

Impact of GABA and 1-MCP on qualitative attributes of apples (*Malus domestica* Borkh. cv. Fuji) during cold storage

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Article

Keywords: γ -Aminobutyric acid, 1-MCP, Apple, Watercore, Flesh browning

Posted Date: August 19th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7306968/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on March 19th, 2026.
See the published version at <https://doi.org/10.1038/s41598-026-44765-1>.

Abstract

This study investigated the efficacy of γ -aminobutyric acid (GABA) and 1-methylcyclopropene (1-MCP), individually and in combination, in mitigating sugar core disappearance, flesh browning, and postharvest quality in apples during 180 days storage. The results showed that the combined GABA + 1-MCP treatment outperformed individual applications, significantly delaying sugar core disappearance by preserving sucrose and sorbitol while moderating glucose and fructose accumulation. Furthermore, the combined treatment significantly reduced flesh browning compared to the control, likely attributed to suppressed polyphenol oxidase activity and enhanced antioxidant capacity. This approach also minimized weight loss and maintained firmness and titratable acidity. Although total phenolics and total flavonoids increased progressively during storage, their levels were effectively regulated by the GABA + 1-MCP treatment. These results indicate that the combined exogenous application of GABA and 1-MCP is a potentially effective method to improve postharvest quality, and enhance storage efficiency of apple fruit.

1. Introduction

The environmental and climatic conditions in Xinjiang are favorable for apple growth, creating a unique quality of watercore apples, which has become a symbol product, and selected as the recommended fruit for the Beijing Olympic Games in 2008[1]. Although watercore is a physiological disorder of apple characterized by glassy or translucent tissue in the flesh[2], and visible only when the fruit is cut in half[3], watercore apples are safe and edible[4]. In some countries, watercore appearance is a desirable trait for apples, as an indicator of full ripeness [5, 6]. However, watercore tissues tend to disappear during storage, leading to a significant loss of unique identity and market value[6]. Additionally, long-term storage often results in flesh browning[4]. Hence, these challenges highlight the need for effective postharvest treatments to maintain post-harvest quality in watercore apples.

γ -Aminobutyric acid (GABA), a non-proteinogenic amino acid, can be rapidly accumulated in response to biotic and abiotic stresses and involves in signaling or regulatory mechanisms, nitrogen and carbon metabolism, and amino acid biosynthesis[7, 8]. Previous reports have shown that GABA postharvest treatments delay the senescence of horticultural commodities and increase fruit chilling tolerance, with additional effects on fruit quality preservation after storage at low temperatures[9-11]. Additionally, Aydin Shekari[12] found that GABA treatment could be employed for retarding cap browning and maintaining the sensory and nutritional quality of button mushrooms during cold storage. On the other hand, 1-MCP, a synthetic compound that works by competitively binding to ethylene receptors and inhibits ethylene action, has been widely used to delay ripening and senescence in climacteric fruits such as apples[13-15]. Although both GABA and 1-MCP are effective individually in preserving fruit quality, their combined effect has not been investigated, specifically in watercore apples.

It was speculated that the combined GABA and 1-MCP treatment could improve the ability of fruit to resist external environmental stress and prolong the storage period. This study aims to evaluate the

efficacy of GABA and 1-MCP, individually and in combination, in postharvest quality of apples during long-term storage. The findings of this study could provide a new perspective for extending the shelf life of watercore apples.

2. Materials and methods

2.1. Plant materials and treatment

Apple fruits (*Malus domestica* Borkh. cv. Fuji) at commercial maturity were hand harvested from an orchard in Wensu, Xinjiang, and transported to the laboratory at the same day with cartons. The fruit with good texture, uniform size and maturity, free of physical injuries and pest were randomly divided into four groups. The first group(G) was immersed in 1.0 mmol/L GABA solutions for 20 min, and the second group(M) was exposed to $1 \mu\text{L L}^{-1}$ 1-MCP at room temperature for 24 h, and the third group(G + M) was treated same as the first group, after desiccating at room temperature, and then treated same as the second group, and the fourth group (CK) was untreated and served as a control. The four groups were then packed in corrugated boxes (30 fruits each), and stored at 0 ± 1 °C. The samples were analyzed periodically and randomly collected at 30 d intervals to evaluate the postharvest quality.

2.2 Watercore incidence and internal browning

After determining fruit weight, fruit were cut at the equatorial region and visually scored for watercore incidence according to the method described by Li[16]. Internal browning was calculated according the method described by Wood[17].

2.3 Weight loss, firmness, and titratable acidity

Fruit weight loss was measured by the difference of final weight from initial weight and expressed as percentage weight loss. The firmness was evaluated following the method reported by Yuan[18] on a Texture Analyzer (GY-4; Zhejiang Top Instrument Co., Ltd., China) equipped with a 3.5 mm diameter cylindrical probe. Five apples were measured for each treatment, and the results were expressed as kg/cm². Titratable acidity (TA) was measured according to the method described by Pu[19], and the TA results were expressed in terms of % malic acid.

2.4 Glucose, sorbitol, fructose and sucrose

The contents of individual sugars were determined using a LC-20A HPLC with a RID-10A detector (Shimadzu, Japan), as per the method described by Pu[19], and the results were expressed as g/kg FW.

2.5 Total phenolics and total flavonoids

Total phenolics content was measured according to the Folin-Ciocalteu colorimetric method[19], and the results were expressed as gallic acid equivalents per gram of fruit (g GAE/kg FW). The total flavonoid content (TFC) was evaluated as per the process described by Pu[19], and the results were expressed as milligrams of rutin equivalent per gram of fruit (g RE/kg FW).

2.6 Statistical Analysis

All the experiments were performed in triplicate independently, and three samples were analyzed for each group. The data was subjected to one-way analysis of variance using the SPSS statistical software (Version 20.0; SPSS, Chicago, IL, USA), and the significant differences were compared by the Duncan's test ($P < 0.05$). Furthermore, principal composition analysis (PCA) was performed using Unscrambler 10.1 (CAMO AS, Trondheim, Norway) software.

3. Results and discussion

3.1 Watercore incidence (WI) and Internal browning

As shown in Figs. 1 and 2, the WI exhibited a progressive decline throughout the refrigerated storage period. During the incipient storage phase, all samples exhibited pronounced watercore distribution ($WI > 90\%$), with affected regions predominantly localized in vascular bundles (Fig. 1). However, as storage duration increased, the watercore gradually decreases and eventually disappears. Similar behavior was observed by Li[16] and Saquet[20]. At 60-day storage, the G, M and G + M groups demonstrated significantly elevated watercore incidence compared to the CK group ($P < 0.05$), with distinct spatial distribution patterns observable through image quantification (Figs. 1 and 2). Notably, after 90-day storage, CK and M groups exhibited accelerated watercore remission ($WI < 20\%$), whereas GABA-treated groups maintained elevated WI values exceeding 50% (G: 56.67%; G + M: 63.33%), preserving the characteristic translucent parenchyma. Intriguingly, the watercore completely disappears in CK and M groups by 120-day storage, while GABA-treated groups retained diagnostically significant watercore manifestations (G: 6.67%; G + M: 13.33%) until 150-day storage.

The IB of apples during cold storage was significantly affected by postharvest treatments ($P < 0.05$, Figs. 1 and 3). Control (CK) group manifested initial flesh browning ($IB = 3.33\%$) at 90 days postharvest, progressing to severe discoloration ($IB = 73.33\%$) by storage terminus. 1-MCP-treated (M) group exhibited delayed onset, with first browning symptoms ($IB = 3.33\%$) emerging at 120 days, contrasting with complete absence in GABA-treated groups (Fig. 3). Additionally, the GABA treated groups did not exhibit fruit flesh browning throughout the entire storage period. Li[21] demonstrated that GABA application enhances the mitochondrial antioxidant system and reduces peel browning in pears following removal from cold storage. Similarly, Shekari[12] reported that GABA-treated mushrooms exhibited elevated activity and gene expression of phenylalanine ammonia-lyase (PAL) alongside reduced polyphenol oxidase (PPO) activity, collectively resulting in retarded cap browning. Consistent with these findings, other studies have shown that exogenous GABA treatment effectively protects membrane integrity in various fruits, as reflected by reduced electrolyte leakage and malondialdehyde (MDA) content, thereby delaying flesh browning during cold storage[12]. In contrast, Jung[22] observed that late-harvested fruit treated with 1-methylcyclopropene (1-MCP) were more susceptible to flesh browning during prolonged storage, primarily due to a compromised antioxidant defense mechanism under stress, along with elevated polyphenol oxidase (PPO) activity and electrolyte leakage rates.

Collectively, these results demonstrate that GABA treatments not only delay watercore dissipation but also effectively inhibit flesh browning.

3.2 Weight loss

The weight loss of apples progressively increased during 180-day cold storage across all treatments. The highest weight loss (9.56%) was observed in control fruit. In this study, 1-MCP and GABA treatments alone or in combination significantly ($P < 0.05$) reduced weight loss of apple fruit compared to control treatment and the lowest weight loss (7.57%) was found in fruit treated with 1-MCP + GABA (Fig. 4). The increase in weight loss during storage is likely attributable to water loss resulting from respiration, transpiration and metabolic activity[23]. Regarding the inhibitory effect of 1-MCP, its reduction of postharvest water loss in tomato has been linked to its regulation of epidermal cuticle composition and morphology[24]. Specifically for apples, 1-MCP treatment may influence quality during cold storage by delaying increases in cuticular wax density and inhibiting wax crystal melting, potentially through reducing the expression of MdCER6[25]. GABA, on the other hand, might mitigate weight loss by reducing membrane lipid peroxidation via modulation of lipoxygenase enzyme activity, thereby enhancing cell wall stability [26]. Additionally, GABA treatment could decrease weight loss by reducing membrane damage, preserving cell membrane integrity, and suppressing malondialdehyde (MDA) production[8].

3.3 Firmness

Firmness serves as a critical determinant of edible quality, consumer acceptability, and commercial value in apples. As illustrated in Fig. 5, both treatment type and storage duration exerted significant effects ($p \leq 0.05$) on fruit firmness. All treatments exhibited progressive firmness loss during storage, with the most pronounced decline observed in control fruit. After 180 days, the combined 1-MCP + GABA treatment maintained the highest firmness (6.69 kg/cm²), significantly surpassing individual GABA (6.03 kg/cm²), 1-MCP (5.83 kg/cm²), and control (5.01 kg/cm²) groups ($P < 0.05$).

3.4 Titratable acid

Titrateable acidity (TA) constitutes a critical determinant of apple flavor quality, with both treatment and storage duration significantly influencing its retention ($p \leq 0.05$; Fig. 6). All treatments exhibited a gradual decline in organic acid content throughout storage, indicative of their catabolism serving as respiratory substrates within senescence-associated metabolic pathways[27, 28]. This reduction in titrateable acidity (TA) is primarily driven by the characteristic increase in respiration rate during storage. Under these conditions, organic acids are metabolized via the TCA cycle to generate cellular energy, leading to the observed decrease in TA[29]. Notably, the combined 1-MCP + GABA treatment proved significantly more effective in mitigating acid degradation than either treatment applied individually. After 180 days of storage, the TA level maintained by the combinatorial treatment was 0.19%, which was higher than that preserved by 1-MCP alone (0.16%) or GABA alone (0.17%). This superior efficacy suggests a synergistic interaction between 1-MCP and GABA, collectively preserving organic acid reserves more effectively.

3.5 Glucose, fructose, sorbitol and sucrose

As shown in Fig. 7, sucrose and sorbitol exhibited a consistent decline throughout the storage period in all treatment groups. In the control group, sucrose content decreased sharply during the first 60 days of storage, primarily due to the activity of invertase enzymes, which hydrolyze sucrose into glucose and fructose. Similarly, sorbitol content declined steadily, as it was metabolized into fructose via the sorbitol dehydrogenase pathway. The 1-MCP treatment slowed the degradation of sucrose and sorbitol compared to the control, likely due to its inhibition of ethylene-mediated senescence, which reduced overall metabolic activity. GABA treated groups also showed a moderate effect in preserving sucrose and sorbitol, possibly by enhancing cellular stability and reducing stress-induced metabolic shifts. However, the combined treatment of 1-MCP and GABA demonstrated the most effective preservation of sucrose and sorbitol, suggesting a synergistic effect in maintaining sugar metabolism stability.

In contrast to sucrose and sorbitol, glucose and fructose levels increased progressively during storage in all treatment groups. This increase is attributed to the hydrolysis of sucrose and the metabolic conversion of sorbitol into fructose. In the control group, glucose and fructose accumulation was most pronounced, reflecting the high activity of invertase and sorbitol dehydrogenase. The 1-MCP treatment significantly slowed the accumulation of glucose and fructose, as ethylene inhibition reduced the overall metabolic rate and delayed sucrose hydrolysis. GABA treatment also moderated the increase in glucose and fructose, likely by stabilizing cellular membranes and reducing stress-induced enzymatic activity. The combined treatment of 1-MCP and GABA resulted in the slowest accumulation of glucose and fructose, further supporting the synergistic effect of these treatments in regulating sugar metabolism.

3.6 Total phenolic content and total flavonoids content

The changes in total phenolics and total flavonoids during storage were significantly influenced by both storage duration and postharvest treatments (Fig. 8). The total phenolic content increased progressively throughout the storage period in all treatment groups. The control group exhibited the highest rate of phenolic accumulation, likely due to the greater oxidative stress experienced by untreated fruit. The 1-MCP and GABA treatments showed a slower but steady increase in total phenolics. The combined treatment of 1-MCP and GABA resulted in the lowest rate of phenolic accumulation. In contrast to TPC, the total flavonoid content exhibited a dynamic trend during storage, characterized by an initial decline followed by a subsequent increase. In the control group, the total flavonoid content decreased significantly during the first 60 days of storage. However, after 60 days, the flavonoid content began to increase. Similar trends were observed in the 1-MCP and GABA treatment groups, although the extent of the initial decline was less pronounced compared to the control. The combined treatment of 1-MCP and GABA maintained the highest stability in flavonoid content throughout storage, exhibiting the smallest initial decline and the most gradual increase during later stages. While water loss during storage may partially contribute to the observed increases in total phenolic content (TPC) and total flavonoid content (TFC) of apple fruit. Wang[8] demonstrated that GABA treatment promoted the accumulation of total phenolics and proline and enhanced antioxidant defense system of banana fruit during storage. Similarly,

Ali[11] reported that the GABA application increased phenylalanine ammonia-lyase (PAL) activity, suppressed polyphenol oxidase (PPO) activity, and consequently elevated total phenol levels. Further supporting this, Ge[30] reported that GABA treatment enhanced the accumulation of total phenolics and flavonoids in blueberry fruit by regulating phenylpropanoid pathway. These results suggest that the combined treatment effectively mitigated oxidative stress and preserved flavonoid and phenolic compounds stability, likely through the synergistic effects of ethylene inhibition and enhanced antioxidant activity.

3.7 Principal component analysis

Principal component analysis (PCA) was performed to comparatively evaluate the effects of different treatments on the postharvest quality of apple fruits. This multivariate approach visually represents relationships between the treatments and measured quality indices. The PCA loading plot extracted two principal components (PC-1 and PC-2) accounting for 99% of total variance, revealing distinct clustering patterns among apples from different treatments. The correlation loadings plot (Fig. 9) showed samples and indices segregated into three distinct groups: Group 1 (Right Plane) clustered sucrose, sorbitol, firmness, titratable acidity (TA), and watercore incidence (WI); Group 2 grouped all samples centrally; Group 3 (Left Plane) clustered glucose, fructose, total phenolic content (TPC), and weight loss (WL). Group 1 exhibited high levels of its constituent indices during early storage, while Group 3 showed high levels in the final storage stage. Based on their positions and associations, sucrose, sorbitol, firmness, TA, and WI are characteristic of fresh apple fruit, whereas glucose, fructose, TPC, and WL are characteristic of apples after long-term storage.

4 Conclusion

In the present study, the combined 1-MCP and GABA treatment remarkably improved the postharvest quality of apple fruits, exhibiting synergistic effects on most indexes, including watercore incidence, internal browning firmness, TA, sucrose, sorbitol, TPC and TFC, compared with the control. The efficacy of the combined treatment became increasingly pronounced with longer storage duration. These findings indicate that the 1-MCP and GABA composite treatment is highly beneficial for preserving the physicochemical quality and freshness of apples during storage. Further research is warranted to elucidate the underlying mechanisms and optimize treatment protocols for commercial implementation.

Declarations

Funding

This work was supported by the National-Local Joint Engineering Laboratory for High-Efficiency Cultivation and Value-Added Processing of Characteristic Fruit Trees in South Xinjiang (FE201905), Bingtuan science and technology program 2023AB063 and Industrial technology innovation team support program (XJLGCYJSTX04-0224-14).

Data Availability

All data supporting the results of this study are available from the corresponding author (email: yfpu@zju.edu.cn).

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Figures

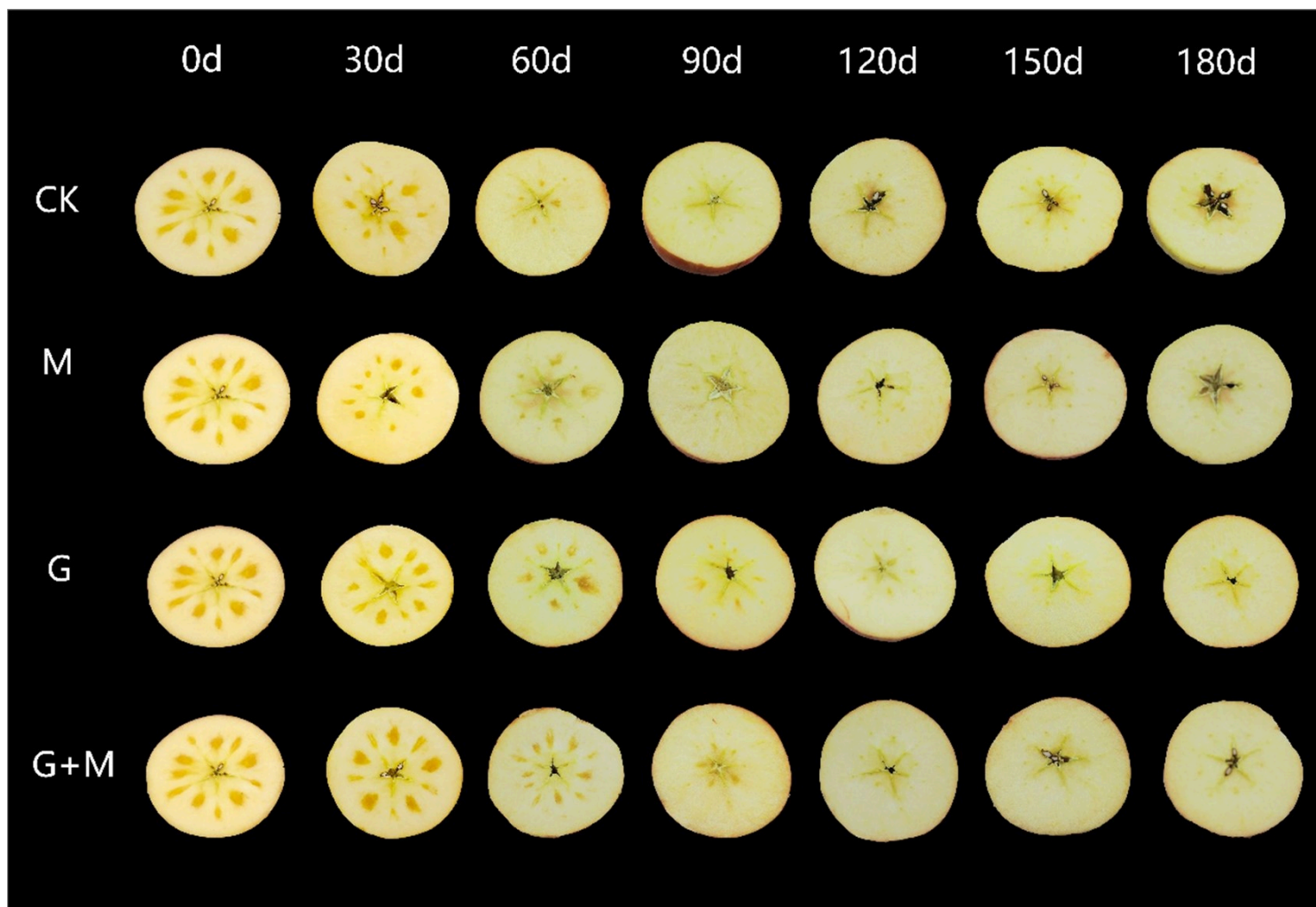


Figure 1

Effects of different treatments on visual quality

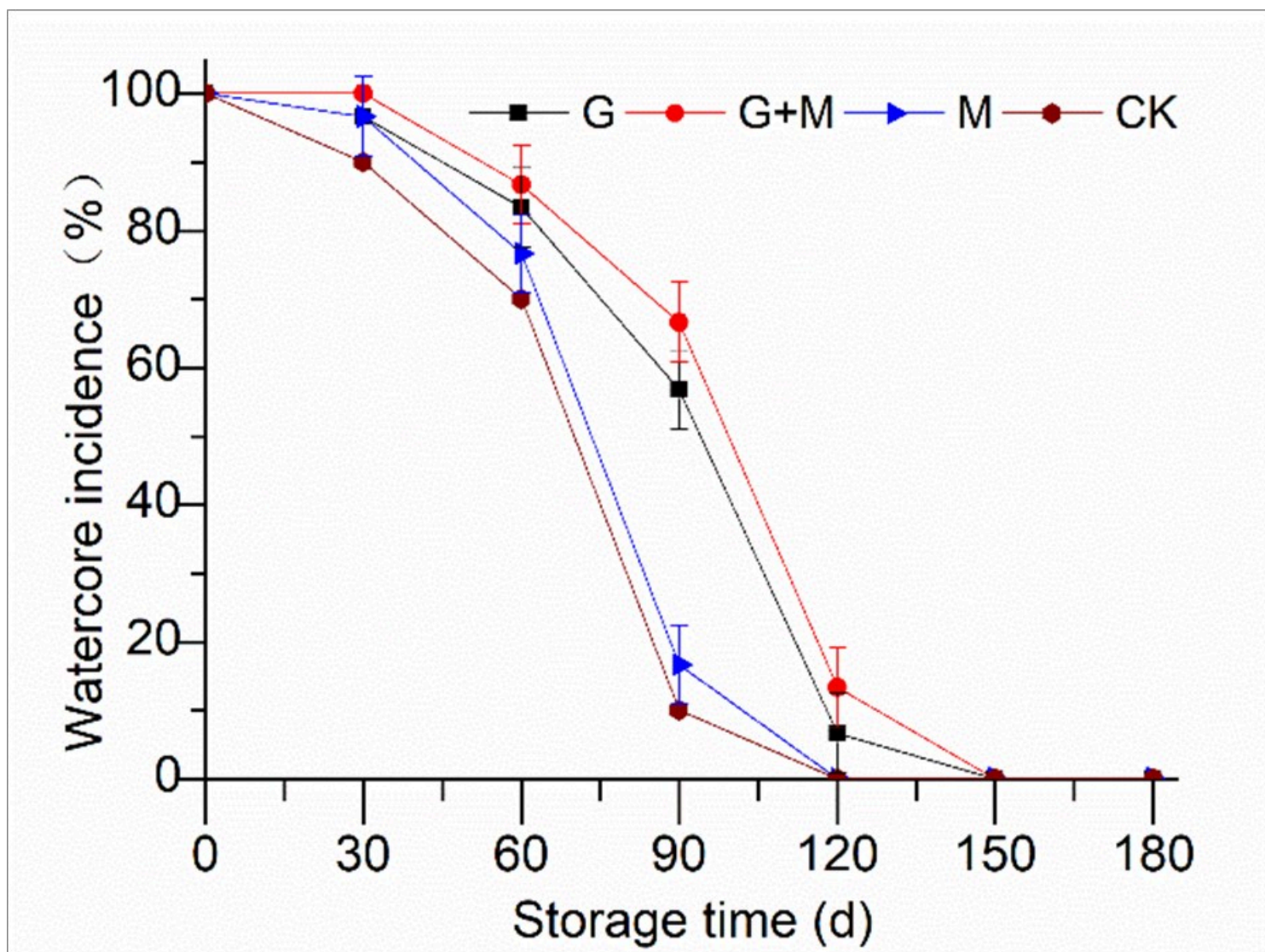


Figure 2

Change in watercore incidence of apples during cold storage.

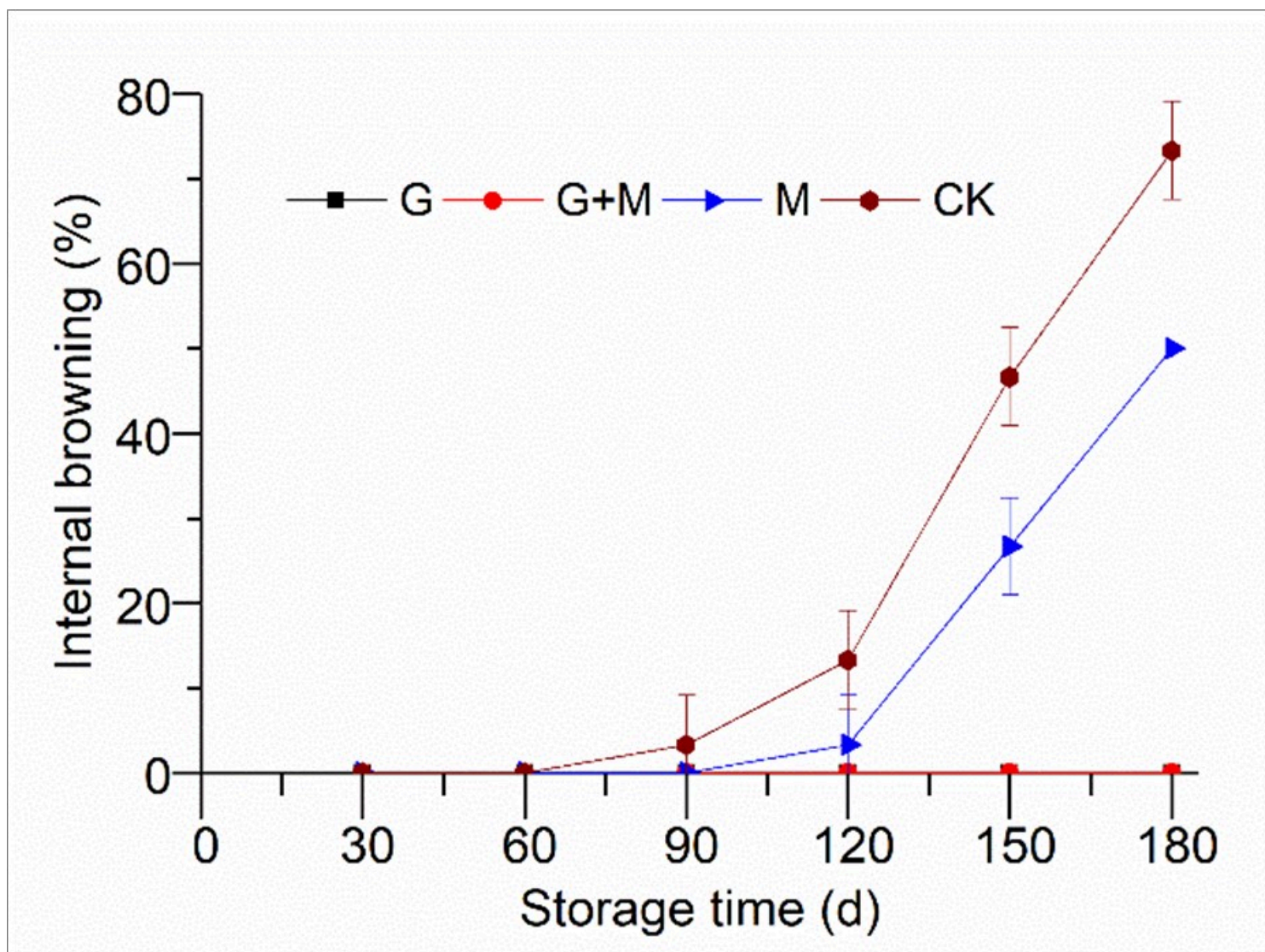


Figure 3

Change in flesh browning of apples during cold storage.

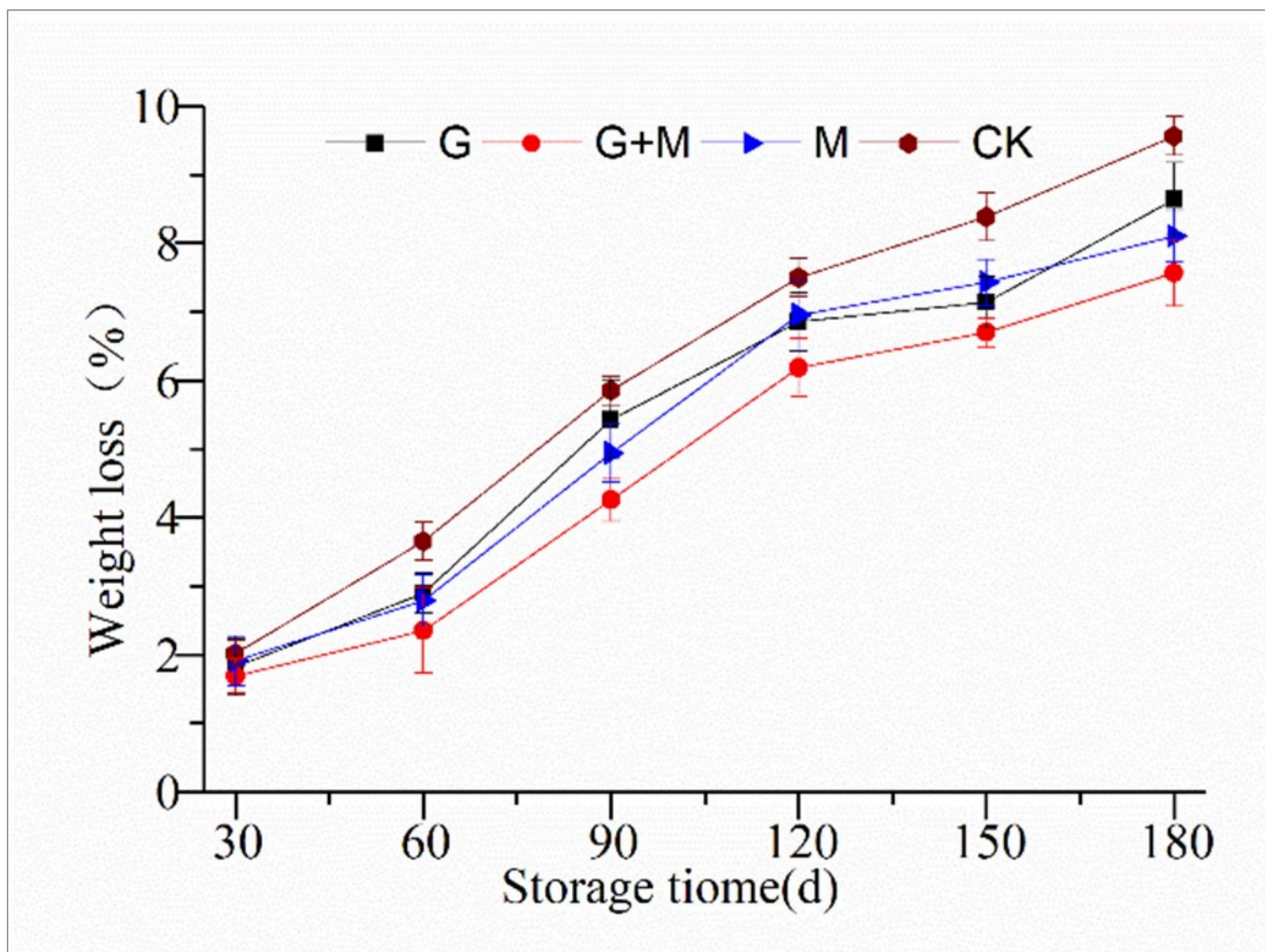


Figure 4

Change in weight loss of apples during cold storage.

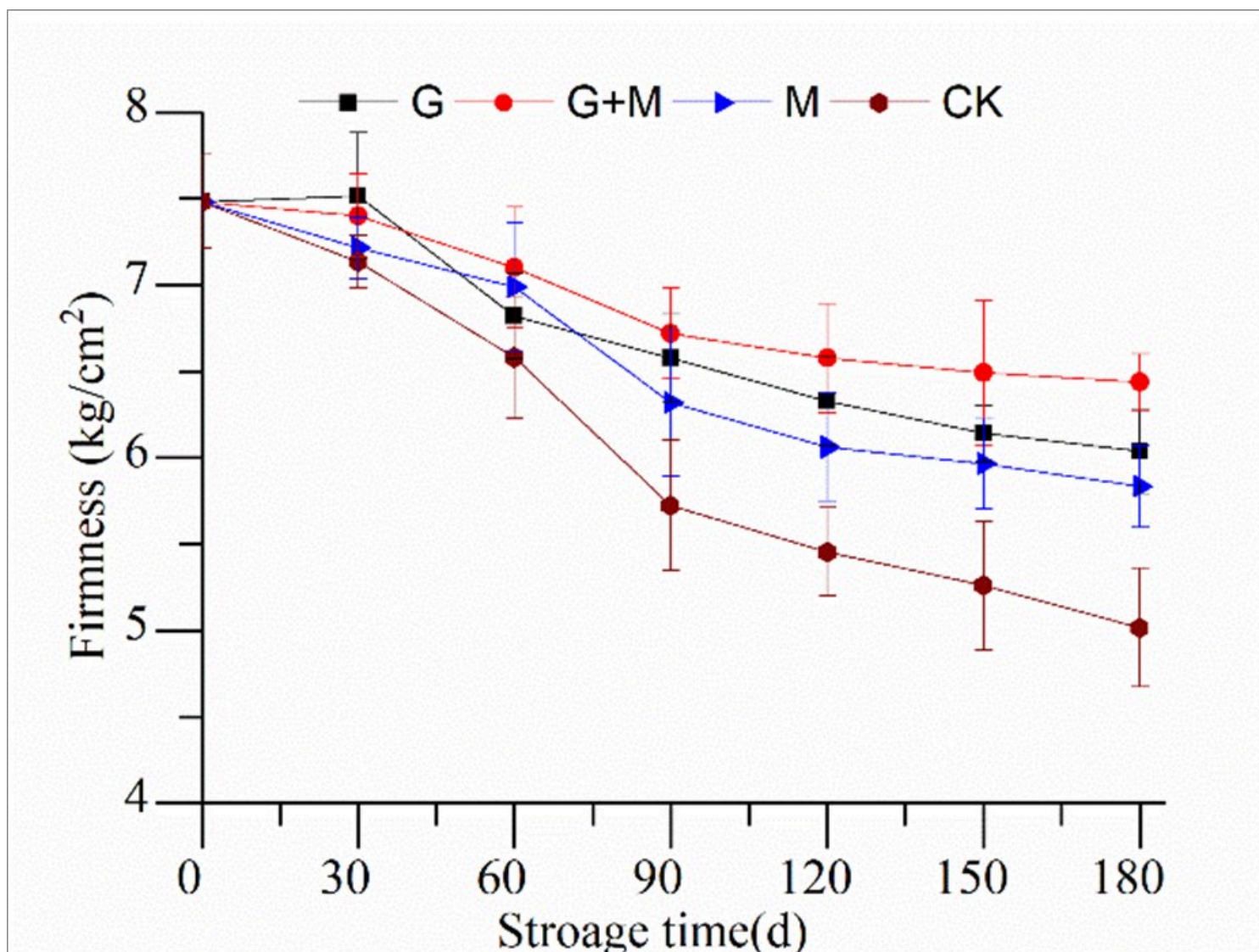


Figure 5

Change in firmness of apples during cold storage.

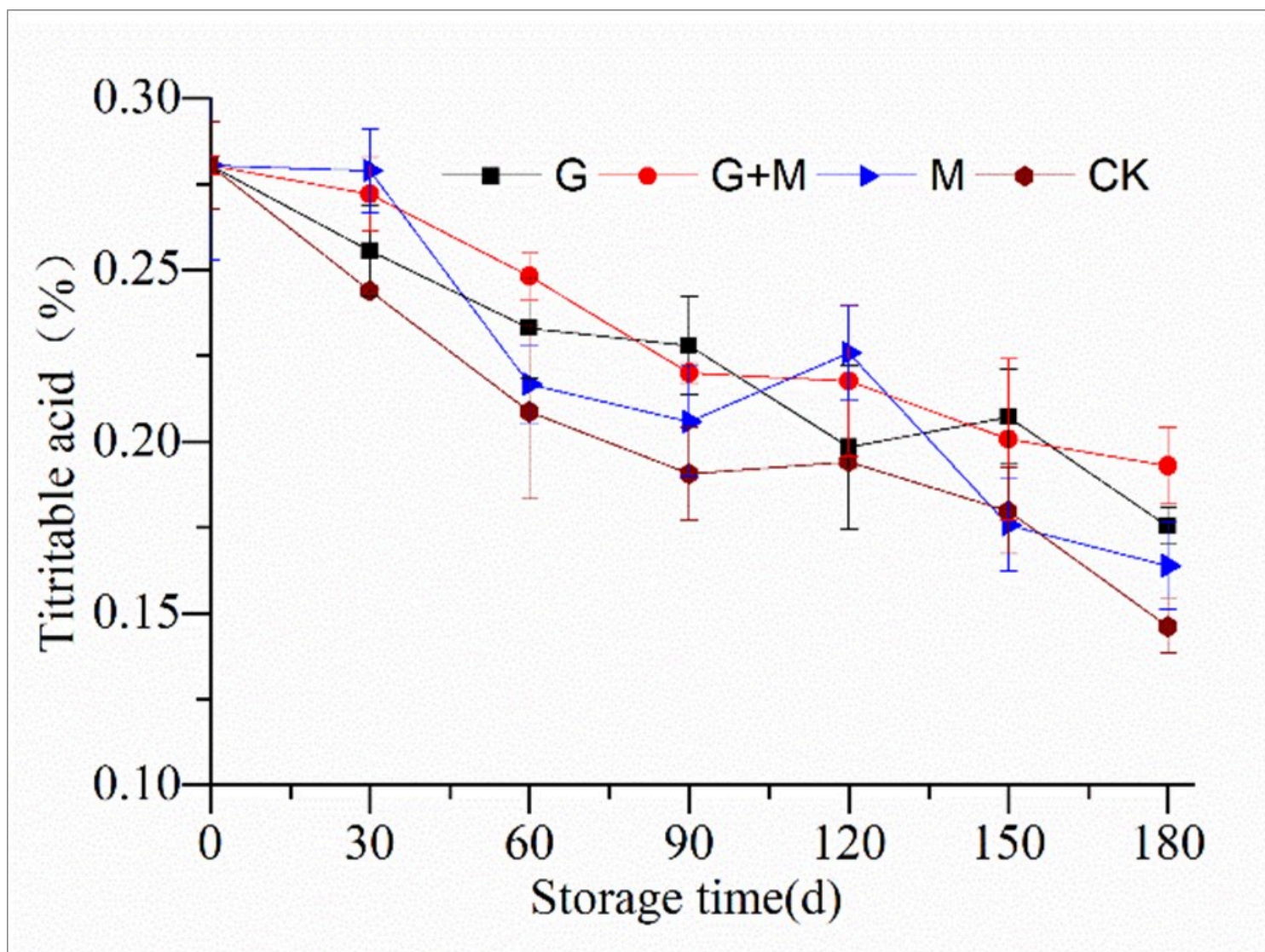


Figure 6

Change in titratable acid of apples during cold storage.

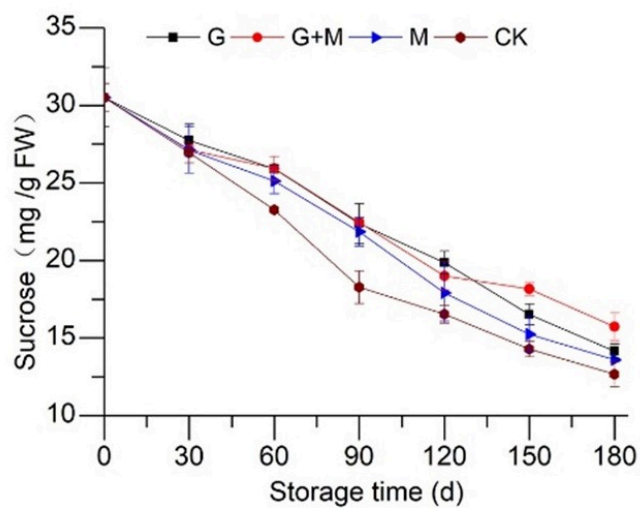
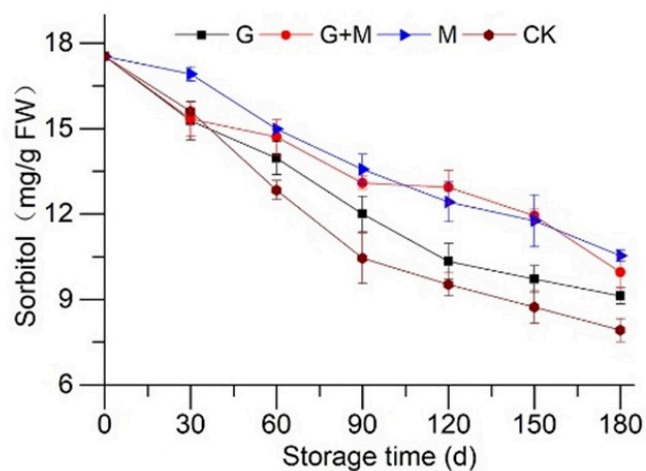
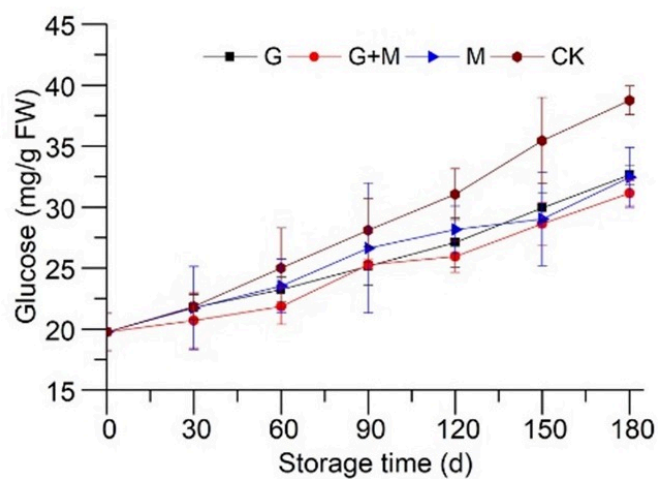
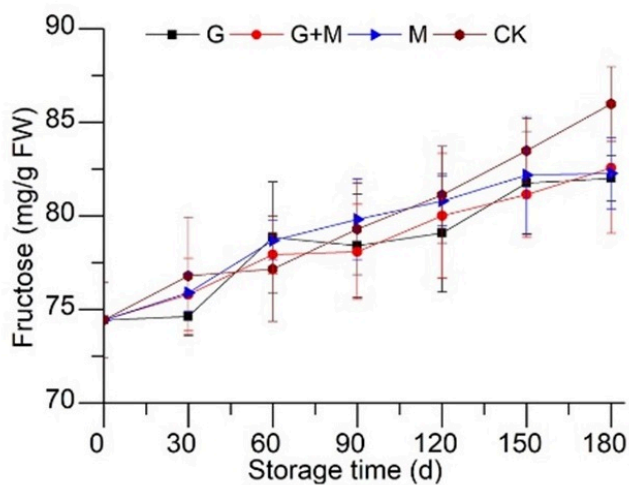


Figure 7

Change in sugars of apples during cold storage.

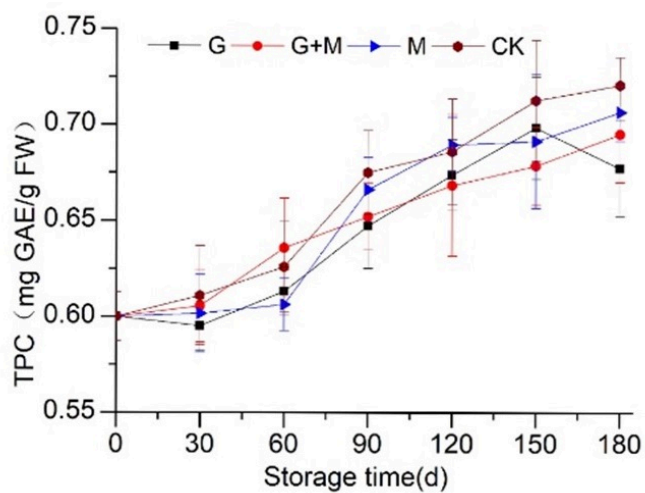
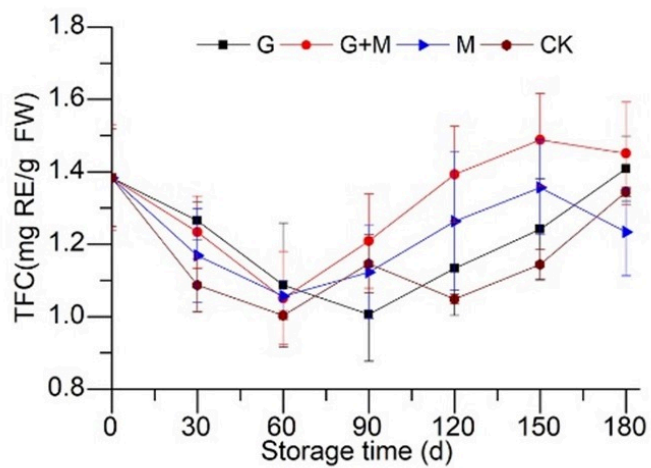


Figure 8

Change in TFC and TPC of apples during cold storage.

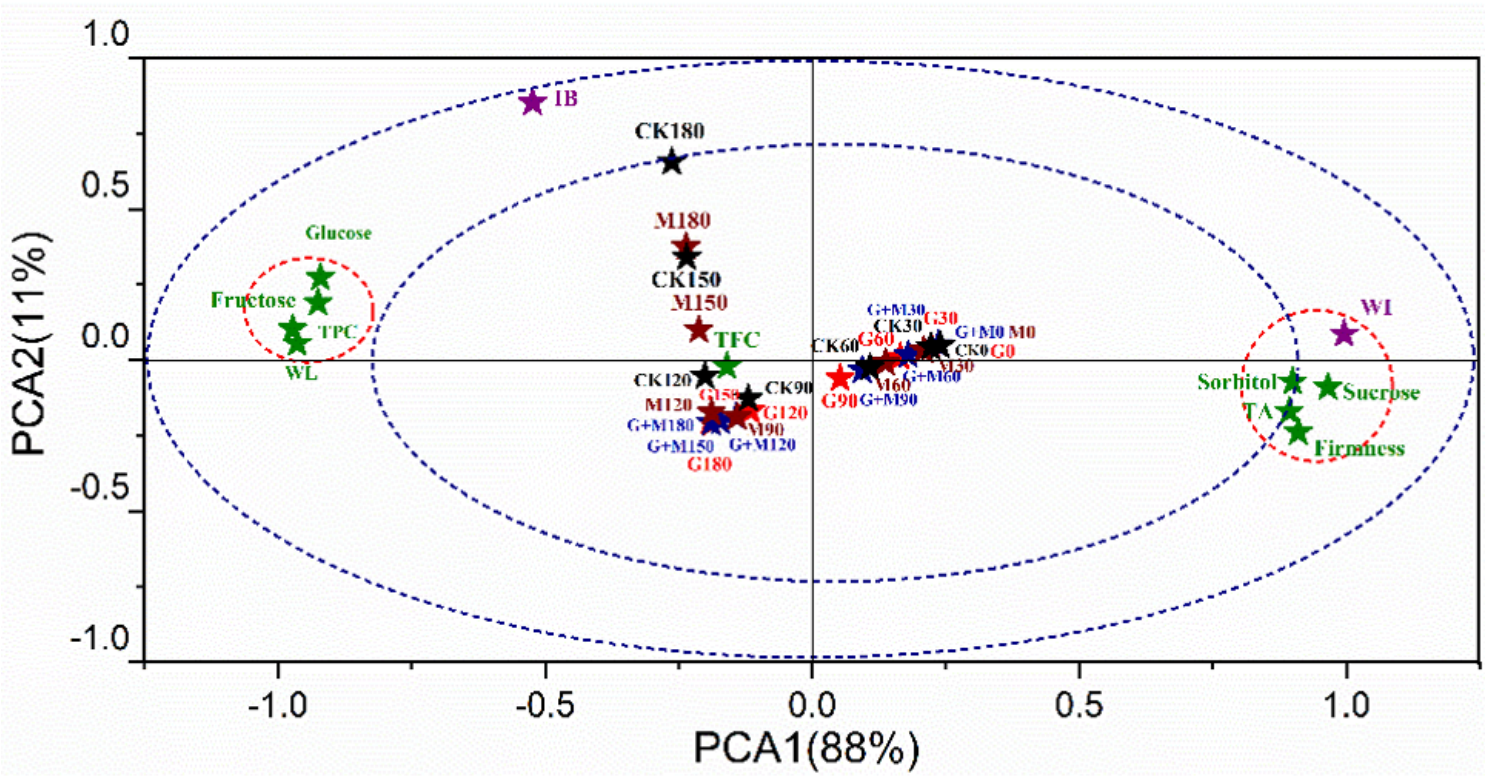


Figure 9

Correlation loadings plots of principal component analysis (PCA).