



Impact of spring and summer cultivation on broccoli seed quality and bioactive composition

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ABSTRACT

Background: Broccoli (*Brassica oleracea* var. *italica*) is a nutritionally and medicinally valuable crop, rich in vitamins (C, B, A, E), minerals, phenolic compounds, flavonoids, glucosinolates, and other bioactive constituents. These compounds contribute to antioxidant, anticancer, anti-inflammatory, and immune-supporting properties, making broccoli seeds particularly relevant for functional food applications. In Armenia, broccoli cultivation is expanding, but seed quality and bioactive composition are strongly influenced by seasonal cultivation conditions, temperature, and water availability.

Objective: This study aimed to evaluate the impact of spring and summer cultivation in the Ararat Valley on the physical, chemical, and biological properties of broccoli seeds, with a focus on their nutritional and functional potential.

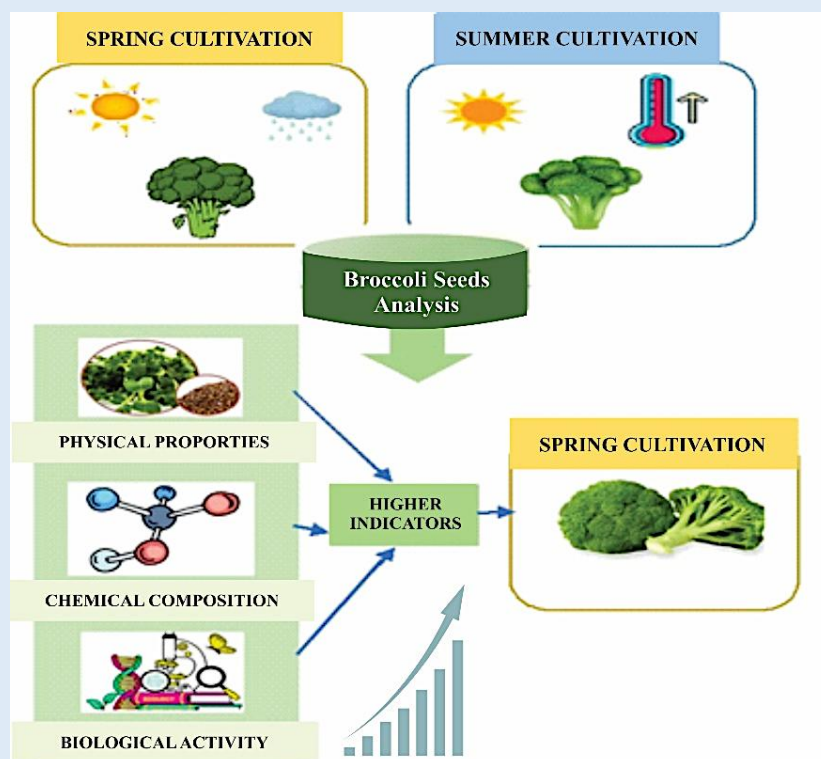
Methods: The 'Hayasa' cultivar was grown under spring and summer field conditions. Phenological observations, seed yield, and biometric parameters were recorded. Seed quality was assessed by germination percentage, germination energy, and seedling viability. Chemical analyses included vitamins C, A, B1, B2, B6, E, total phenolic compounds, soluble sugars, and mineral (ash) content, using spectrophotometric and colorimetric methods. Data were statistically analysed by ANOVA with four replications.

Results: Spring-grown seeds exhibited higher germination rates (92.3%), greater germination energy (85.3%), and superior seed mass (3.6 g/1000 seeds) compared to summer-grown seeds (germination 80.3%, energy 70%, seed mass 2.9 g/1000 seeds). Spring seeds also contained higher levels of vitamin C (49.1 mg/100 g DW), β -carotene (3.6 mg/100 g DW), B-group vitamins (0.43 mg/100 g), total phenolics (4.5–6.0 mg/g DW), soluble sugars (30–35%), and ash/mineral content, while summer seeds showed elevated vitamin E (4.6 mg/100 g DW) and total phenolics (6.0–8.0 mg/g DW), likely as a stress response to high temperature and solar radiation.

Novelty: This is the first comprehensive assessment of broccoli seed quality under different seasonal cultivation regimes in the Ararat Valley, integrating physical, chemical, and biological properties. The study demonstrates how environmental conditions modulate functional compounds in seeds, linking agronomic practices to health-promoting potential.

Conclusion: Spring cultivation provides optimal conditions for producing broccoli seeds with superior biological value, germination quality, and functional composition, suitable for agricultural propagation and functional food applications. Summer cultivation reduces seed quality but induces stress-related increases in specific bioactive compounds, highlighting the importance of seasonal management strategies to maximize functional food potential.

Keywords: broccoli seeds, vitamins, total phenolics, functional foods, seasonal cultivation



Graphical Abstract: Impact of Spring and Summer Cultivation on Broccoli Seed Quality and Bioactive

INTRODUCTION

Ensuring access to healthy food is a complex, multifactorial process that depends on environmental conditions, socioeconomic factors, advances in medicine and the fundamental sciences, and the introduction of nutritionally valuable crops alongside innovative agricultural technologies. Among such crops, broccoli (*Brassica oleracea* var. *italica*), a member of the Brassicaceae family, has gained global importance due to its nutritional and medicinal properties [1-2]. It is commonly cultivated in Europe, Asia, and the Americas, and in recent decades has expanded into developing countries, including Armenia. Despite being a relatively new crop in the Republic of Armenia, broccoli is gaining popularity.

Broccoli is rich in vitamins (C, K, and E), minerals, antioxidants, and sulfur-containing bioactive compounds that support the immune system and help prevent disease [3]. It exhibits strong antioxidant and detoxifying properties. Scientific interest has increasingly focused not only on edible plant parts but also on seeds, which contain higher concentrations of bioactive compounds.

Improving agricultural efficiency is closely linked to seed production, especially for crops sensitive to environmental conditions, such as broccoli. In Armenia, dependence on imported seeds and increasing climatic stress present significant challenges for establishing sustainable local seed production systems. In Armenia, broccoli cultivation is still developing in terms of certified and locally adapted seed production. Key constraints currently include limited varietal diversity, variability in seed quality under changing environmental conditions, and insufficient laboratory and seed production infrastructure.

Broccoli seeds and sprouts have attracted significant scientific interest in recent decades, as they contain high amounts of oils (28–35%), proteins (20–25%), glucosinolates, flavonoids, vitamins, and minerals, which play both a protective role in the plant and

demonstrate anticancer, antioxidant, and antibacterial potential for human health [4-5]. Glucosinolate levels are determined not only by genetic factors but also by growing conditions, particularly temperature regimes and the plant's developmental stage [6]. High temperatures and limited water availability can reduce their accumulation [7-8].

Previous studies have shown that the antioxidant activity of broccoli seeds is largely associated with phenolic compounds, vitamins, and minerals, which positively influence the oxidative-reductive balance in the human body [9]. At the same time, environmental factors can significantly influence the accumulation of these compounds [10-11]. Numerous studies have also shown that spring-grown seeds and plants contain higher concentrations of phenolic compounds, exhibit stable antioxidant activity, and demonstrate favorable morphological traits, whereas summer conditions, due to heat and water stress, lead to decreases in both biological and chemical indicators [12-14].

The biological value of broccoli seeds depends not only on chemical composition but also on physiological activity. Seedlings at early stages contain higher levels of sulforaphane and other bioactive compounds than mature plants, making them particularly valuable for both food and pharmaceutical applications. Due to their high sulforaphane content, broccoli sprouts are considered among the most potent plant-based activators of cancer-protective enzymes [15].

The quality and yield of broccoli seeds are strongly influenced by environmental conditions such as temperature, humidity, light, and soil properties. The full biological development, germination capacity, and storage potential of seeds are sensitive to abiotic factors. Variability in weather conditions across different climatic zones can disrupt the vegetative and generative phases of the plant, thereby affecting the quality and quantity of seed production. In this context, studying broccoli seed production under different climatic conditions is

scientifically important from both nutritional and agricultural perspectives [16-18].

The semi-arid climate of the Ararat Valley, with hot summers and mild springs, can differentially affect broccoli's biological phases, particularly the generative phases of seed formation and maturation. Spring cultivation generally provides more favorable conditions, with balanced temperature and moisture, which promote higher seed germination capacity and biochemical activity. Conversely, under summer cultivation, heat and water stress often result in reduced seed physiological performance and decreased levels of some bioactive compounds. Therefore, studying broccoli seed production under different seasonal conditions in the Ararat Valley is essential not only to improve agricultural productivity but also to enhance the nutritional and functional value of seeds, which are a rich source of bioactive compounds with significant potential for functional food development, disease prevention, and human health promotion.

MATERIALS AND METHODS

Experimental Site and Plant Material: The study was conducted in 2023–2025 at the experimental farm of the Scientific Centre of Vegetable and Technical Crops, Republic of Armenia. The study focused on the “Hayasa” broccoli cultivar, developed at the Scientific Center of Vegetable and Industrial Crops (SCVIC). Seeds used for sowing and subsequent plant studies were obtained from the SCVIC genebank collection [19]. Field trials were established under spring and summer cultivation conditions in the Ararat Valley of the Republic of Armenia, a region characterized by semi-arid climate, hot summers, mild springs, and significant temperature fluctuations.

Experimental Design and Field Measurements: Field experiments were arranged in a block design with four replications. Standard agronomic practices were applied for broccoli cultivation, including soil preparation, irrigation, fertilization, and pest management. During the

growing season, phenological observations were recorded to monitor growth stages, including germination, vegetative growth, flowering, and seed formation. Biometric measurements and seed yield per plant were recorded. Seed germination and vigor were evaluated based on germination percentage, germination energy, and seedling viability. Data were statistically analyzed using ANOVA [20], and significant differences were determined at $p < 0.05$.

Seed Analyses:

- Seed moisture content was determined by oven-drying at 105°C until constant weight.
- Vitamin C was determined by the 2,6-dichlorophenolindophenol titration method [21].
- β -carotene (Vitamin A) content was measured using a spectrophotometric method at 450 nm [22].
- B-group vitamins (B1, B2, B6) were analysed using standard colorimetric assays [23].
- Vitamin E (tocopherols) was quantified using a UV-Vis spectrophotometer at 292 nm after extraction with ethanol and hexane [24].
- Total phenolic compounds were determined using the Folin–Ciocalteu reagent method and quantified with a Cary 60 UV-Vis spectrophotometer at 765 nm [25].
- Soluble sugars were analyzed using the anthrone-sulfuric acid method with spectrophotometric detection at 620 nm.
- Mineral (ash) content was measured by dry ashing at 550°C, followed by gravimetric determination.
- Vitamin contents are expressed on a mass basis (mg/100 g) according to the analytical procedures described; the fresh or dry weight basis was not explicitly differentiated.

RESULTS AND DISCUSSIONS

According to the Functional Food Center's framework [26], the present study contributes to the initial stages of

functional food development by identifying and quantifying bioactive compounds in broccoli seeds, which form the scientific basis for subsequent validation of health benefits, particularly:

Step 1 – establishing the functional food goal, as the study focuses on evaluating broccoli seeds as a potential functional food source;

Step 2 – identification of bioactive compounds, as we quantified key vitamins (C, β -carotene, B-group vitamins, and tocopherols) that contribute to the functional and nutritional value of the crop.

While our study does not extend to later stages such as clinical validation or biomarker analysis, it provides essential baseline data that support further development within the Functional Food Center framework.

The aim of this study was to compare the biological and agronomic indicators of broccoli (*Brassica oleracea* var. *italica*) seed production under spring and summer cultivation in the Ararat Valley, to determine the most favorable cultivation period for obtaining high-quality, high-yielding seeds with enhanced nutritional and functional properties. To achieve this aim, the study addressed the following objectives:

- analyze the growth and developmental stages of broccoli under spring and summer sowing.
- measure and compare key seed production indicators (seed quantity, germination capacity, viability, and seedling yield).

- Conduct qualitative analysis of the obtained seeds in terms of germination, energy, and storage potential.
- Evaluate the role of temperature, light, and moisture conditions on seed formation, maturation, and biochemical traits.

The biological properties of seeds were assessed based on germination energy, seedling viability, and field emergence indicators. A combined analysis of the physical, chemical, and biological characteristics of broccoli seeds allows not only the prediction of field germination but also the optimization of sowing periods under different agroclimatic conditions. This is particularly important in the Ararat Valley, where water scarcity and large temperature fluctuations are typical.

Studies conducted in Ararat Valley conditions showed that seeds sown under different conditions germinated at different rates. As shown in Table 1, spring-sown seeds germinated on days 5–7 after sowing, while summer-sown seeds germinated two days earlier, due to higher air temperatures. The rosette formation phase in spring-sown crops was delayed by 5–7 days compared with summer-sown crops. A similar pattern was observed for the period from mass germination to head maturation, as well as during the flowering and seed-formation stages.

Table 1. Comparative analysis of growth and development stages of broccoli under spring and summer cultivation.

Growth stage	Spring sowing	Summer sowing
Sowing time	late February – early March	early June
Germination (days)	5.7±0.5	4.0±0.8
Vegetative growth (leaf formation), days	23.3±2.5	17±1.6
Flower bud formation stage (days)	16.7±1.3	13±1.6
Flowering (days)	10.7±2.1	6.7±0.9
Seed formation and maturation (days)	23.0±2.2	16.3±1.0
Total vegetation period (days)	76.7±6.2	62.3±5.3

Previous research confirms that broccoli grown under different conditions exhibits morphological changes in seed-producing plants [27].

Our studies also indicate that climatic differences affected seed germination quality and germination

energy. This is because seeds produced under spring conditions mature fully, whereas summer heat reduces seed viability and decreases both germination rate and seedling vigor (Table 2).

Table 2. Comparison of quality indicators of broccoli seeds under spring and summer cultivation.

Indicator	Spring cultivation	Summer cultivation
Germination rate (%)	92.3±0.47	8.3±1.7
Germination energy (%)	85.3±3.7	70.0±2.2
Seed yield per plant (g)	13.9±1.03	9.9±0.3
Average seed weight (g/1000 seeds)	3.6±0.2	2.9±0.3
Seed dry matter content (%)	92.3±1.25	89.3±1.3
Storage duration (under optimal conditions)	2–3 years	1.5–2 years
Damaged seeds (%)	4.7±1.3	8.3±1.4

It is known that seed sowing quality depends on growth conditions, applied agronomic practices, and cultivar characteristics. Our research showed that, on average, spring-sown plants produced 14.3 g of seeds per plant, 26.6% more than seeds obtained from summer-grown plants. Spring-sown seeds were larger, more uniform, and had a lower proportion of damaged seeds, with a 1000-seed weight of 3.6 g, compared to 2.9 g in summer. The smaller and damaged seeds in summer are attributed to higher temperatures.

Additionally, the research supports that seed biochemical composition is most strongly influenced by absolute temperature, temperature fluctuations, solar radiation intensity, water stress, and photoperiod. These environmental factors play a critical role not only in plant metabolism but also in determining the concentrations of bioactive compounds directly relevant to functional food development.

As shown in Table 3, vitamin C content was higher in seeds produced under spring conditions than in summer. This can be explained by vitamin C's sensitivity to high temperatures. At moderate temperatures (15–

22°C), typical of spring in the Ararat Valley, vitamin C synthesis remains more stable, leading to higher accumulation in seeds. In contrast, elevated summer temperatures (28–35°C) and increased solar radiation induce heat stress, which can inhibit ascorbic acid biosynthesis and accelerate its degradation. Similar trends have been reported in previous studies, where elevated temperatures can negatively affect vitamin C stability and promote its degradation in *Brassica* crops, although the extent of this effect depends on species and growing conditions [28–29]. From a functional food perspective, higher vitamin C levels enhance the antioxidant potential of seeds, contributing to their value in preventing oxidative stress-related disorders

A comparable pattern was observed for β -carotene (provitamin A). Moderate environmental conditions favor stable carotenoid biosynthesis, whereas high light intensity and temperature can lead to oxidative degradation of carotenoids. Since carotenoids are important bioactive compounds with provitamin A activity and antioxidant properties, their reduction under stress conditions may decrease the nutritional and

functional quality of seeds. Therefore, cultivation conditions that preserve carotenoid content are essential for maximizing the health-promoting properties of plant-derived functional foods.

Table 3. Vitamin content in broccoli seeds under spring and summer cultivation.

Chemical component	Spring cultivation (mean % in dry matter)	Summer cultivation (mean % in dry matter)
Vitamin C (mg/100 g)	49.1±2.2	39.0±5.4
β-Carotene (Vitamin A) (mg/100 g)	3.6±0.3	3.1±0.3
Vitamin B1 (mg/100 g)	0.59±0.03	0.52±0.04
Vitamin B2 (mg/100 g)	0.25±0.03	0.21±0.02
Vitamin B6 (mg/100 g)	0.46±0.03	0.42±0.03
Vitamin E (Tocopherols) (mg/100 g)	3.8±0.3	4.6±0.6

B-group vitamins showed greater stability than other vitamins, as their accumulation is primarily associated with photosynthetic activity during the seed-filling stage. Under spring conditions, optimal temperatures and balanced environmental factors support efficient photosynthesis, resulting in higher accumulation of these vitamins. In contrast, heat stress during summer may negatively affect seed filling and reduce the overall biochemical quality of seeds. B vitamins are essential for energy metabolism in humans, and their stable presence contributes to the nutritional reliability of seeds as functional food ingredients.

Vitamin E (tocopherols), known for its strong antioxidant properties, tended to increase under summer conditions. This may be explained by the plant’s physiological response to stress, as higher temperatures and intense radiation stimulate the production of antioxidant compounds to protect cellular structures from oxidative damage. As a result, seeds produced under summer conditions contained approximately 10–30% higher levels of vitamin E. Similar stress-induced increases in tocopherol content have been reported in other crops exposed to abiotic stress conditions [30–31].

This increase may enhance the oxidative stability of functional food products and provide additional health benefits, including lipid protection and cellular defense mechanisms.

Several studies have shown that flavonoid and other phenolic contents may increase or decrease depending on heat and radiation conditions. Phenolics constitute part of the plant’s defense system and often increase under stress conditions [32–34]. Our analyses support these findings: as shown in Fig. 1, phenolic content in spring seeds ranged from 4.5–6.0 mg/g, whereas in summer seeds it was 20–50% higher (6.0–8.0 mg/g). These compounds are widely recognized as key bioactive constituents in functional foods due to their antioxidant, anti-inflammatory, and potential disease-preventive properties.

Similarly, as shown in Fig. 2, heat often increases soluble sugar accumulation, accelerating physiological maturity and resulting in 30–35% sugar content in spring seeds and 35–38% in summer seeds. While sugars primarily contribute to energy value and sensory characteristics, their interaction with bioactive compounds may influence the overall functional profile of the final product.

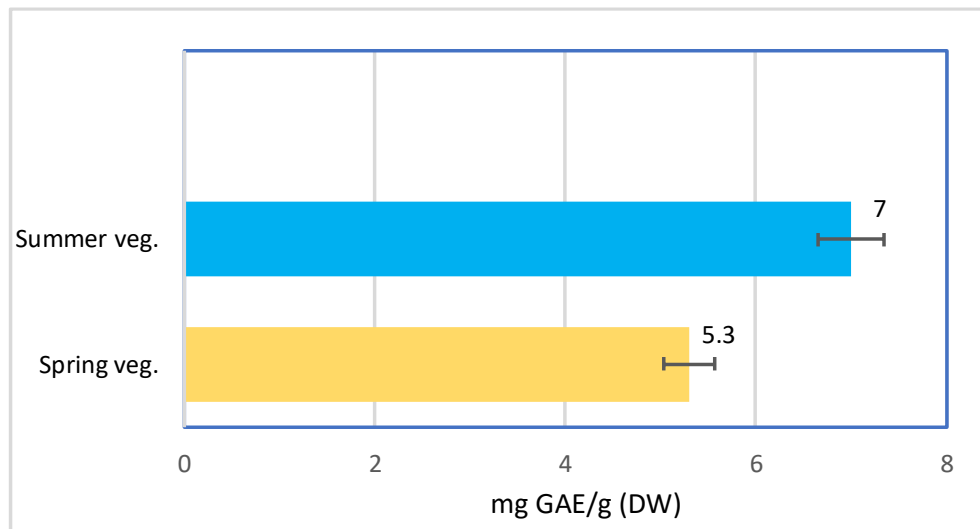


Figure 1. Content of total phenolics in broccoli seeds depending on the growing season

Overall, the results demonstrate that environmental conditions significantly affect the accumulation of bioactive compounds in broccoli seeds, thereby influencing their potential application in functional foods. From a functional food science perspective, optimizing cultivation conditions is essential to enhance the concentration of health-promoting compounds and to develop plant-based products with targeted nutritional and physiological benefits.

Regarding ash and mineral content, seeds produced under spring conditions exhibited higher levels compared

to summer-grown seeds (Fig. 2). This may be attributed to slower plant growth and more favorable moisture conditions in spring, which enhance nutrient uptake and accumulation from the soil. Under summer conditions, water deficit and accelerated plant development can limit mineral absorption and translocation to seeds. Mineral composition is an important factor determining the nutritional value of seeds, particularly in the context of functional foods, as seeds are rich sources of essential macro- and micronutrients that contribute to human health and dietary quality [35].

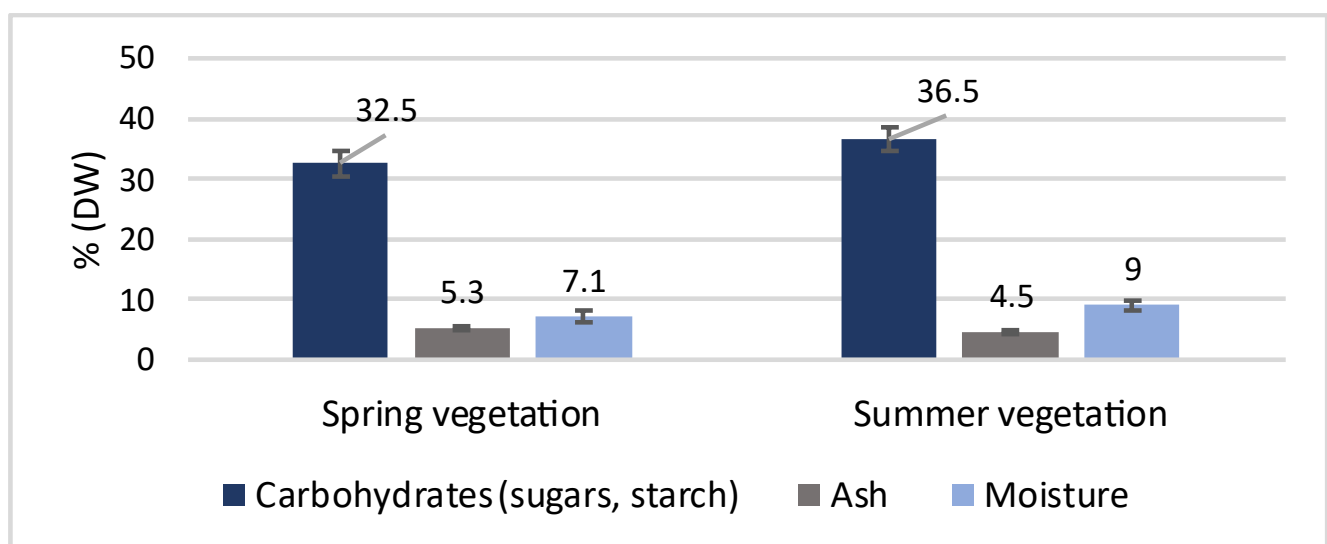


Figure 2. Content of total carbohydrates (sugars, starch), ash (mineral elements), and moisture in broccoli seeds depending on the growing season ($p \leq 0.05$)

Moisture content plays a critical role in seed storage stability and susceptibility to microbial development. Seeds harvested under summer conditions exhibited higher moisture levels, likely due to elevated temperatures and rapid maturation, which necessitate additional drying before storage. In contrast, spring-produced seeds generally had lower moisture content and demonstrated better storage stability, maintaining germination capacity for longer periods and showing a lower proportion of damaged seeds (Fig. 2). These findings are consistent with previous studies demonstrating that reduced seed moisture content is critical for maintaining viability, preserving seed quality, and preventing deterioration during storage [36].

Practical implications: The findings of this study provide important guidance for optimizing broccoli seed production under the agroclimatic conditions of the Ararat Valley. Spring cultivation is recommended as the optimal period for producing high-quality seeds with superior germination, improved storage stability, and enhanced nutritional composition. These characteristics are particularly important for both agricultural use and the development of functional food products.

Seeds produced under spring conditions, characterized by higher levels of vitamins (C, β -carotene, and B-group vitamins) and minerals, offer greater potential as raw materials for nutritionally enriched foods and health-related applications. In contrast, summer-produced seeds, although showing increased levels of certain stress-related compounds such as phenolics and vitamin E, require additional post-harvest handling, including drying and careful storage, due to their higher moisture content and reduced viability.

From a practical perspective, the results support the implementation of season-specific cultivation strategies to improve seed quality and functional value. This approach can help reduce dependence on imported seeds, strengthen local seed production systems, and

promote the use of broccoli seeds in functional food development and nutraceutical applications.

CONCLUSIONS

The results of this study demonstrate that spring cultivation is the most favorable period for broccoli seed production in the Ararat Valley. Seeds obtained under spring conditions exhibited higher biological value, improved germination characteristics, and better storage stability, which can be attributed to a more balanced and complete chemical composition. In contrast, seeds produced under summer conditions showed reduced nutritional quality and higher moisture content, necessitating additional post-harvest drying and resulting in lower storage stability. From a functional food perspective, the superior biochemical profile of spring-produced seeds, including higher levels of essential nutrients and stable bioactive compounds, enhances their potential for use in functional food products and health-promoting applications. These findings highlight the importance of optimizing cultivation practices not only to improve agricultural productivity but also to maximize the nutritional and functional value of broccoli seeds for human health.

The findings contribute to the early stages of the Functional Food Center framework, particularly in identifying bioactive compounds in broccoli seeds.

List of Abbreviations: Vitamin B – B; Vitamin A – A; Vitamin C – C; Ascorbic Acid – AA; TPC – Total Phenolic Content; mg GAE/g (DW)- milligrams of Gallic Acid Equivalents per gram of Dry Weight, milligram - mg; gram -g; dry matter – DW.

Competing Interests: The authors declare that they have no competing interests.

Authors' Contributions: LT designed the research and wrote the article, AA analyzed the results, IT drew the graphs, AH and ZH performed laboratory analysis, LM

performed statistical analyses, HN performed field experiments, and RB edited the article. All authors read and approved the final version of the manuscript.

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