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ARTICLE

Folic Acid Treatment Delays Senescence and Maintains the Postharvest Quality of Baby Mustard (*Brassica juncea* var. *gemmifera*)

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ABSTRACT: Baby mustard is rich in nutrients; however, it is prone to postharvest yellowing and wilting, which leads to the loss of nutritional components. Folic acid, an important water-soluble vitamin, exhibits substantial physiological antioxidant activity. This study explored the impact of folic acid immersion treatments on the visual quality and health-promoting compounds of baby mustard stored at 20°C. The results showed that, compared with other concentrations, 5 mg L^{-1} folic acid treatment (F5) was the most effective in improving baby mustard storability. In terms of appearance and sensory acceptability, the F5 treatment was more effective than 0 mg L^{-1} folic acid treatment (CK), while the a* value was significantly lower than that of the control. In terms of pigments, chlorophyll and carotenoid contents were higher in the F5-treated samples than in the control, contributing to improved color retention during storage. In addition, the F5 treatment maintained glucosinolate content, especially by preserving aliphatic glucosinolates. This treatment also increased the ascorbic acid content of baby mustard, increased total phenolic content, and improved antioxidant activity. Overall, these findings indicate that the application of 5 mg L^{-1} folic acid is a promising strategy for improving the postharvest quality and commercial value of baby mustard, providing a theoretical basis and technical support for its preservation during room-temperature storage.

KEYWORDS: Folic acid; baby mustard; sensory; pigment; glucosinolate

1 Introduction

Baby mustard (*Brassica juncea* var. *gemmifera*), commonly known as baby mustard, is a unique cruciferous vegetable endemic to southwestern China [1]. It is rich in glucosinolates, ascorbic acid, and various antioxidant active components, which contribute to its high nutritional value and favorable physiological health benefits [2–4]. These bioactive compounds have been associated with the prevention of chronic diseases such as cancer, diabetes, and cardiovascular conditions [5]. However, baby mustard is prone to postharvest yellowing and wilting, which results in nutritional losses [6,7]. Therefore, effective preservation strategies essential [8,9]. In recent years, various approaches have been investigated to improve its postharvest quality and reduce associated economic losses. These include physical treatments, such as long-term freezing [10] and light exposure [11], as well as chemical treatments, including melatonin application [12] and combined treatments with 2,4-epibrassinolide and calcium chloride [1], all of which have shown promising effects in extending shelf life and maintaining the quality of baby mustard.

Folic acid, also known as vitamin B9, is a water-soluble vitamin abundantly present in green leafy vegetables, beans, nuts, fruits, and other foods [13,14]. It plays an important role in regulating plant responses to environmental stresses, such as waterlogging and salinity, by modulating antioxidant systems, maintaining cell membrane stability, and interacting with hormones to enhance stress tolerance [15–17].

Recent studies have shown that folic acid application under salt stress increases chlorophyll content in broad beans [18]. Similar results have been reported in other plants, where folic acid not only enhanced chlorophyll content under salt stress but also increased ascorbic acid levels and antioxidant capacity [19]. Additionally, in maize subjected to sodium-alkali stress, folic acid treatment increased chlorophyll, carotenoid, and ascorbic acid contents [20]. In terms of postharvest preservation, the role of folic acid has also been explored in fruits and vegetables. For example, folic acid treatment in broccoli helped maintain chlorophyll, glucosinolate, and total phenolic contents [21]. Moreover, studies have demonstrated that folic acid application during postharvest storage of tomatoes and grapes improves antioxidant capacity and delays quality deterioration [22,23].

Although folic acid has shown potential in maintaining the postharvest quality in several horticultural crops, studies on cruciferous vegetables remain limited, and its application in baby mustard has not yet been reported. Therefore, this study evaluated the effects of different concentrations of folic acid on the postharvest quality of baby mustard. Specifically, the study investigated whether folic acid treatment could reduce the loss of bioactive compounds, enhance antioxidant capacity, prolong storage life, and determine the optimal concentration for postharvest preservation. The evaluated parameters included sensory quality, color difference, chlorophyll and carotenoid contents, glucosinolate composition and content, ascorbic acid content, total phenolic content, and antioxidant capacity. The study findings provide a theoretical basis and technical reference for the postharvest preservation, storage, and processing of baby mustard, while also offering practical guidance for optimizing its production, reducing postharvest losses, and extending shelf life.

2 Materials and Methods

2.1 Plant Materials and Treatments

On 4 December 2024, baby mustard (*Brassica juncea* var. *gemmifera*) samples were randomly hand-harvested from open-field planting base in Chengdu, Sichuan, China. Plants reaching both physiological and commercial maturity were chosen, featuring fully expanded, thick and plump lateral buds with uniform size and morphology. Specimens with bolting, wounds, decay or pest infestation were strictly eliminated, and the qualified samples were prepared for the following postharvest preservation experiments. The samples were immediately transported to the laboratory for pretreatment. After preliminary processing, 144 uniform, undamaged, pest- and disease-free samples were selected for postharvest treatments. On the day of harvest (0 d), 24 samples were frozen at −80°C for the subsequent analysis of bioactive compounds and antioxidant capacity. The remaining 120 samples were randomly divided into five groups and immersed for 10 min in folic acid solutions at concentrations of 0 $mg{\cdot}L^{-1}$ (CK), 2.5 $mg{\cdot}L^{-1}$ (F2.5), 5 $mg{\cdot}L^{-1}$ (F5), 7.5 $mg{\cdot}L^{-1}$ (F7.5), and 10 $mg{\cdot}L^{-1}$ (F10), respectively. The treated samples were air-dried in perforated trays at room temperature. Each treatment consisted of four replicates, with six baby mustard heads per replicate. All samples were then stored at 20°C and 75% relative humidity. At the end of the storage period (4 d), the samples were frozen at −80°C for the subsequent analysis of bioactive compounds and antioxidant capacity.

2.2 Sensory Quality Evaluation and Color Difference

At the end of the storage period (4 d), sensory evaluation was conducted by five trained panelists. All panelists had received systematic training in postharvest vegetable quality evaluation, including the identification and scoring of color, wilting, and browning. Sensory acceptability was scored as follows: 5 = bright green without defects, straight leaves without wilting, no browning or off-odor, firm texture, and excellent quality; 3 = light green appearance with slight browning spots, mild leaf wilting and shrinkage, slight off-odor, and slightly soft but acceptable texture; and 1 = yellow appearance with severe browning, significant leaf wilting and shrinkage, strong off-odor, very soft texture, and no commercial value [1].

Color difference was measured using an NR110 colorimeter (3nh Co., Ltd., Shenzhen, China) at 0 d and 4 d of storage. The appearance color of baby mustard, that is, the a* value (indicating the red/green balance) in the control and treatment groups was recorded [11].

2.3 Chlorophyll and Carotenoids Content

The samples were extracted with 90% acetone. Subsequently, the supernatant was analyzed by HPLC, and absorbance was detected at 448 nm and 428 nm [1].

2.4 Glucosinolate Composition and Content

The samples were extracted with methanol solution (90%). The collected supernatant was loaded onto a DEAE-Sephadex A-25 column and treated with desulfurase for 16 h to convert glucosinolates into desulfo-glucosinolate analogs. Subsequent HPLC detection was performed at 226 nm [1].

2.5 Antioxidant Activities

The samples were extracted with 1.0% oxalic acid and analyzed by HPLC. The ascorbic acid content was calculated based on absorbance at 243 nm [11].

For antioxidant assays, the samples were extracted with 50% ethanol for 12 h, followed by centrifugation. The supernatant was used for the spectrophotometric determination of $ABTS^{+}$ scavenging activity. Additionally, the samples were extracted with 50% ethanol for 24 h to determine FRAP and total phenolic content using spectrophotometric methods [11].

2.6 Statistical Analysis

Data were analyzed using one-way analysis of variance. Mean comparisons were performed using the least significant difference (LSD) test at a significance level of 0.05, and analysis of single-factor variance was performed using the DPS 9.01 data processing system. Results are presented as the mean ± standard deviation (SD). Principal component analysis was conducted using SIMCA 14.1 software. Correlation analysis was visualized using Cytoscape v. 3.5.1 [6], and the corresponding data are presented in Supplementary Table S1.

3 Results

3.1 Sensory Quality and Color Difference

As shown in Fig. 1a, after 4 d of storage, varying degrees of wilting were observed in all treatment groups, with the most severe wilting occurring at the top of baby mustard in the control group. Compared with the control, folic acid treatments effectively delayed wilting to different extents, resulting in improved visual appearance.

According to Fig. 1b, the overall sensory acceptability scores of all folic acid-treated samples were higher than those of the control. Among the treatments, the F5 treatment exhibited the highest score, indicating the most pronounced preservation effect. These results suggest that the F5 treatment effectively delayed senescence and maintained superior sensory quality.

The results of the a* value are presented in Fig. 1c. After 4 d of storage, the a* value in the F5 treatment was significantly lower than that in the control, indicating better retention of green coloration in baby mustard.

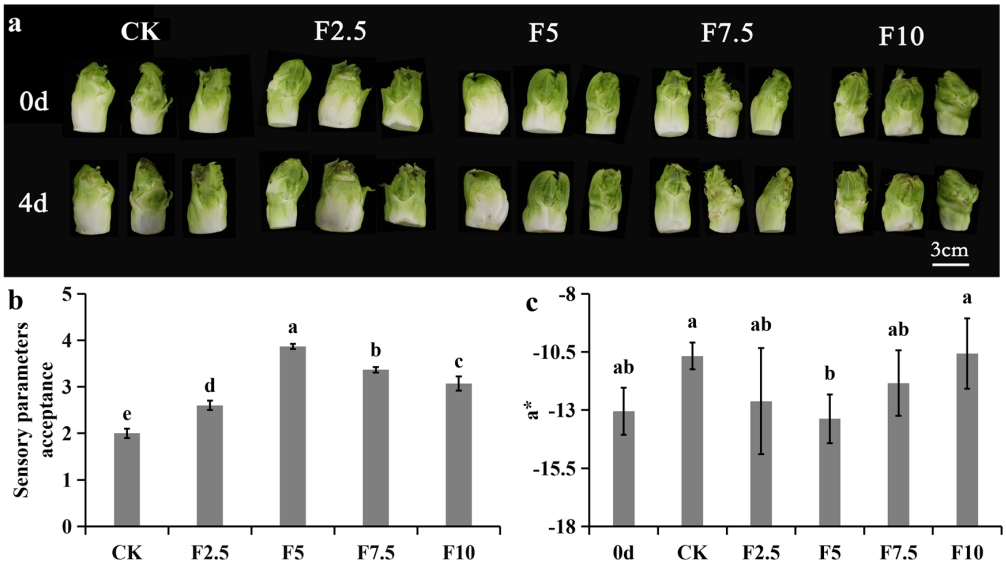

Figure 1: Sensory quality evaluation and color difference of baby mustard during storage at 20°C. (**a**) Baby mustard at each sampling time under different treatments. Scale bar = 3 cm; (**b**) Sensory parameter-acceptance; (**c**) a*; CK: 0 mg L^{-1} folic acid; F2.5: 2.5 mg L^{-1} folic acid; F5: 5 mg L^{-1} folic acid; F7.5: 7.5 mg L^{-1} folic acid; F10: 10 mg L^{-1} folic acid. Different letters indicate statistically significant differences among treatments ($p < 0.05$).

3.2 Chlorophyll and Carotenoids

As shown in Fig. 2a, chlorophyll a content decreased in all treatments after 4 d of storage, with a reduction of nearly 28% observed in the control. However, chlorophyll a levels in the F5 and F7.5 treatments were 1.15- and 1.12-fold higher than those in the control, respectively. Similarly, chlorophyll b content declined by approximately 13% in the control (Fig. 2b), whereas the F5 and F7.5 treatments maintained significantly higher levels, reaching 1.09-fold of the control value. As shown in Fig. 2g, total chlorophyll content in the control decreased by nearly 22% during storage. In contrast, the F5 and F7.5 treatments maintained higher total chlorophyll contents, which were 1.12- and 1.11-fold higher than those of the control, respectively.

In this study, the contents of carotenoids, including lutein, neoxanthin, β-carotene, and violaxanthin, declined during storage. However, the F5 and F7.5 treatments effectively alleviated these reductions. As shown in Fig. 2c, lutein levels in the F5 and F7.5 treatments were 1.04- and 1.11-fold higher than those in the control, respectively, at the end of storage. Similarly, β-carotene content (Fig. 2e) in these two treatments was 1.08- and 1.10-fold higher than that in the control, respectively. Total carotenoid content (Fig. 2h) showed a similar trend, being 1.02- and 1.05-fold higher in the F5 and F7.5 treatments, respectively, compared with the control. No significant differences were observed in neoxanthin and violaxanthin

contents between the F5 treatment and the control (Fig. 2d,f). However, violaxanthin content in the F7.5 treatment was significantly higher than that in the control.

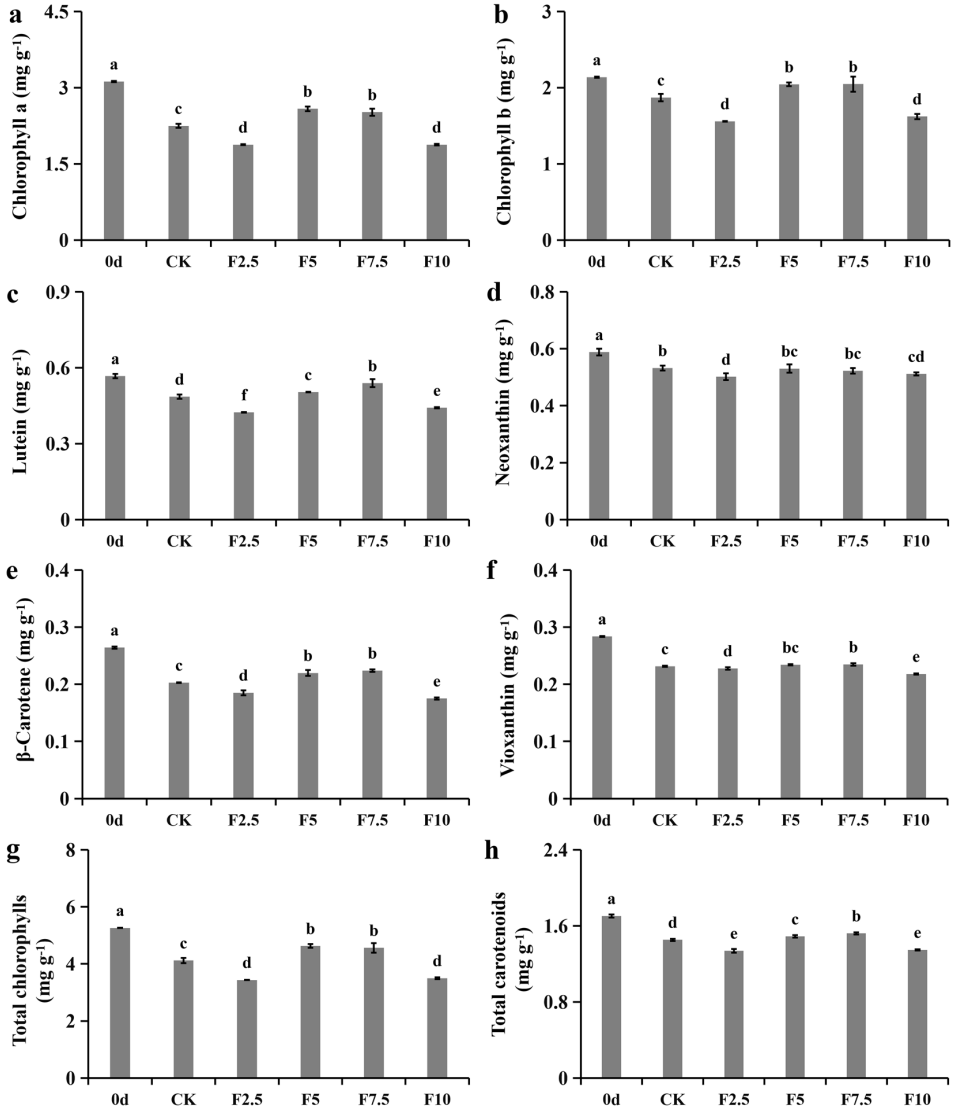

Figure 2: The content of chlorophyll and carotenoids in baby mustard under different treatments. (**a**) Chlorophyll a; (**b**) Chlorophyll b; (**c**) Lutein; (**d**) Neoxanthin; (**e**): β-carotene; (**f**) Violaxanthin; (**g**) Total chlorophyll; (**h**) Total carotenoids; CK: 0 mg L^{-1} folic acid; F2.5: 2.5 mg L^{-1} folic acid; F5: 5 mg L^{-1} folic acid; F7.5: 7.5 mg L^{-1} folic acid; F10: 10 mg L^{-1} folic acid. Different letters indicate statistically significant differences among treatments ($p < 0.05$).

3.3 Glucosinolates

Changes in glucosinolate content are shown in Fig. 3. Six glucosinolates were identified in baby mustard, including two aliphatic glucosinolates (sinigrin and gluconapin) and four indolic glucosinolates (4-hydroxyglucobrassicin, glucobrassicin, 4-methoxyglucobrassicin, and neoglucobrassicin). Sinigrin was the predominant glucosinolate in baby mustard, accounting for 95.1% of aliphatic glucosinolates and 77.9% of total glucosinolates. After 4 d of storage, glucosinolate levels in all five treatment groups decreased to varying extents compared with the initial levels (0 d), with 4-hydroxyglucobrassicin showing the greatest reduction.

At the end of storage, different concentrations of folic acid exerted varying effects on glucosinolate content in baby mustard. The F5 treatment showed clear advantages over the control in maintaining glucosinolate levels (Fig. 3). Among aliphatic glucosinolates, the contents of sinigrin, gluconapin, and total aliphatic glucosinolates were markedly elevated in the F5 treatment group than in the control, with increases of 1.33-, 1.86-, and 1.36-fold, respectively (Fig. 3a,b,g). For indolic glucosinolates, no significant differences were observed between the F5 treatment and the control. However, indolic glucosinolate levels were relatively low overall in in baby mustard (Fig. 3). Regarding total glucosinolates, the F5 treatment resulted in a 1.30-fold increase compared with the control (Fig. 3i).

The F7.5 treatment also showed advantages over the control in maintaining glucosinolate content (Fig. 3). Compared with the control, the F7.5 treatment promoted gluconapin accumulation, with its content reaching 1.88-fold of the control level among aliphatic glucosinolates (Fig. 3b). For indolic glucosinolates, the F7.5 treatment showed higher levels of 4-hydroxy glucobrassicin and 4-methoxyglucobrassicin, which were 2.49- and 1.29-fold higher than those in the control (Fig. 3c,e). In contrast, glucobrassicin and neoglucobrassicin contents were lower than those in the control, although these compounds were present only in small amounts in baby mustard (Fig. 3d,f). No significant difference in total glucosinolate content was observed between the F7.5 treatment and the control (Fig. 3i). Overall, the F5 treatment showed the greatest advantage in maintaining glucosinolate content in baby mustard.

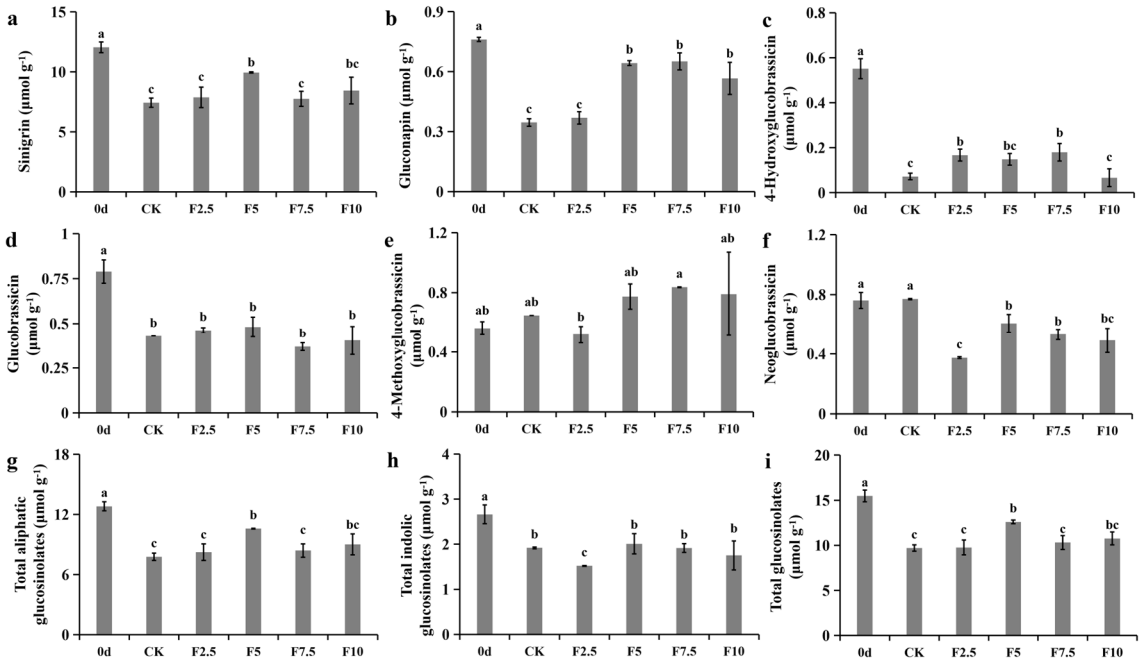

Figure 3: Glucosinolate content in baby mustard under different treatments. (**a**) Sinigrin; (**b**) Gluconapin; (**c**) 4-Hydroxy glucobrassicin; (**d**) Glucobrassicin; (**e**) 4-Methoxyglucobrassicin; (**f**) Neoglucobrassicin; (**g**) Total aliphatic gulcosinolates; (h) Total indolic gulcosinolates; (**i**) Total gulcosinolates; CK: 0 mg L^{-1} folic acid; F2.5: 2.5 mg L^{-1} folic acid; F5: 5 mg L^{-1} folic acid; F7.5: 7.5 mg L^{-1} folic acid; F10: 10 mg L^{-1} folic acid. Different letters indicate statistically significant differences among treatments ($p < 0.05$).

3.4 Ascorbic Acid, Total Phenolics, and Antioxidant Capacity

After 4 d of storage, the ascorbic acid content was 1.18-fold higher in the F5 treatment than in the control (Fig. 4a). After treatment with different folic acid concentrations, the total phenolic content of baby

mustard was higher than that in the control. Specifically, the total phenolic content in the F2.5, F5, F7.5, and F10 treatments was 1.08-, 1.15-, 1.19-, and 1.17-fold higher, respectively, than that in the control (Fig. 4b). The antioxidant capacity of baby mustard in the F5, F7.5, and F10 treatments was higher than that in the control. As shown in Fig. 4c, the $ABTS^+$ antioxidant activity in the F5, F7.5, and F10 treatments was 1.18-, 1.18-, and 1.17-fold higher than that in the control, respectively. FRAP levels in the F2.5, F5, F7.5, and F10 treatments were 1.16-, 1.32-, 1.19-, and 1.19-fold higher than those in the control, respectively. In particular, the FRAP level in the F5 treatment showed the most significant advantage (Fig. 4d).

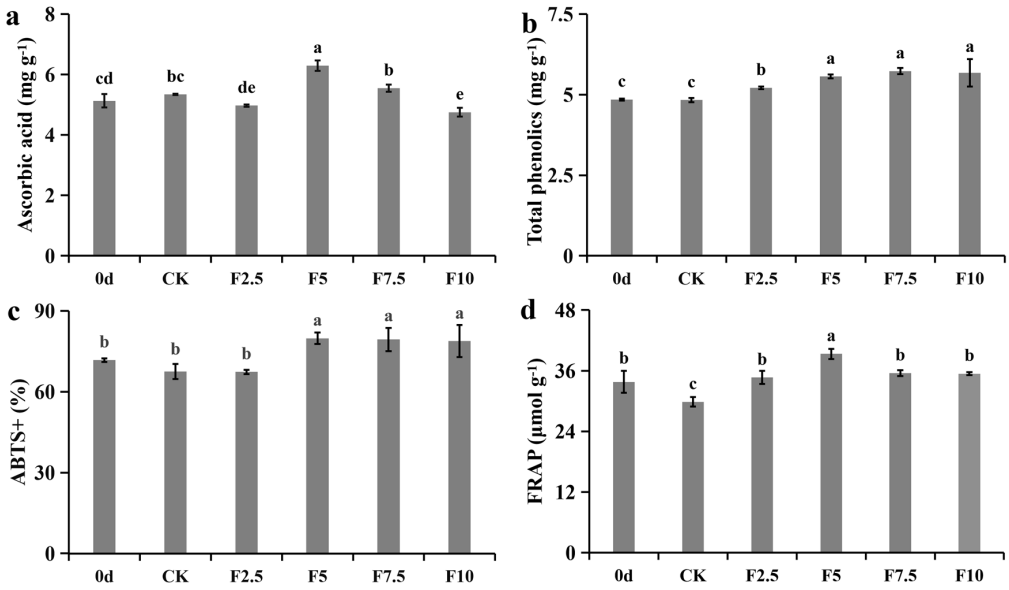

Figure 4: The content of the main antioxidants and antioxidant capacity in baby mustard under different treatments. (**a**) Ascorbic acid; (**b**) Total phenolics; (**c**) $ABTS^+$; (**d**) FRAP; CK: 0 mg L^{-1} folic acid; F2.5: 2.5 mg L^{-1} folic acid; F5: 5 mg L^{-1} folic acid; F7.5: 7.5 mg L^{-1} folic acid; F10: 10 mg L^{-1} folic acid. Different letters indicate statistically significant differences among treatments ($p < 0.05$).

3.5 Principal Component Analysis

The first component (PC1) and the second component (PC2) explained 62.9% and 19.1% of the total variance, respectively (Fig. 5a). PC1 distinguished the initial 0 d group and the F5 treatment from the control, F2.5, F7.5, and F10 treatments. Moreover, the F5 treatment was located closest to the initial 0 d group, indicating that the F5 treatment exerted the most significant preservation effect. PC2 further distinguished the F5, F7.5, and F10 treatments from the 0 d initial group, control, and F2.5 treatment. According to the loading plot results, quality-related indicators of baby mustard were mainly distributed in the third and fourth quadrants. Among these variables, the F5 and F7.5 treatments had greater effects on 4-methoxyglucobrassicin content, ascorbic acid content, total phenolic content, $ABTS^+$ activity, and FRAP levels (Fig. 5b).

3.6 Correlation Analysis

Visual quality assessment and correlation analysis of various phytochemicals provided further insights into the relationship between sensory and nutritional quality. In this study, Cytoscape was used to visualize the high correlation between visual quality indicators (green circles in Fig. 5c) and nutritional quality indicators (red, blue, and yellow circles in Fig. 5c) ($|\rho| > 0.65$). Dashed lines between indices indicate negative

correlations, whereas solid lines indicate positive correlations. The network analysis included two sensory quality indices, 20 nutritional quality indices, and 122 correlation edges. Sensory acceptability scores were positively correlated with chlorophyll and carotenoid contents, glucosinolate content, ascorbic acid content, total phenolic content, and antioxidant capacity. By contrast, the sensory acceptability score was negatively correlated with the a* value. Overall, the F5 treatment effectively maintained the postharvest quality of baby mustard, delayed nutrient loss, and improved storage stability and commercial value by slowing down the degradation of pigments and secondary metabolites.

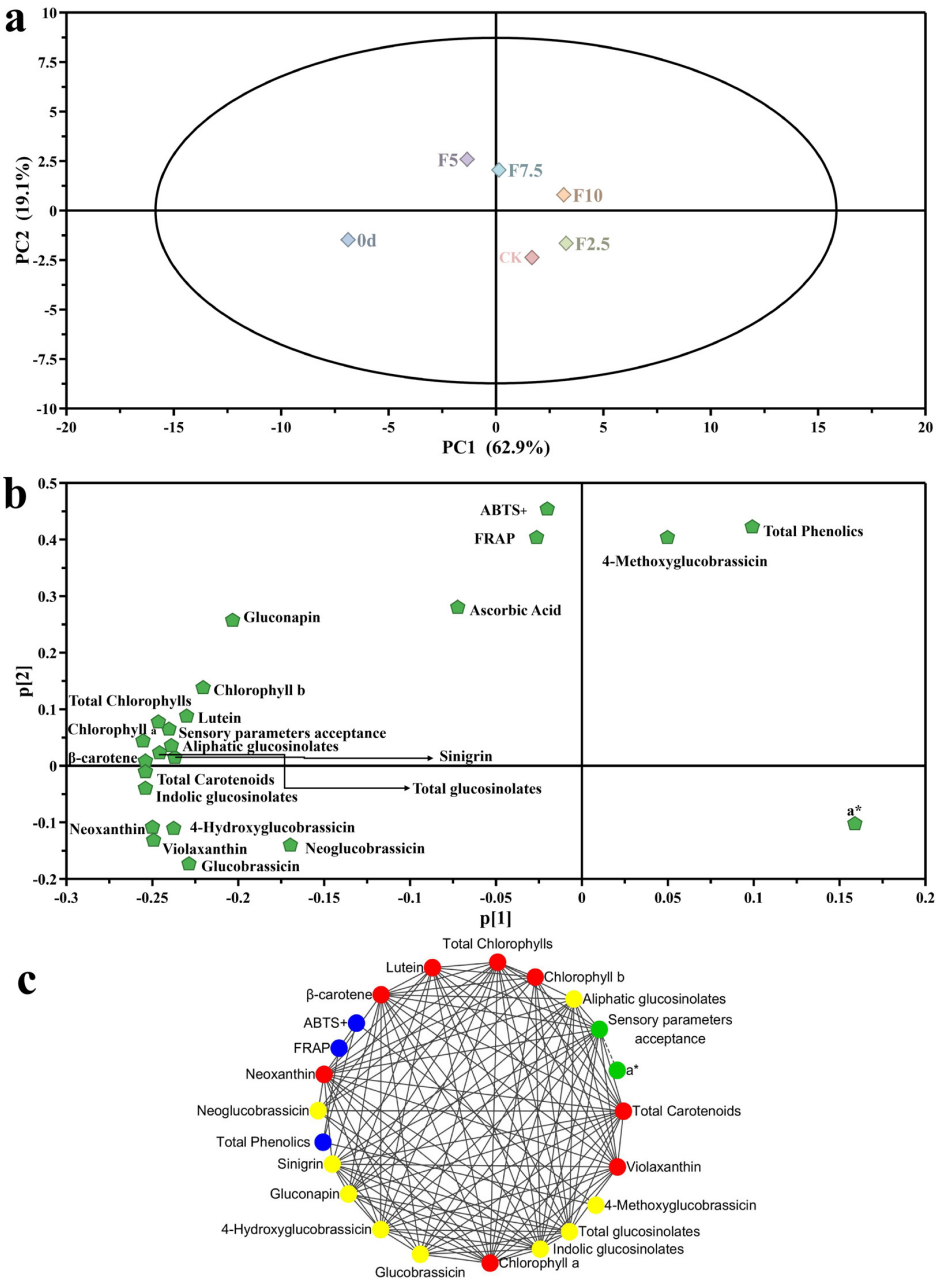

Figure 5: PCA and correlation analysis of baby mustard. (**a**) PCA score plot; (**b**) PCA loading plot; (**c**) Correlation plot between the visual and nutritional qualities. All correlations in the figure reflect Pearson correlation coefficient values above the threshold ($|\rho| > 0.65$).

4 Discussion

Baby mustard is widely appreciated for its compact appearance and high nutritional value; therefore, safe and effective preservation methods are needed to extend its shelf life [1,24]. The present study demonstrated that folic acid treatment effectively delayed postharvest yellowing and inhibited off-odor development in baby mustard. This finding is consistent with previous studies in broccoli, where folic acid was shown to regulate ethylene, chlorophyll, and glucosinolate metabolic pathways through DNA methylation, thereby exerting postharvest preservation effects [25]. In this study, the effects of folic acid treatment on the postharvest quality of baby mustard were systematically investigated. The results showed that treatment with 5 mg L^{-1} folic acid (F5) effectively delayed senescence; reduced yellowing and wilting; preserved chlorophyll, carotenoids, glucosinolates, ascorbic acid, and total phenolics; and enhanced antioxidant capacity (Fig. 6). However, the beneficial effects of folic acid began to decline at 7.5 mg L^{-1} (F7.5) (Fig. 6).

During storage at room temperature, baby mustard undergoes a series of adverse physiological changes. Over time, leaves gradually yellow and may eventually decay under conditions of high temperature and humidity [1]. Similar patterns of quality deterioration have been reported in other cruciferous vegetables [26–29]. In the present study, folic acid treatment (F5) improved the appearance quality of baby mustard, delayed wilting, enhanced sensory acceptability, and extended shelf life. Previous studies have also shown that soaking harvested grapes in folic acid solution effectively maintains their appearance, texture, and sensory quality during storage, and our findings further support these observations [23]. Appearance color is a key factor influencing consumer perception of vegetable quality [29–31]. As senescence progresses, chlorophyll degradation accelerates, while the expression of genes related to chlorophyll-degrading enzymes is downregulated, leading to noticeable color changes [12,32]. In our study, treatment with 5 mg L^{-1} folic acid inhibited chlorophyll degradation by the end of storage, because this concentration effectively activates antioxidant and chlorophyll-protective pathways without imposing physiological stress on the tissues. The protective effects of folic acid on chlorophyll have also been reported in previous studies. For example, folic acid application in pea plants increased chlorophyll content, possibly by activating glycine biosynthesis and promoting chlorophyll synthesis [33]. Additionally, folic acid treatment during broccoli storage maintained chloroplast integrity and suppressed the expression of chlorophyll degradation-related genes [21]. Folic acid alleviated chlorophyll degradation in baby mustard, which may be maintained by a similar mechanism. Folic acid reduces postharvest yellowing of baby mustard by inhibiting chlorophyll degradation, suppressing oxidative damage, upregulating the expression of synthesis-related genes, and maintaining chloroplast structural stability. However, when the concentration of exogenous folic acid exceeds the plant tolerance threshold, it may disrupt cellular osmotic balance and endogenous metabolic homeostasis. Excessive folic acid may also interfere the expression of functional genes associated with chlorophyll metabolism, thereby accelerating chlorophyll degradation. The combined effects of these multiple adverse physiological responses may aggravate postharvest deterioration of baby mustard quality and weaken the preservation efficacy of folic acid [5,34].

Glucosinolates are key health-promoting compounds unique to *Brassica* vegetables. Studies have demonstrated that glucosinolates and their bioactive derivatives exert anticancer effects against a broad range of cancer types [35–37]. Baby mustard is particularly favored by consumers because of its high glucosinolates content. However, glucosinolates are unstable during room-temperature storage and are susceptible to oxidation and degradation, resulting in diminished nutritional value [25,38,39]. Therefore, maintaining glucosinolate levels in postharvest baby mustard is essential for preserving its nutritional quality. In this study, glucosinolate content decreased during storage; however, folic acid treatment

effectively alleviated this decline. Previous research similarly demonstrated that folic acid treatment preserved glucosinolate content in postharvest broccoli, with treated samples maintaining higher levels than untreated controls at the end of storage [21]. Metabolomic analysis further revealed that folic acid treatment inhibited the expression of β-thioglucoside glucohydrolase, a key enzyme involved in glucosinolate degradation, resulting in markedly lower enzyme expression levels in treated samples than in the control group [25]. Similar regulatory mechanisms may also exist in baby mustard. Folic acid may maintain glucosinolate content in baby mustard by upregulating the expression of biosynthetic genes and suppressing the expression of degradation-related enzymes, thereby delaying senescence and reducing off-odor formation. Overall, the F5 and F7.5 treatments showed better performance than the other treatments. These concentrations may effectively modulate glucosinolate metabolism and antioxidant systems without causing metabolic disruption or physiological stress. In contrast, excessive folic acid concentrations may induce metabolic disorders and weaken preservation effects. It is possible that the F10 treatment disrupted the normal expression of preservation-related genes, interfered with plant metabolic processes, and disturbed the antioxidant balance, thereby reducing the preservation effect [34].

Ascorbic acid and total phenolics, both potent antioxidants, play essential roles in plant metabolic processes by effectively scavenging reactive oxygen species, protecting cell membranes, and maintaining the intracellular redox balance [40,41]. In this study, at the end of postharvest storage, the ascorbic acid content in baby mustard was higher than that in the initial 0 d group. Studies have suggested that the ascorbic acid content of baby mustard can surpass that of freshly harvested mustard [24]. A similar increase in ascorbic acid levels during storage has been observed in other vegetables [42]. For example, the ascorbic acid content of *Toona sinensis* (A. Juss.) M. Roem increased during the early stages of storage, likely as a natural plant response to oxidative stress aimed at maintaining cellular viability and preventing the accumulation of reactive oxygen species [43] The increase in ascorbic acid content observed following folic acid treatment in this study may also be associated with such oxidative stress responses. During postharvest storage, vegetables often enhance the production of secondary metabolites, particularly phenolic compounds, to counteract external stress. These metabolites help mitigate oxidative stress, thereby protecting cells from oxidative damage and preserving vegetable quality and nutritional value [44]. The present study results revealed that the total phenolic content of baby mustard treated with different folic acid concentrations was significantly higher than that of the blank control group at the end of storage, which is consistent with previous findings. Studies have confirmed that folic acid treatment can markedly promote the accumulation of total phenols in broccoli during storage [21] and facilitate the synthesis and accumulation of phenolic secondary metabolites during seed germination [45]. These findings indicate that the regulatory effect of folic acid on plant phenolic antioxidants is universal. In terms of the action mechanism, folic acid has strong free radical scavenging capacity. Thus, it can directly quench reactive oxygen species produced during postharvest plant senescence and inhibit membrane lipid peroxidation. In addition, by regulating endogenous metabolic pathways in plants, folic acid can induce the biosynthesis and accumulation of endogenous antioxidants such as ascorbic acid and phenols, thereby further improving the antioxidant defense capacity [16,46,47]. The aforementioned dual antioxidant mechanism can effectively block the oxidative stress-mediated cell senescence pathway, and ultimately prolong the postharvest storage life of fruits and vegetables [21–24]. In this study, folic acid treatment retarded the decline in FRAP and $ABTS^+$ antioxidant capacities in postharvest baby mustard through the aforementioned antioxidant regulatory mechanisms. Meanwhile, folic acid stabilizes the chlorophyll structure, alleviates leaf yellowing, and synergizes with antioxidant pathways to maintain the appearance and nutritional quality of baby mustard by indirectly preventing oxidative degradation of pigments and

glucosinolates, thereby creating a synergistic quality-preserving network [27]. However, the molecular mechanisms underlying folic acid-induced postharvest changes warrant further investigation, and the effects under different storage scenarios require systematic validation.

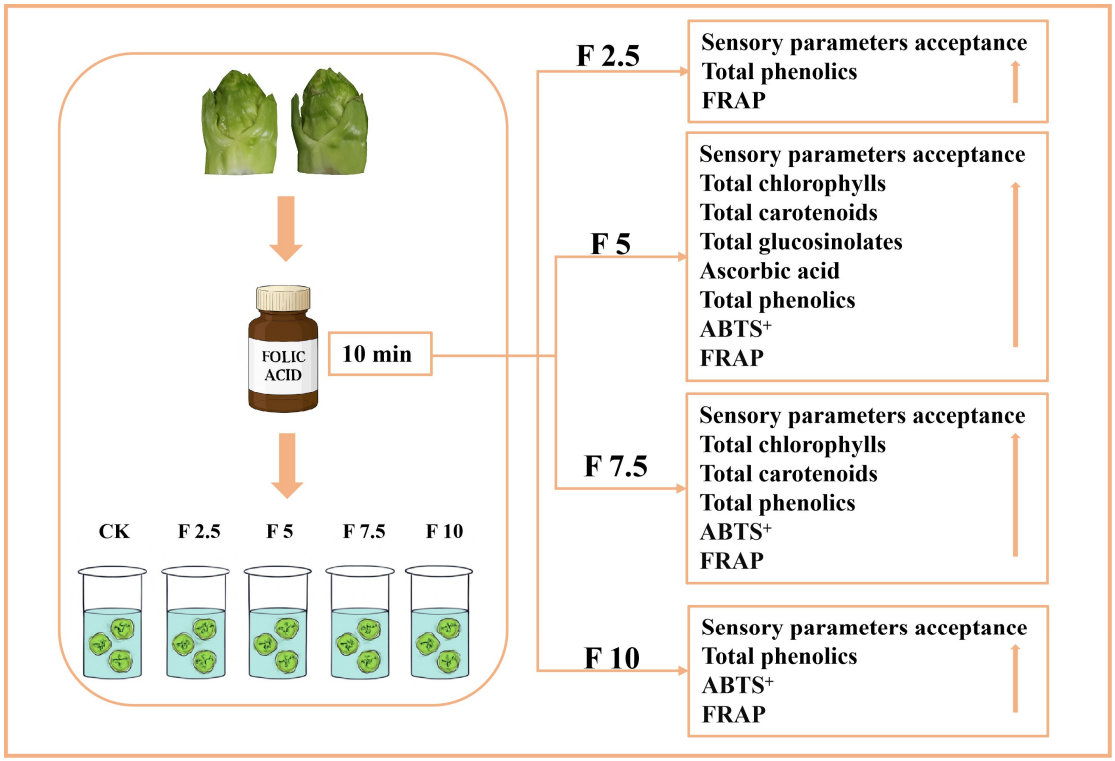

Figure 6: Mechanism of folic acid regulating postharvest quality of baby mustard.

5 Conclusions

The results indicated that folic acid-treated baby mustard maintains significantly better sensory quality at the end of storage. Folic acid application effectively delays postharvest senescence and quality deterioration, alleviates yellowing and decay incidence during storage, preserves the contents of pigments and glucosinolates, and improves antioxidant capacity, thereby markedly extending the shelf life of baby mustard. In general, a 5 mg L^{-1} folic acid concentration is the most effective in improving baby mustard storability. This treatment is safe, simple, and low-cost and has exhibits promising application prospects in the ambient transportation, low-temperature refrigeration, and commercial fresh-keeping storage of cruciferous vegetables. The results provide theoretical support for reducing postharvest losses, improving economic value, and extending the market supply period of vegetables. However, the molecular mechanisms underlying folic acid-induced postharvest changes in baby mustard warrant further investigation. Moreover, the effects under different storage scenarios and combined treatments require systematic investigation. In the future, transcriptomics and metabolomics can be integrated to dissect the regulatory network, and pilot tests can be conducted to promote the industrial application of folic acid for improving the postharvest quality of baby mustard.

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Author Contributions: The authors confirm contribution to the paper as follows: study conception and design: Bo Sun, Fen Zhang; data curation: Yong Li, Jie Ma; investigation and funding acquisition: Yunong Zhou, Zhi Huang; analysis and interpretation of results: Xuena Yu; draft manuscript preparation: Xinyao Li, Dongyang Sun. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The authors confirm that the data supporting the findings of this study are available within the article.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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References

1. Di H, Liu R, Zhang Y, Chen Z, Ma J, Escalona VH, et al. Individual and combined treatments of 2, 4-epibrassinolide (EBR) and calcium chloride ($CaCl_2$) maintain the postharvest quality of baby mustard. Postharvest Biol Technol. 2024;212:112901. [CrossRef].
2. Bansal S, Lakra N, Mishra S, Ahlawat YK. Unraveling the potential of glucosinolates for nutritional enhancement and stress tolerance in *Brassica* crops. Veg Res. 2024;4(1):e015. [CrossRef].
3. Cheng B, Ran R, Qu Y, Verkerk R, Henry R, Dekker M, et al. Advancements in balancing glucosinolate production in plants to deliver effective defense and promote human health. Agric Commun. 2024;2(2):100040. [CrossRef].
4. Zhu B, Liang Z, Wang D, He C, Zhu Z, Yang J. The effect of glutathione on glucosinolate biosynthesis through the sulfur assimilation pathway in pakchoi associated with the growth conditions. Hortic Plant J. 2024;10(2):473–87. [CrossRef].
5. Brindisi LJ, Lyu W, Juliani HR, Wu Q, Tepper BJ, Simon JE. Determination of glucosinolates and breakdown products in Brassicaceae baby leafy greens using UHPLC-QTOF/MS and GC/MS. Food Chem Adv. 2023;3:100389. [CrossRef].
6. Cano-Lamadrid M, Martínez-Zamora L, Castillejo N, Cattaneo C, Pagliarini E, Artés-Hernández F. How does the phytochemical composition of sprouts and microgreens from *Brassica* vegetables affect the sensory profile and consumer acceptability? Postharvest Biol Technol. 2023;203:112411. [CrossRef].
7. Fu C, Hu C, Wu C, Han C, Wang N, Yu Z, et al. Sucrose delays post-harvest pakchoi yellowing through maintaining chloroplast ultrastructure and retarding chlorophyll degradation. Postharvest Biol Technol. 2025;229:113701. [CrossRef].
8. Zhang X, Zhao K, Wang W, Alabd A, Li J, Zhang A. Gibberellin delays kiwifruit postharvest ripening via the AcDELLA gene family. Plant Horm. 2025;1:e005. [CrossRef].
9. Wang H, Li L, Ma L, Fernie AR, Fu A, Bai C, et al. Revealing the specific regulations of nitric oxide on the postharvest ripening and senescence of bitter melon fruit. aBIOTECH. 2024;5(1):29–45. [CrossRef].
10. Sun B, Lin PX, Xia PX, Di HM, Zhang JQ, Zhang CL, et al. Low-temperature storage after harvest retards the deterioration in the sensory quality, health-promoting compounds, and antioxidant capacity of baby mustard. RSC Adv. 2020;10(60):36495–503. [CrossRef].
11. Sun B, Di H, Zhang J, Xia P, Huang W, Jian Y, et al. Effect of light on sensory quality, health-promoting phytochemicals and antioxidant capacity in post-harvest baby mustard. Food Chem. 2021;339:128057. [CrossRef].

12. Zhang R, Wei Z, Shi Y, Zhang Y, Liu Y, Khan A, et al. Effects of blue light combined with melatonin on antioxidant activity and nutritional value of postharvest Chinese cabbage (*Brassica rapa* L. ssp. *pekinensis*). Sci Hortic. 2026;363:114906. [CrossRef].
13. Rébeillé F, Ravanel S, Jabrin S, Douce R, Storozhenko S, Van Der Straeten D. Folates in plants: Biosynthesis, distribution, and enhancement. Physiol Plant. 2006;126(3):330–42. [CrossRef].
14. Wald NJ. Folic acid and neural tube defects: Discovery, debate and the need for policy change. J Med Screen. 2022;29(3):138–46. [CrossRef].
15. El-Khateeb EA, Youssef MS, Mira MM, Igamberdiev AU, Hill RD, Stasolla C. Interplay between the *Brassica napus* phytoglobin (BnPgb1), folic acid, and antioxidant responses enhances plant tolerance to waterlogging. Plant Sci. 2023;334:111775. [CrossRef].
16. Joshi R, Adhikari S, Patro BS, Chattopadhyay S, Mukherjee T. Free radical scavenging behavior of folic acid: Evidence for possible antioxidant activity. Free Radic Biol Med. 2001;30(12):1390–9. [CrossRef].
17. Kilic S, Aca HT. Role of exogenous folic acid in alleviation of morphological and anatomical inhibition on salinity-induced stress in barley. Ital J Agron. 2016;11(4):777. [CrossRef].
18. Omar SA, Feng Y, Yu M, Eldin SAG, Eldenary ME, Shabala S, et al. Exogenous application of 5-azacitidin, royal jelly and folic acid regulate plant redox state, expression level of DNA methyltransferases and alleviate adverse effects of salinity stress on *Vicia faba* L. plants. Heliyon. 2024;10(10):e30934. [CrossRef].
19. Al-Elwany OAAI, Hemida KA, Abdel-Razek MA, El-Mageed TAA, El-Saadony MT, AbuQamar SF, et al. Impact of folic acid in modulating antioxidant activity, osmoprotectants, anatomical responses, and photosynthetic efficiency of *Plectranthus amboinicus* under salinity conditions. Front Plant Sci. 2022;13:887091. [CrossRef].
20. Aljuaid BS, Mukherjee S, Sayed AN, El-Gabry YAE, Omar MMA, Mahmoud SF, et al. Folic acid reinforces maize tolerance to sodic-alkaline stress through modulation of growth, biochemical and molecular mechanisms. Life. 2022;12(9):1327. [CrossRef].
21. Xu D, Zuo J, Fang Y, Yan Z, Shi J, Gao L, et al. Effect of folic acid on the postharvest physiology of broccoli during storage. Food Chem. 2021;339:127981. [CrossRef].
22. Ghorbani Z, Koushesh Saba M, Mansouri S. Preserving postharvest quality and mitigating chilling injury in tomatoes through folic acid treatment. Postharvest Biol Technol. 2025;228:113669. [CrossRef].
23. Pei MS, Liu HN, Yu YH, Wei TL, Guo DL. Folic acid delays postharvest quality deterioration of table grape by regulating cell wall metabolism-associated hub WRKY31 transcription factor. Postharvest Biol Technol. 2023;197:112207. [CrossRef].
24. Lin P, Di H, Wang G, Li Z, Li H, Zhang F, et al. Modified atmosphere packaging maintains the sensory and nutritional qualities of post-harvest baby mustard during low-temperature storage. Front Nutr. 2021;8:730253. [CrossRef].
25. Zhao Y, Shi J, Feng B, Yuan S, Yue X, Shi W, et al. Multi-omic analysis of the extension of broccoli quality during storage by folic acid. J Adv Res. 2024;59:65–78. [CrossRef].
26. Han Y, He X, Luo S, Hu H, Li P. The regulatory effect of slightly acidic electrolyzed water ice on the postharvest quality decline and glucosinolate metabolism of broccoli. Postharvest Biol Technol. 2024;215:113015. [CrossRef].
27. Ye X, Wang M, Zhao L, Wang Z, Yu L, Yuan S, et al. Synergistic effect of lactopeptide and ectoine on delaying yellowing and maintaining the postharvest quality of pak choi (*Brassica rapa* subsp. *chinensis*). Int J Biol Macromol. 2025;311:143384. [CrossRef].
28. Testone G, Sobolev AP, Lambreva MD, Aturki Z, Mele G, Lamprillo M, et al. The molecular pathways leading to GABA and lactic acid accumulation in florets of organic broccoli rabe (*Brassica rapa* subsp. *sylvestris*) stored as fresh or as minimally processed product. Hortic Res. 2025;12:uhae274. [CrossRef].
29. Wang Q, He H, Liu C, Wang C, Chen B, Wang X, et al. Insights of freshness phenotype detection for postharvest fruit and vegetables. Plant Phenomics. 2025;7(2):100042. [CrossRef].
30. Rocha Lacerda V, Aparecida dos Santos J, Sílvia Angélica de Oliveira H, Gaona Acevedo A, Lopes Vieites R. Doses of aminoethoxyvinylglycine (AVG) in tomato postharvest storage. Tecnologia Em Hortic. 2024;4(1):e011. [CrossRef].
31. Liu X, Yu X, Wu Y, Wei B, Zhou Q, Cheng S, et al. Light water loss delays simulation of mechanical injuries from transportation vibration of *Actinidia arguta* by inhibiting cell wall metabolism. Technol Hortic. 2025;5:e023. [CrossRef].

32. Chai X, Yue X, Wang Z, Lei S, Zhang Y, Yuan S, et al. Food-grade sodium benzoate delays postharvest yellowing of broccoli by coordinating chlorophyll, flavonoid, and amino acid metabolism. Postharvest Biol Technol. 2026;239:114364. [CrossRef].
33. Farouk S, Abdul Qados AMS. Enhancing seed quality and productivity as well as physio-anatomical responses of pea plants by folic acid and/or hydrogen peroxide application. Sci Hortic. 2018;240:29–37. [CrossRef].
34. Venkatachalam K, Charoenphun N, Nguyen TTH, Pham HN. Effect of folic acid on mitigation of chilling injury and extending quality and shelf life of eggplant stored under prolonged low temperature. Appl Food Res. 2026;6(1):101905. [CrossRef].
35. Elkashty OA, Tran SD. Sulforaphane as a promising natural molecule for cancer prevention and treatment. Curr Med Sci. 2021;41(2):250–69. [CrossRef].
36. Wang M, Li Y, Yang Y, Tao H, Mustafa G, Meng F, et al. Biofortification of health-promoting glucosinolates in cruciferous sprouts along the whole agro-food chain. Trends Food Sci Technol. 2023;140:104164. [CrossRef].
37. Gao W, Lai S, Liu G, Liu Y, Han F, Zhang S, et al. Metabolome insights into nutrients and glucosinolates in broccoli and lacinato kale. Food Chem. 2025;480:143924. [CrossRef].
38. Wang J, Jiang H, Chen S, Li Y, Hamouda HI, Balah MA, et al. Strategy for preparing of glucosinolate derivatives with outstanding functional activities based on myrosinase. Food Chem. 2025;479:143778. [CrossRef].
39. Yue L, Kang Y, Li Y, Kang D, Zhong M, Chai X, et al. 1-Methylcyclopropene promotes glucosinolate biosynthesis through BrWRKY12 mediated jasmonic acid biosynthesis in postharvest flowering Chinese cabbage. Postharvest Biol Technol. 2023;203:112415. [CrossRef].
40. Arabia A, Munné-Bosch S, Muñoz P. Ascorbic acid as a master redox regulator of fruit ripening. Postharvest Biol Technol. 2024;207:112614. [CrossRef].
41. Wei Z, Wang L, Wei Y, Niu S, Liu Y, Pan C, et al. Plant-derived phenolic antioxidants inhibit degradation of petroleum hydrocarbons via denitrification in coastal wetlands soils. Environ Res. 2025;274:121373. [CrossRef].
42. Lin S, Chen C, Luo H, Xu W, Zhang H, Tian J, et al. The combined effect of ozone treatment and polyethylene packaging on postharvest quality and biodiversity of *Toona sinensis* (A.Juss.) M.Roem. Postharvest Biol Technol. 2019;154:1–10. [CrossRef].
43. Datir S, Kumbhar R, Kumatkar P. Understanding physiological and biochemical mechanisms associated with post-harvest storage of Yam tuber (*Dioscorea* sp.). Technol Hortic. 2024;4:e004. [CrossRef].
44. Jin P, Yao D, Xu F, Wang H, Zheng Y. Effect of light on quality and bioactive compounds in postharvest broccoli florets. Food Chem. 2015;172:705–9. [CrossRef].
45. Burguieres E, McCue P, Kwon YI, Shetty K. Effect of vitamin C and folic acid on seed vigour response and phenolic-linked antioxidant activity. Bioresour Technol. 2007;98(7):1393–404. [CrossRef].
46. Alsamadany H, Mansour H, Elkelish A, Ibrahim MFM. Folic acid confers tolerance against salt stress-induced oxidative damages in snap beans through regulation growth, metabolites, antioxidant machinery and gene expression. Plants. 2022;11(11):1459. [CrossRef].
47. Ali Sahito Z, Zehra A, Yu S, Chen S, Arif MAR, Raza ST, et al. Folic acid supplementation improves seed germination, seedling growth and cadmium uptake in a mining ecotype of *Solanum nigrum* L. Environ Technol Innov. 2024;34:103600. [CrossRef].