LONG-TERM STORAGE PERFORMANCE AND RETENTION OF BIOACTIVE COMPOUNDS IN POWDERS FROM DIFFERENT BROCCOLI HYBRIDS

Sherzod.Sh.Nurmatov
PhD Student, Samarkand Institute of Agroinnovations and Research
Samarkand, Uzbekistan
ORCID: 0009-0007-6338-2439
e-mail: nurmatovsherzod1988@gmail.com
https://doi.org/10.5281/zenodo.22247064

Abstract.

This study investigated the long-term storage performance and retention of bioactive compounds in powders produced from different broccoli hybrids using an optimized drying technology. Broccoli samples were dried at 55°C using infrared radiation combined with an air velocity of 1.5 m/s and stored for 12 months. Changes in moisture content, water activity (aw), color characteristics, ascorbic acid, total phenolic compounds, flavonoids, chlorophyll, and antioxidant activity were evaluated during storage. Among the studied hybrids, **Naxos F1** exhibited the highest overall stability. After 12 months, it retained 83.2% of ascorbic acid, 88.7% of phenolic compounds, 87.9% of flavonoids, 83.5% of chlorophyll, and 89.0% of antioxidant activity. Its water activity remained at 0.33, while the total color difference was ΔE = 3.91. **Agassi F1** also demonstrated high storage stability. The results confirmed that the long-term quality of broccoli powder is significantly influenced by hybrid characteristics and identified Naxos F1 and Agassi F1 as promising raw materials for producing stable, bioactive-rich broccoli powder.

Keywords: broccoli, broccoli powder, broccoli hybrids, long-term storage, bioactive compounds, ascorbic acid, phenolic compounds, chlorophyll, antioxidant activity, quality stability.

1. Introduction

Broccoli (Brassica oleracea var. italica) is widely recognized as a nutritionally valuable vegetable due to its high concentrations of ascorbic acid, phenolic compounds, flavonoids, chlorophyll pigments, carotenoids, glucosinolates, and other health-promoting constituents. These compounds contribute to the antioxidant and functional properties of broccoli and support its use as a raw material for the development of nutrient-dense and functional food products.

Fresh broccoli is highly perishable because of its high moisture content and continued physiological activity after harvest. During storage, moisture loss, chlorophyll degradation, discoloration, and depletion of biologically active compounds may progressively reduce product quality. Therefore, the development of processing technologies capable of stabilizing broccoli while preserving its valuable constituents is of considerable scientific and practical importance.

Drying broccoli and converting it into powder can substantially reduce moisture content, slow microbial and enzymatic deterioration, extend shelf life, and provide a convenient ingredient that can be used throughout the year. Previous studies have shown that both drying conditions and processing intensity may strongly influence the retention of bioactive compounds in broccoli. In particular, temperature, drying duration, and the mode of heat transfer can affect thermolabile constituents such as ascorbic acid, phenolic compounds, chlorophyll, and related antioxidants.

Recent research has increasingly focused on the production of broccoli powders and powdered ingredients from broccoli-derived biomass. Such powders may retain considerable levels of phenolics, flavonoids, pigments, and other functional constituents, which makes them promising ingredients for food fortification. However, obtaining a high-quality powder immediately after drying does not necessarily ensure that its physicochemical and bioactive properties will remain unchanged during prolonged storage.

Even in dried plant products, oxidative and physicochemical transformations continue during storage. Their rates depend on moisture content, water activity, oxygen exposure, light, packaging properties, and storage duration. Consequently, gradual losses of ascorbic acid, phenolic compounds, flavonoids, and pigments may occur, accompanied by reductions in antioxidant activity and changes in sensory quality.

Moisture content and water activity (aw) are particularly important indicators of the storage stability of vegetable powders. Excessive moisture uptake may increase hygroscopicity, promote particle agglomeration, reduce flowability, and accelerate chemical deterioration. At the same time, preservation of the characteristic green color of broccoli powder is strongly associated with chlorophyll stability. Monitoring CIELAB color parameters together with chlorophyll retention therefore provides a more comprehensive assessment of quality changes during storage.

Genotypic characteristics may also influence the post-processing stability of broccoli products. Different hybrids may vary in their initial composition and in the resistance of their bioactive constituents to processing and storage conditions. Therefore, powders produced under identical technological conditions may exhibit different rates of quality deterioration during storage.

In this study, powders produced from **Agassi F1, Ironman F1, Atlantis F1, Heraklion F1, Naxos F1, Marathon F1, and Tiburon F1** broccoli hybrids were comparatively evaluated. All samples were processed under identical drying and storage conditions to determine whether hybrid-specific characteristics affected long-term quality preservation.

Previous experiments identified a combination of **55°C drying temperature, infrared radiation, and an air velocity of 1.5 m/s** as an appropriate processing regime for broccoli powder production. The present study therefore focused on the subsequent storage behavior of powders obtained under this optimized condition rather than on further optimization of the drying process.

The **aim of this study** was to compare changes in physicochemical quality, color stability, and bioactive compound retention in powders produced from seven broccoli hybrids during 12 months of storage and to identify the hybrids with the highest long-term storage performance.

2. Materials and Methods

2.1. Plant Material and Sample Preparation

Seven broccoli (Brassica oleracea var. italica) hybrids — **Agassi F1, Ironman F1, Atlantis F1, Heraklion F1, Naxos F1, Marathon F1, and Tiburon F1** — were used as

IBAST | Volume 6, Issue 08, August

experimental materials. Broccoli heads of uniform maturity, free from visible mechanical damage and external defects, were selected for the study.

To ensure comparability among hybrids, all samples were subjected to identical preparation, drying, grinding, packaging, and storage conditions. The broccoli heads were sorted, washed, and divided into florets of approximately **20–30 mm** before drying.

2.2. Drying and Powder Production

Based on the results of previous experiments, broccoli samples were dried under the optimized regime combining a temperature of **55°C, infrared radiation, and an air velocity of 1.5 m/s**. Drying was continued until a stable final moisture level was achieved.

After drying, the samples were cooled to room temperature and ground using a laboratory mill. The resulting material was passed through a **0.5-mm sieve** to obtain a uniform powder.

The same processing conditions were applied to all seven hybrids so that **broccoli hybrid and storage duration** were considered the principal experimental factors.

2.3. Storage Conditions

The broccoli powders were packed in hermetically sealed packages designed to minimize exposure to environmental moisture, oxygen, and light. The samples were stored under dry, light-protected conditions for **12 months**.

Quality analyses were performed at the beginning of storage (**0 months**) and after **3, 6, 9, and 12 months**. Measurements obtained at 0 months were used as the initial reference values for evaluating changes during storage.

2.4. Determination of Physicochemical Properties

Moisture content and **water activity (aw)** were determined to evaluate the physical stability of broccoli powders during storage. Changes in these parameters were used to characterize moisture uptake and the overall stability of the powdered products.

Color characteristics were evaluated using the **CIELAB color system**. The parameters L*, a*, and b* represented lightness, the green–red coordinate, and the blue–yellow coordinate, respectively.

The total color difference (ΔE) at each storage interval was calculated relative to the initial color values according to the following equation:

$$\Delta E = \sqrt{[(L^*_t - L^*_0)^2 + (a^*_t - a^*_0)^2 + (b^*_t - b^*_0)^2]}$$

where **L^*_0, a^*_0, and b^*_0** are the initial color coordinates and **L*t, a*t, and b*t** are the corresponding values after a given storage period.

2.5. Determination of Bioactive Components

The biological quality of broccoli powders was evaluated by determining **ascorbic acid, total phenolic compounds, flavonoids, total chlorophyll, and antioxidant activity** throughout the storage period.

To enable direct comparison among hybrids with potentially different initial concentrations, the retention of each bioactive component was expressed as a percentage of its initial value:

$$R = (Ct / C0) \times 100$$

where **R** is the retention of the corresponding bioactive component (%), **C_0** is its concentration at the beginning of storage, and **C_t** is its concentration after the specified storage period.

IBAST | Volume 6, Issue 08, August

This approach allowed the relative stability of bioactive constituents to be compared among broccoli hybrids independently of differences in their initial composition.

2.6. Statistical Analysis

All experimental determinations were performed in triplicate, and the results were expressed as **mean ± standard deviation (SD)**. The effects of broccoli hybrid, storage duration, and their interaction were evaluated using **two-way analysis of variance (ANOVA)**. Differences were considered statistically significant at **$p < 0.05$**.

Correlation analysis was additionally used to evaluate the relationships between chlorophyll retention and color changes, as well as between the retention of phenolic compounds and flavonoids and the antioxidant activity of broccoli powders.

3. Results and Discussion

3.1. Changes in Moisture Content and Water Activity During Storage

Moisture content and water activity are important indicators of the physical stability of vegetable powders during prolonged storage. At the beginning of the experiment, the moisture content of broccoli powders ranged from **6.6 to 6.9%**, while water activity varied between **0.29 and 0.31**. A gradual increase in both parameters was observed in all samples as storage time progressed.

Table 1. Changes in moisture content and water activity (aw) of powders from different broccoli hybrids during storage

Broccoli hybrid	Storage period, months	Moisture content, %	Water activity (aw)
Agassi F1	0	6.7 ± 0.2	0.30 ± 0.01
	3	6.9 ± 0.2	0.31 ± 0.01
	6	7.1 ± 0.2	0.32 ± 0.01
	9	7.3 ± 0.2	0.33 ± 0.01
	12	7.6 ± 0.2	0.34 ± 0.01
Ironman F1	0	6.8 ± 0.2	0.30 ± 0.01
	3	7.0 ± 0.2	0.31 ± 0.01
	6	7.2 ± 0.2	0.32 ± 0.01
	9	7.5 ± 0.2	0.34 ± 0.01
	12	7.8 ± 0.3	0.35 ± 0.01
Atlantis F1	0	6.9 ± 0.2	0.31 ± 0.01
	3	7.1 ± 0.2	0.32 ± 0.01
	6	7.4 ± 0.2	0.33 ± 0.01
	9	7.7 ± 0.3	0.35 ± 0.01
	12	8.0 ± 0.3	0.37 ± 0.01
Heraklion F1	0	6.7 ± 0.2	0.30 ± 0.01
	3	6.9 ± 0.2	0.31 ± 0.01
	6	7.1 ± 0.2	0.32 ± 0.01
	9	7.4 ± 0.2	0.33 ± 0.01
	12	7.7 ± 0.2	0.35 ± 0.01
Naxos F1	0	6.6 ± 0.2	0.29 ± 0.01
	3	6.8 ± 0.2	0.30 ± 0.01
	6	7.0 ± 0.2	0.31 ± 0.01

IBAST | Volume 6, Issue 08, August

	9	7.2 ± 0.2	0.32 ± 0.01
	12	**7.4 ± 0.2**	**0.33 ± 0.01**
Marathon F1	0	6.8 ± 0.2	0.30 ± 0.01
	3	7.0 ± 0.2	0.31 ± 0.01
	6	7.3 ± 0.2	0.33 ± 0.01
	9	7.6 ± 0.2	0.34 ± 0.01
	12	7.9 ± 0.3	0.36 ± 0.01
Tiburon F1	0	6.9 ± 0.2	0.31 ± 0.01
	3	7.1 ± 0.2	0.32 ± 0.01
	6	7.3 ± 0.2	0.33 ± 0.01
	9	7.6 ± 0.2	0.35 ± 0.01
	12	7.9 ± 0.3	0.36 ± 0.01

After six months of storage, differences among the hybrids became more pronounced. **Naxos F1** maintained a moisture content of 7.0% and an aw value of 0.31, whereas Agassi F1 and Heraklion F1 showed moisture contents of 7.1% and aw values of 0.32. Atlantis F1 exhibited comparatively greater changes, reaching 7.4% moisture and an aw of 0.33.

By the end of the 12-month storage period, **Naxos F1 showed the lowest final moisture content (7.4%) and water activity (0.33)** among the evaluated hybrids. Its moisture content increased by only 0.8 percentage points from the initial value of 6.6%.

Agassi F1 also demonstrated high physical stability, with a final moisture content of 7.6% and an aw value of 0.34. Heraklion F1 and Ironman F1 reached moisture contents of 7.7 and 7.8%, respectively, while their water activity values were both 0.35.

In comparison, Marathon F1 and Tiburon F1 reached 7.9% moisture and an aw of 0.36 after 12 months. The highest values were recorded for **Atlantis F1**, with a moisture content of 8.0% and water activity of 0.37.

Overall, moisture content increased by **0.8–1.1 percentage points**, while water activity increased by approximately **0.04–0.06 units**, depending on the hybrid. Nevertheless, aw did not exceed **0.37** in any sample after 12 months, indicating that the powders retained a relatively stable physical state throughout storage. Naxos F1 exhibited the highest physical stability, followed by Agassi F1 and Heraklion F1.

3.2. Changes in Bioactive Compounds During Storage

The retention of bioactive compounds is a key criterion for evaluating the nutritional and functional quality of broccoli powder during prolonged storage. The results showed a gradual decline in ascorbic acid, total phenolic compounds, flavonoids, chlorophyll, and antioxidant activity in all broccoli hybrids as storage duration increased. However, the rate of degradation differed considerably among the hybrids.

Table 2. Retention of bioactive components in broccoli powders during 12 months of storage, %

Hybrid	Storage, months	Ascorbic acid	Total phenolics	Flavonoids	Chlorophyll	Antioxi-dant activity
Agassi F1	3	96.0	97.4	96.9	96.0	97.5
	6	91.8	94.7	94.0	92.0	94.8

	9	87.0	91.3	90.5	87.5	91.5
	12	82.1	88.0	87.1	82.7	88.3
Ironman F1	3	95.3	97.0	96.4	95.4	97.1
	6	90.5	93.9	93.0	90.8	94.0
	9	85.1	90.0	88.9	85.3	90.2
	12	79.4	85.9	84.6	79.7	85.8
Atlantis F1	3	94.4	96.5	95.8	94.5	96.6
	6	88.8	92.3	91.5	88.9	92.6
	9	82.6	87.6	86.3	82.5	87.9
	12	75.9	82.9	81.5	76.1	83.2
Heraklion F1	3	95.6	97.2	96.6	95.7	97.3
	6	91.0	94.2	93.5	91.3	94.4
	9	85.8	90.5	89.6	86.1	90.7
	12	80.2	86.5	85.3	80.8	86.6
Naxos F1	3	**96.5**	**97.8**	**97.3**	**96.5**	**97.9**
	6	**92.5**	**95.2**	**94.6**	**92.6**	**95.3**
	9	**87.9**	**91.9**	**91.2**	**88.1**	**92.1**
	12	**83.2**	**88.7**	**87.9**	**83.5**	**89.0**
Marathon F1	3	94.9	96.8	96.1	95.0	96.9
	6	89.7	93.3	92.4	89.9	93.5
	9	83.9	88.8	87.6	84.1	89.1
	12	77.6	84.4	82.9	77.9	84.7
Tiburon F1	3	94.7	96.6	96.0	94.8	96.8
	6	89.2	92.8	91.9	89.4	93.1
	9	83.2	88.1	86.9	83.4	88.5
	12	76.8	83.7	82.3	77.1	84.0

During the first three months, losses of bioactive compounds were relatively limited. Most of the evaluated components retained more than 94% of their initial levels. **Naxos F1** exhibited the highest stability at this stage, retaining 96.5% of ascorbic acid, 97.8% of total phenolic compounds, 97.3% of flavonoids, 96.5% of chlorophyll, and 97.9% of antioxidant activity.

After six months, differences among the hybrids became more evident. Naxos F1 retained **92.5% of ascorbic acid, 95.2% of total phenolics, 94.6% of flavonoids, 92.6% of chlorophyll, and 95.3% of antioxidant activity**. Agassi F1 showed a similar pattern, although its retention values were slightly lower.

A further decline in bioactive compounds was observed after nine months of storage. Nevertheless, Naxos F1 maintained 91.9% of its initial total phenolic compounds, 91.2% of flavonoids, and 92.1% of antioxidant activity. The corresponding values for Agassi F1 were 91.3, 90.5, and 91.5%, respectively.

The greatest differences among hybrids were recorded at the end of the 12-month storage period. **Naxos F1 showed the highest overall retention of bioactive compounds**, preserving 83.2% of ascorbic acid, 88.7% of total phenolic compounds, 87.9% of flavonoids, 83.5% of chlorophyll, and 89.0% of antioxidant activity. Agassi F1 ranked second, retaining

82.1, 88.0, 87.1, 82.7, and 88.3% of these parameters, respectively. These results are consistent with the overall pattern observed in the final quality assessment of the hybrids.

Heraklion F1 and Ironman F1 exhibited intermediate stability. In contrast, greater losses of bioactive compounds were observed in Marathon F1, Tiburon F1, and Atlantis F1. After 12 months, Tiburon F1 retained 76.8% of its initial ascorbic acid and 77.1% of chlorophyll, whereas the corresponding values for Atlantis F1 were 75.9 and 76.1%, respectively.

Among the investigated compounds, **ascorbic acid and chlorophyll were the most sensitive to prolonged storage**, whereas total phenolic compounds and flavonoids showed comparatively greater stability. Antioxidant activity followed a pattern similar to that of phenolic compounds and flavonoids, suggesting that the preservation of these phytochemicals contributed substantially to maintaining the antioxidant potential of broccoli powder.

The observed differences indicate that the stability of bioactive constituents cannot be attributed solely to the drying and storage conditions, since all samples were processed and stored under identical conditions. Hybrid-specific characteristics therefore appear to play an important role in determining the long-term retention of biologically active compounds.

3.3. Changes in Color Characteristics During Storage

Color is an important quality attribute of broccoli powder because its characteristic green appearance is closely associated with pigment stability and overall product acceptability. After 12 months of storage, all samples showed a decrease in L* values and a shift of a* values toward less negative values, indicating gradual darkening and loss of green color intensity.

Among the studied hybrids, **Naxos F1 exhibited the highest color stability**. Its L* value decreased from 60.4 to 57.4, while the a* coordinate changed from −12.7 to −10.7. The total color difference was only **ΔE = 3.91**, representing the lowest value among all tested hybrids.

Agassi F1 also showed relatively high color stability, with a ΔE value of 4.16. Heraklion F1 and Ironman F1 exhibited intermediate changes, with ΔE values of 4.61 and 4.82, respectively. More pronounced color deterioration was observed in Marathon F1 and Tiburon F1, whereas Atlantis F1 showed the greatest total color change (ΔE = 6.36).

Table 3. Color stability of broccoli powders after 12 months of storage

Broccoli hybrid	L* (0 months)	L* (12 months)	a* (0 months)	a* (12 months)	ΔE (12 months)
Agassi F1	60.2	57.0	−12.5	−10.4	**4.16**
Ironman F1	60.0	56.0	−12.3	−9.8	4.82
Atlantis F1	59.7	54.8	−12.1	−8.7	6.36
Heraklion F1	60.1	56.3	−12.4	−10.0	4.61
Naxos F1	**60.4**	**57.4**	**−12.7**	**−10.7**	**3.91**
Marathon F1	59.9	55.5	−12.2	−9.4	5.45
Tiburon F1	59.8	55.2	−12.2	−9.1	5.76

The hybrids could therefore be ranked according to their color stability as follows:

Naxos F1 > Agassi F1 > Heraklion F1 > Ironman F1 > Marathon F1 > Tiburon F1 > Atlantis F1.

The observed pattern was closely associated with chlorophyll retention. Naxos F1 retained 83.5% of its initial chlorophyll and simultaneously exhibited the lowest ΔE value, whereas Atlantis F1 retained only 76.1% of chlorophyll and showed the greatest color

IBAST | Volume 6, Issue 08, August

difference. These findings indicate that chlorophyll degradation was one of the major factors contributing to the loss of the characteristic green color during storage.

3.4. Relationship Between Chlorophyll Retention and Color Stability

Changes in instrumental color parameters corresponded closely with chlorophyll retention. Naxos F1, which retained the highest proportion of chlorophyll after 12 months (**83.5%**), also exhibited the lowest total color difference ($\Delta E = 3.91$). Similarly, Agassi F1 retained 82.7% of its initial chlorophyll and showed a relatively low ΔE value of 4.16.

In contrast, Atlantis F1 retained only 76.1% of its initial chlorophyll and exhibited the greatest total color difference ($\Delta E = 6.36$). This pattern indicates that increased chlorophyll degradation was accompanied by a greater loss of the characteristic green appearance of broccoli powder.

The shift of a* values toward less negative values further supports this relationship. As chlorophyll degradation progressed, the intensity of green coloration decreased. Therefore, the combined assessment of **chlorophyll retention and ΔE** provides a useful approach for evaluating the visual and pigment stability of broccoli powder during long-term storage.

3.5. Relationship Between Bioactive Compound Retention and Antioxidant Activity

The reduction in antioxidant activity during storage followed a pattern similar to the decline in total phenolic compounds and flavonoids. After 12 months, Naxos F1 retained **88.7% of total phenolics, 87.9% of flavonoids, and 89.0% of antioxidant activity**, while the corresponding values for Agassi F1 were 88.0, 87.1, and 88.3%, respectively. These values are also reflected in the final comparative assessment reported in the article. Heraklion F1 and Ironman F1 showed intermediate retention, whereas greater reductions were observed in Marathon F1, Tiburon F1, and particularly Atlantis F1. The parallel trends in phenolic compounds, flavonoids, and antioxidant activity suggest that preservation of these phytochemical groups is an important factor in maintaining the functional properties of broccoli powder during storage.

3.6. Overall Storage Performance of Broccoli Hybrid Powders

The integrated assessment of physicochemical parameters, bioactive compound retention, antioxidant activity, and color stability revealed clear differences among the seven broccoli hybrids after 12 months of storage.

Table 4. Overall quality characteristics of broccoli hybrid powders after 12 months of storage

Quality parameter	Agassi F1	Ironman F1	Atlantis F1	Heraklion F1	Naxos F1	Marathon F1	Tiburon F1
Moisture content, %	7.6	7.8	8.0	7.7	**7.4**	7.9	7.9
Water activity (aw)	0.34	0.35	0.37	0.35	**0.33**	0.36	0.36
Ascorbic acid retention, %	82.1	79.4	75.9	80.2	**83.2**	77.6	76.8

Total phenolics retention, %	88.0	85.9	82.9	86.5	**88.7**	84.4	83.7
Flavonoid retention, %	87.1	84.6	81.5	85.3	**87.9**	82.9	82.3
Chlorophyll retention, %	82.7	79.7	76.1	80.8	**83.5**	77.9	77.1
Antioxidant activity retention, %	88.3	85.8	83.2	86.6	**89.0**	84.7	84.0
Total color difference (ΔE)	4.16	4.82	6.36	4.61	**3.91**	5.45	5.76

Naxos F1 demonstrated the best overall storage performance. It had the lowest moisture content (7.4%) and water activity (0.33), while retaining the highest levels of ascorbic acid (83.2%), total phenolic compounds (88.7%), flavonoids (87.9%), chlorophyll (83.5%), and antioxidant activity (89.0%). Furthermore, its ΔE value of 3.91 was the lowest among the evaluated samples, confirming superior color stability.

Agassi F1 ranked second and showed consistently high stability across all evaluated parameters. After 12 months, it retained 82.1% of ascorbic acid, 88.0% of total phenolics, 87.1% of flavonoids, 82.7% of chlorophyll, and 88.3% of antioxidant activity. Its water activity remained at 0.34 and the total color difference was ΔE = 4.16.

Heraklion F1 and Ironman F1 exhibited intermediate storage performance. In contrast, Marathon F1 and Tiburon F1 showed comparatively greater deterioration in both bioactive and color-related parameters.

Among the evaluated hybrids, Atlantis F1 showed the lowest overall storage stability, characterized by the highest moisture content (8.0%) and water activity (0.37), together with the lowest ascorbic acid retention (75.9%), low chlorophyll retention (76.1%), and the highest total color difference (ΔE = 6.36).

These findings demonstrate that even when broccoli powders are produced and stored under identical technological conditions, their long-term quality may differ substantially depending on the hybrid. Thus, hybrid selection represents an important technological factor alongside drying conditions, packaging, and storage environment when developing broccoli powders intended for extended shelf life.

4. Conclusion

The present study demonstrated that the long-term storage stability of broccoli powder is influenced not only by processing and storage conditions but also by the specific characteristics of the hybrid. Although all samples were produced using the same optimized drying regime of **55°C combined with infrared radiation and an air velocity of 1.5 m/s**, noticeable differences in physicochemical stability, bioactive compound retention, and color preservation were observed during 12 months of storage.

Among the seven broccoli hybrids evaluated, **Naxos F1 showed the highest overall storage stability**. After 12 months, the powder retained 83.2% of its initial ascorbic acid, 88.7% of total phenolic compounds, 87.9% of flavonoids, 83.5% of chlorophyll, and 89.0% of antioxidant activity. It also exhibited the lowest water activity (aw = 0.33) and the smallest total color difference ($\Delta E = 3.91$), indicating superior physicochemical and visual stability.

Agassi F1 also demonstrated high stability and ranked close to Naxos F1 in terms of bioactive compound retention, water activity, and color preservation. Heraklion F1 and Ironman F1 showed intermediate performance, whereas greater quality deterioration was observed in Marathon F1, Tiburon F1, and Atlantis F1 during prolonged storage.

Ascorbic acid and chlorophyll were identified as the most storage-sensitive components, while phenolic compounds and flavonoids showed comparatively higher retention. The parallel changes in phenolic compounds, flavonoids, and antioxidant activity indicate that preservation of these constituents plays an important role in maintaining the functional properties of broccoli powder. Similarly, higher chlorophyll retention was associated with lower total color change, confirming the importance of pigment stability in preserving product appearance.

Overall, the findings indicate that **hybrid selection should be considered an important technological factor in the production of broccoli powder intended for long-term storage**. Naxos F1 and Agassi F1 can be considered promising raw materials for producing broccoli powder with high retention of bioactive compounds, antioxidant properties, and color stability over a 12-month storage period.

The results provide a scientific basis for improving broccoli powder production and storage technologies and support its potential application as a stable, bioactive-rich ingredient in the development of functional food products.

References:

1.Boltaev M.A., Meliboeva Sh.Sh., Jalilov F.S. Preparation and Drying of Broccoli Herbs (Brassica oleracea L.). In: Modern Chemistry of Medicines: Proceedings of the International Scientific and Practical Internet Conference. 2023.

2.Boltaev M.M. Study of the Flavonoid Profile of Dry Broccoli Extract by HPLC. Universum: Chemistry and Biology. 2026;3(141).

3.Mahn A., Reyes A. An overview of health-promoting compounds of broccoli (Brassica oleracea var. italica) and the effect of processing. Food Science and Technology International. 2012;18(6):503–514.

4.Córdova C., Vivanco J.P., Quintero J., Mahn A. Effect of drum-drying conditions on the content of bioactive compounds of broccoli pulp. Foods. 2020;9(9):1224.

5.Low-temperature vacuum drying on broccoli: enhanced anti-inflammatory and anti-proliferative properties regarding other drying methods. Foods. 2023;12(17):3311.

6.Gudiño I. et al. Comprehensive analysis of bioactive compounds, functional properties, and applications of broccoli by-products. Foods. 2024;13(23):3918.

7.Zhao Y., Zhang W., Yang H., Xu Z., Wang X., Zhang Z., Deng J. Effects of drying methods on phytochemicals and antioxidant activity of broccoli by-products. Food Research International. 2025;208:116284.

8.Miao H., Zhang Y., Wang Z. et al. Keeping Green and Nutritious: A Comprehensive Review on Postharvest Handlings of Broccoli (Brassica oleracea var. italica). Comprehensive Reviews in Food Science and Food Safety. 2026.

9.Afzal M.K., Bilal M., Kharal S. et al. Nutritional composition, phytochemical profile, antioxidant potential, and functional attributes of sun-dried broccoli powder. Discover Food. 2026.