further research to determine its efficacy, optimal dosage, and long-term safety in human populations.

Non- Cancer Prevention

Sulforaphane, a bioactive isothiocyanate found in broccoli sprouts, has garnered significant attention for its broader role in promoting overall health. One of its key mechanisms of action involves the activation of the nuclear factor erythroid 2-related factor 2 (Nrf2) pathway, which regulates the expression of antioxidant and detoxifying enzymes. Through this pathway, SFN contributes to cellular defense against oxidative stress, a major factor implicated in the development of chronic diseases such as neurodegenerative disorders, metabolic syndromes, and cardiovascular conditions [6, 7].

The neuroprotective effects of SFN have been widely studied, with evidence suggesting its potential to mitigate neurodegeneration through antioxidant and anti-inflammatory mechanisms. SFN has been shown to enhance neuronal resilience by modulating oxidative stress, reducing neuroinflammation, and influencing epigenetic factors. These effects are particularly relevant in conditions such as Alzheimer's disease and Parkinson's disease, where oxidative damage and inflammation play a central role in disease progression. Additionally, SFN may help preserve proteostasis by activating the proteasome, which supports protein degradation and prevents the accumulation of misfolded proteins, a hallmark of neurodegenerative diseases [8,9]. Additionally, scientists have observed that, beyond its antioxidant and anti-inflammatory effects, SFN exerts neuroprotective properties, making it a potential therapeutic option for conditions such as traumatic brain injury, epilepsy, intracranial hemorrhage, and cerebral ischemic injury [5].

Beyond neurological health, SFN demonstrates significant metabolic benefits, particularly in the regulation of insulin sensitivity and glucose metabolism. Studies have shown that SFN

administration can improve insulin signaling and glucose uptake while reducing oxidative stress markers in models of high-fat diet (HFD)-induced insulin resistance. This effect is mediated through the activation of the AMPK-Nrf2-GPx4 pathway, which enhances cellular antioxidant capacity and mitigates lipid peroxidation, thereby alleviating metabolic dysfunction. Furthermore, SFN has demonstrated antidiabetic and anti-obesity properties, including improvements in glucose tolerance and reductions in fat accumulation [5]. Therefore, these findings highlight SFN as a promising candidate for managing type 2 diabetes and other metabolic disorders associated with insulin resistance [10].

In addition to its metabolic effects, SFN has shown potential in supporting cardiovascular health by modulating lipid metabolism and reducing inflammation. Oxidative stress plays a crucial role in the development of atherosclerosis, and SFN's ability to activate detoxification pathways can contribute to vascular protection. Moreover, SFN has been found to upregulate fibroblast growth factor 21 (FGF21), a key regulator of lipid metabolism, thereby improving hepatic steatosis and lipid balance in models of non-alcoholic fatty liver disease (NAFLD). This suggests that SFN may serve as a valuable dietary intervention for individuals at risk of cardiovascular diseases associated with metabolic dysregulation [11].

Furthermore, SFN's role in cellular detoxification extends to its potential anti-aging properties. By inducing autophagy and lysosomal biogenesis through transcription factor EB (TFEB), SFN enhances the clearance of damaged cellular components and promotes mitochondrial health. This mechanism not only contributes to longevity but also offers protection against age-related diseases linked to chronic oxidative stress and impaired cellular repair systems [12].

The cumulative evidence underscores SFN's multifaceted role in disease prevention. By influencing key molecular pathways involved in oxidative stress, inflammation, metabolic balance, and neuroprotection, SFN presents itself as a valuable functional compound with widespread health benefits.

Cancer Prevention

Among the many health benefits of broccoli sprouts, their role in cancer prevention stands out. Sulforaphane, the primary bioactive compound in broccoli sprouts, exhibits potent anticancer

properties by modulating cellular pathways involved in carcinogenesis, reducing oxidative stress, and promoting detoxification mechanisms that prevent cancer initiation and progression [1]. Epidemiological evidence consistently highlights the health benefits of broccoli consumption, with sulforaphane being the key driver behind these outcomes. This compound is produced through the enzymatic conversion of glucoraphanin by myrosinase, enhancing its bioavailability and absorption in the human body, making it highly effective in cancer prevention [13]. Research has shown that sulforaphane helps prevent and treat various cancers by influencing cancer cell growth and inducing apoptosis. As part of the broader concept of "green chemoprevention," whole plant foods like broccoli sprouts are utilized to reduce cancer risk, with more than 3,000 studies exploring sulforaphane's efficacy in animal models and human clinical trials, solidifying its potential as a complementary or alternative chemopreventive agent [13,14].

Recent studies have also highlighted the role of polysulfides, such as cysteine hydropersulfide and glutathione hydropersulfide, which are produced in higher concentrations during broccoli seed germination and exhibit strong antioxidant properties, further contributing to the cancer-protective effects of broccoli sprouts [15]. Additionally, SFN activates the Nrf2 antioxidant response pathway, detoxifies carcinogens, and reduces oxidative stress—two key factors in cancer prevention [16]. It also promotes the expression of cytoprotective enzymes, mitigating oxidative stress and inflammation while modulating pathways related to immune regulation, DNA repair, and apoptosis [17]. SFN exerts epigenetic modifications that influence gene expression and acts as a potent inhibitor of histone deacetylases (HDACs), restoring the expression of tumor suppressor genes and preventing tumor growth [16]. Research has shown that sulforaphane can trigger programmed cell death in multiple cancer types, such as presented below.

Prostate Cancer

Prostate cancer is a significant health concern worldwide, and numerous studies have explored the chemopreventive role of broccoli sprouts in prostate cancer. Research using the transgenic adenocarcinoma of the mouse prostate (TRAMP) model has shown that a diet enriched with broccoli sprouts reduces the incidence and progression of prostate cancer. The mechanism involves the inhibition of histone deacetylase (HDAC) enzymes, which are

critical in epigenetic regulation of gene expression. The consumption of broccoli sprouts significantly decreased the expression of HDAC3 and altered histone modifications in prostate tissues, contributing to the suppression of cancer cell proliferation and metastasis. These findings suggest that SFN in broccoli sprouts may offer a novel approach for prostate cancer prevention through epigenetic modulation [18].

Head and Neck Squamous Cell Carcinoma (HNSCC)

Head and neck squamous cell carcinoma (HNSCC) is a major type of cancer associated with tobacco and alcohol consumption. Sulforaphane, derived from broccoli sprouts, has demonstrated significant chemopreventive effects in HNSCC models. In vitro studies revealed that sulforaphane induces the expression of NRF2 and its target genes, which are involved in carcinogen detoxification. Additionally, sulforaphane was shown to inhibit key oncogenic pathways, including the inactivation of pSTAT3, which is critical in HNSCC progression. In vivo, sulforaphane-rich broccoli sprout extract reduced the incidence and size of tumors induced by carcinogens in mouse models, further supporting its potential as a therapeutic agent for tobacco-related cancers [19].

Oral Squamous Cell Carcinomas (OSCC)

Oral squamous cell carcinomas (OSCC) represent a subset of cancers that are difficult to treat due to their aggressive nature. Recent studies have focused on the effects of sulforaphane on oral cancer stem cells (CSCs), which are known to drive tumorigenesis. Sulforaphane treatment has been shown to reduce the proliferation, migration, and invasion of OSCC-CSCs in vitro, while also inhibiting their tumorigenic potential in xenograft models. The reduction in cancer stemness properties was associated with a decrease in key markers such as CD44 and ALDH1, which are commonly expressed in OSCC-CSCs [20]. These findings suggest that sulforaphane from broccoli sprouts may be effective in targeting the root of oral cancer, providing a promising chemotherapeutic strategy.

Glioma

Gliomas are among the most aggressive and difficult-to-treat brain cancers, with poor prognosis for affected patients. Epidemiological studies suggest that a diet rich in fruits and vegetables, including broccoli, may reduce the risk of glioma development. In a rat glioma model, broccoli sprout extract, rich in sulforaphane, significantly halted tumor growth and progression. This was attributed to the activation of the Keap1/Nrf2/ARE signaling pathway, which enhances cellular defense mechanisms against oxidative stress and carcinogenesis [21]. Although these results are from animal models, they provide a strong rationale for further investigation into the use of broccoli sprouts as a preventive strategy for gliomas.

Mammary Tumors

Breast cancer remains one of the leading causes of cancer-related deaths among women. Several studies have explored the potential of broccoli sprouts in preventing breast cancer, particularly in models of estrogen receptor-negative mammary tumors. Research has shown that both maternal and adult exposure to broccoli sprouts can prevent the development of mammary tumors, with effects linked to alterations in the epigenetic regulation of tumor suppressor genes [22, 23].

For instance, maternal exposure to a broccoli sprout diet has been associated with significant changes in gene expression and DNA methylation patterns in offspring, offering long-term protection against breast cancer. Through multi-omics studies, researchers have identified differentially expressed genes and altered DNA methylation in key tumor-related genes, suggesting that maternal nutrition may play a crucial role in modifying cancer susceptibility. Additionally, these findings highlight how maternal broccoli sprout consumption influences DNA methyltransferase and histone deacetylase activity, providing mechanistic insight into early-life dietary interventions for breast cancer prevention [24].

Beyond maternal influences, dietary isothiocyanates (ITCs) derived from cruciferous vegetables, including broccoli sprouts, have demonstrated anticancer properties. A clinical trial investigating ITC-rich broccoli sprout extract (BSE) in postmenopausal breast cancer

patients found promising results. Participants consuming BSE for two weeks exhibited trends of increased tumor-infiltrating lymphocytes and cleaved caspase-3, alongside reductions in Ki-67 and estrogen receptor (ER)-α nuclear-to-cytoplasmic ratio. These biomarker changes, supported by urinary proteomic analysis, suggest a potential role for ITCs in improving breast cancer prognosis [25].

Together, these studies reinforce the importance of dietary interventions, particularly with broccoli sprouts, in both cancer prevention and treatment. The evidence suggests that ITC-containing cruciferous vegetables could contribute to breast cancer risk reduction through epigenetic modulation and immune system activation.

Pancreatic Cancer

Pancreatic cancer is another aggressive malignancy for which treatment options remain limited. Recent clinical studies have examined the potential of broccoli sprouts in improving the outcomes of pancreatic cancer patients. A trial involving 40 patients receiving palliative chemotherapy found that the intake of broccoli sprout capsules enriched with sulforaphane led to a lower death rate in the treatment group compared to the placebo group. Although the results did not reach statistical significance, the study highlighted the potential for sulforaphane to improve survival rates and suggested the need for further investigation into its therapeutic use in pancreatic cancer [26].

Possible Limitations

While broccoli sprouts offer numerous health benefits, their potential impact on thyroid function remains a concern, particularly for individuals with hypothyroidism. Although the current study suggests that broccoli sprouts have a satisfactory safety profile in both in vitro and in vivo models, the data on their long-term effects on thyroid health are still limited. Given that brassica vegetables contain goitrogenic compounds that may interfere with iodine uptake, further research is needed to determine whether regular consumption of broccoli sprouts could exacerbate iodine deficiency or influence thyroid hormone levels in vulnerable

populations. Additionally, while the study provides insights into the effects of broccoli sprouts on thyroid cancer cells and inflammatory markers, broader clinical investigations involving diverse human populations are necessary to validate these findings. As thyroid disorders continue to rise globally, a more comprehensive understanding of the relationship between brassica vegetable consumption and thyroid health is crucial to ensure safe dietary recommendations for the general public [27].

Conclusions

Broccoli sprouts, rich in bioactive compounds such as sulforaphane, have emerged as a powerful dietary intervention with significant health benefits beyond basic nutrition. Their ability to activate critical cellular pathways, particularly the Nrf2 antioxidant response, positions them as potent agents in preventing and mitigating a wide range of chronic diseases. Evidence strongly supports their role in reducing oxidative stress, inflammation, and metabolic dysfunction, making them valuable in managing conditions such as neurodegenerative disorders, cardiovascular disease, and metabolic syndromes.

The anticancer properties of sulforaphane further highlight the potential of broccoli sprouts as a natural chemopreventive agent. Studies have demonstrated its ability to modulate epigenetic mechanisms, inhibit histone deacetylases, and induce apoptosis in various cancer models, including prostate, breast, pancreatic, and head and neck cancers. These findings underscore the growing recognition of functional foods as an accessible and effective approach to disease prevention and adjunctive therapy.

Despite the promising preclinical and epidemiological evidence, further well-designed clinical trials are needed to establish optimal dosing, long-term safety, and efficacy in human populations. The potential applications of broccoli sprouts in personalized nutrition and integrative medicine warrant continued exploration. As research progresses, these sprouts may become a key component of evidence-based dietary strategies for enhancing health and preventing disease.

Disclosure:

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All authors have read and agreed with the published version of the manuscript.

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