Research Article

**Received:** 24 May 2026
**Accepted:** 29 October 2026
**Published:** 02 November 2026

# Effects of Postharvest Methyl Jasmonate (MeJA) and $\gamma$-Aminobutyric Acid (GABA) on the Quality and Storability of Granny Smith Apple Fruit

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**Cite this article:**
R. K. A. Al-mzori and S. F. A. Al-Bamarny (2026). Effects of Postharvest Methyl Jasmonate (MeJA) and $\gamma$-Aminobutyric Acid (GABA) on the Quality and Storability of Granny Smith Apple Fruit. Revista Cultura Científica, (24), pp. 2179–2193. https://doi.org/10.70517/revcc2624178

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## Abstract

This study investigated the effects of postharvest methyl jasmonate (MeJA) and $\gamma$-aminobutyric acid (GABA) treatments on the quality and storability of Granny Smith apples harvested from a private orchard in Duhok Governorate, Kurdistan Region, Iraq. The reported treatment concentrations were 0, 0.75, 1.5, and 2.5 mM MeJA, applied by dipping for five minutes, and 0, 5, 10, and 15 mM GABA, applied by dipping for fifteen minutes. Fruit were stored for 30, 60, and 120 days at a reported temperature of $1 \pm 1\,^{\circ}\mathrm{C}$ and 85–90% relative humidity. The tabulated results showed that 2.5 mM MeJA maintained greater firmness and ascorbic acid content and reduced weight loss compared with the untreated MeJA level. GABA treatments also maintained firmness, while their effects on weight loss, acidity, and ascorbic acid depended on concentration. Main effects of either treatment on total soluble solids and total phenolic content were not statistically significant according to the reported Duncan groupings. Titratable acidity was numerically higher at the two highest MeJA concentrations, but the MeJA main-effect means shared the same significance letter. Superoxide dismutase and catalase activities were evaluated after 120 days and were generally greater in treated fruit, although the strongest response depended on the enzyme and treatment combination. Across storage periods, firmness and titratable acidity decreased, whereas weight loss and total soluble solids increased. Ascorbic acid and total phenolic content reached their highest storage-period means at 60 days. Overall, the results support the potential of MeJA and GABA dipping treatments to preserve selected quality attributes, while demonstrating that benefits were specific to the response variable and storage interval rather than uniform across all measured characteristics.


**Keywords:** Methyl jasmonate; $\gamma$-aminobutyric acid; postharvest dipping; Granny Smith apples; cold storage; antioxidant enzymes.

## 1. INTRODUCTION

Granny Smith apple (*Malus domestica* Borkh.) belongs to the family Rosaceae and is a climacteric fruit widely valued for fresh consumption. Apple cultivars can be produced under different ecological conditions, including temperate regions and suitably managed subtropical environments, although their yield and fruit quality depend on cultivar, rootstock, and growing conditions [1]. Granny Smith apples have also been investigated specifically for changes in postharvest quality under simulated shelf-life conditions, demonstrating the importance of evaluating both physical and chemical characteristics during storage [2]. For producers, the commercial value of this cultivar depends not only on the quantity harvested but also on the maintenance of acceptable texture, acidity, appearance, and nutritional composition throughout distribution and marketing.

In the Kurdistan Region of Iraq, particularly in Duhok Governorate, apples are an economically important fruit crop. Production is also established in other Iraqi growing areas, where the relative importance of locally adapted cultivars differs with climate and production practices. Nevertheless, harvesting, handling, transportation, and storage remain important points at which fruit quality can deteriorate. Mechanical damage and physiological changes can reduce marketable yield even when fruit are initially harvested in sound condition. The concentration of supply during the harvest season further increases the need for suitable storage practices, because fruit that cannot be marketed immediately must retain their quality for later sale. Water loss is especially important in apples because it reduces saleable weight and can contribute to shrivelling, changes in texture, and reduced consumer acceptance [3]. Effective postharvest management therefore requires attention to both the rate of deterioration and the specific quality attributes that determine marketability.

Apples contain phenolic compounds, organic acids, vitamins, and other constituents associated with their nutritional value. Antioxidant characteristics vary among cultivars and should not be assumed to remain constant during storage or following treatment [4]. Consequently, a treatment that preserves firmness or reduces water loss may not necessarily improve every biochemical attribute. Assessing several complementary quality parameters is necessary to distinguish a broad preservative response from an improvement limited to a single measurement. In the present study, this distinction is particularly relevant because the treatments were evaluated over a storage period extending to 120 days.

Methyl jasmonate (MeJA; $C_{13}H_{20}O_3$) is a naturally occurring plant signalling compound investigated for its effects on ripening, stress responses, and postharvest preservation. Its biological origin does not, by itself, establish that every application is residue-free or suitable for commercial use; treatment concentration, formulation, exposure, and crop response must also be considered. In Nanguo pears, postharvest MeJA dipping maintained firmness, ascorbic acid, and titratable acidity and suppressed respiration and weight loss, with responses associated with mitochondrial energy metabolism [5]. Jasmonate effects are not restricted to delayed deterioration: Qi et al. [6] also reported changes in ester aroma formation and ripening-related characteristics in stored Nanguo pears. Such findings indicate that the direction of the response depends on the particular quality attribute being measured.

Research across horticultural crops has identified MeJA as a potential means of improving antioxidant defence, reducing chilling injury, and modifying resistance to postharvest pathogens [7]. Asghari [8] discussed the broader effects of jasmonates on food-crop physiology, quality, and productivity, while Li et al. [9] examined their influence on pear colour development and quality. These studies provide a physiological basis for investigating MeJA in apples, but they do not establish an effective concentration for Granny Smith fruit under the conditions used here. Lata et al. [10] similarly emphasized the relevance of MeJA to postharvest fruit quality. Evidence for decay management also includes the enhancement of yeast-mediated control of blue mould in pears, rather than an established universal commercial fungicidal effect of MeJA alone [11]. Chen et al. [12] found that MeJA treatment increased antioxidant and defence-related enzyme activities in pear fruit and reduced blue-mould lesion development. Their results support investigating the antioxidant response, while remaining distinct from the unmeasured incidence of disease in the present experiment.

The non-protein amino acid $\gamma$-aminobutyric acid (GABA; $C_4H_9O_2N$), also known as 4-aminobutyric acid, occurs naturally in plants, animals, and microorganisms. In plants, it participates in metabolic and signalling processes under both stressful and non-stressful conditions [13]. Its roles include relationships with carbon and nitrogen metabolism, cellular pH regulation, growth, and stress tolerance. However, responses to exogenous GABA vary between crops and cultivars. In a study of Honeycrisp apples, Al Shoffe et al. [14] investigated preharvest and postharvest applications in relation to fruit quality and physiological disorders; their findings do not support assuming that GABA consistently prevents disorder development. This variability provides an additional reason to assess treatment performance directly in Granny Smith apples rather than extrapolating an optimum from another cultivar.

Positive responses have nevertheless been reported in other fruit systems. GABA treatment maintained quality and enhanced antioxidant-system responses in strawberries [15], while research on Orlando tangelo examined its potential, alongside melatonin, to mitigate chilling injury through antioxidant regulation [16]. In apples, Han et al. [17] associated GABA treatment with the regulation of malate metabolism and ethylene synthesis during storage. Zhu et al. [18] investigated GABA-induced resistance to blue mould together with changes in polyamine metabolism, the GABA shunt,

and reactive oxygen species metabolism. These studies support measuring acidity and antioxidant enzymes, but disease resistance, malate-pathway activity, and gene expression cannot be inferred directly when they have not been measured in the experimental fruit.

Cold storage is an essential component of apple preservation, although fruit continue to undergo physiological and biochemical changes during storage. Research on Gala Schniga SchniCo Red apples has examined the interaction between long-term storage and preharvest or postharvest 1-methylcyclopropene application [19]. Work on Gala apples has also considered aminoethoxyvinylglycine and 1-methylcyclopropene in relation to fruit quality and preharvest disorders [20]. These studies illustrate the importance of treatment context; they should not be interpreted as direct evidence for identical MeJA or GABA responses. The objective of the present research was therefore to evaluate the effects of postharvest MeJA and GABA dipping treatments on the physical quality, biochemical composition, and selected antioxidant enzyme activities of Granny Smith apples during cold storage. The study also examined the reported treatment combinations to identify whether responses were consistent across quality parameters and storage intervals.

## 2. MATERIALS AND METHODS

### 2.1. FRUIT MATERIAL AND STORAGE CONDITIONS

Mature, medium-sized Granny Smith apples were harvested manually during the early morning of 14 September 2024 from ten-year-old trees in a private orchard at Majulmakht, Duhok Governorate, Kurdistan Region, Iraq. Harvest selection was based on fruit maturity indicators, including total soluble solids and firmness. The fruit were transported to the Central Laboratory of the College of Agricultural Engineering Sciences, University of Duhok. After cleaning, grading, sorting, and precooling, sound fruit were selected for the experiment. The purpose of these preparation steps was to obtain fruit of comparable initial condition before treatment and storage; numerical harvest-maturity thresholds and the number of fruit per experimental unit were not reported in the available experimental description.

### 2.2. TREATMENTS AND EXPERIMENTAL DESIGN

The reported MeJA concentrations were 0, 0.75, 1.5, and 2.5 mM, with a dipping duration of five minutes. The reported GABA concentrations were 0, 5, 10, and 15 mM, with a dipping duration of fifteen minutes. Each treatment was represented by three replicates. After treatment, fruit were air-dried and placed in perforated polyethylene bags according to their treatment allocation. The bags were tied and transferred to cold storage at a reported temperature of $1 \pm 1\,^{\circ}\mathrm{C}$ and 85–90% relative humidity. Fruit were sampled after 30, 60, and 120 days, corresponding to the reported storage intervals of one, two, and four months.

The tabulated results describe four MeJA levels crossed with four GABA levels and, for the quality measurements, three storage intervals. Superoxide dismutase and catalase activities are reported only at 120 days. The experiment was described as factorial and arranged in a completely randomized design. Treatment means were compared using Duncan's multiple range test at the 5% significance level, and the data were analysed using SAS software. The interpretation below follows the significance letters provided in the tables: means sharing one or more letters within the relevant comparison are not treated as significantly different. Numerical differences are distinguished from statistically supported treatment effects.

### 2.3. PHYSICAL AND BIOCHEMICAL MEASUREMENTS

Fruit firmness was measured using a hand penetrometer and is reported in pounds (lb), consistent with the units in the dataset. Penetrometer-based firmness assessment is also used in apple storage research [21]. Probe dimensions, peel removal, measurement positions, and the number of readings per fruit should be specified from the laboratory record before the method is reproduced. No additional instrument settings are assumed here.

Fruit weight loss was determined using an electronic balance. The initial mass of each experimental unit was recorded, and the mass of the same fruit was measured after the corresponding storage interval. Weight loss was expressed as the percentage reduction relative to the initial mass. Repeated weighing is an established approach to assessing storage-related mass loss in apples [22].

Ascorbic acid in expressed juice was determined by titration with 2,6-dichlorophenolindophenol, following the analytical approach described for fruit and vegetable products [23]. Results are retained in the originally reported units of mg per 100 mL of juice. Total soluble solids were measured using a hand refractometer, an approach consistent with apple quality assessment [24], and are reported as the percentage values supplied in the dataset. Titratable acidity was measured by titrating a 5 mL juice sample with 0.1 N sodium hydroxide using phenolphthalein as the indicator and expressing the result as a percentage of malic acid [25].

Total phenolic content was determined using the method cited by Ranganna [23] and is retained in the supplied units of mg per 100 g of juice. Superoxide dismutase activity was determined with reference to the method of Marklund and

Marklund [26], and catalase activity with reference to Luhová et al. [27]. These enzyme measurements were reported after 120 days of storage. The original units are retained as $\mathrm{unit\,min^{-1}\,mg^{-1}}$ for superoxide dismutase and $\mathrm{mmol\,min^{-1}\,mg^{-1}}$ for catalase. Because the available description does not identify the normalization basis for the milligram denominator, these values are interpreted only within the reported experiment rather than compared quantitatively with differently normalized enzyme assays.

## 3. RESULTS AND DISCUSSION

### 3.1. FRUIT FIRMNESS

The results in Table 1 indicate that fruit treated with 2.5 mM MeJA had significantly greater mean firmness than fruit at the other MeJA concentrations. The GABA main-effect means at 5, 10, and 15 mM were also greater than the untreated GABA mean, although these three treated means did not differ significantly from one another. Firmness decreased significantly with storage duration, with storage-period means of 14.31, 12.60, and 10.80 lb after 30, 60, and 120 days, respectively. Thus, the treatments moderated softening but did not prevent the progressive loss of firmness during storage.

The preservation of firmness following MeJA treatment is consistent with the maintenance of flesh firmness reported for Nanguo pears [5]. Fruit softening is associated with modifications of cell-wall polysaccharides, particularly the solubilization and degradation of pectic components. GABA has been linked to lower expression of selected cell-wall-degrading genes and maintained firmness in tomatoes, providing a possible physiological explanation that requires direct verification in apples [28]. Research on MeJA-treated peaches and Kinnow mandarins likewise supports a relationship between postharvest treatment and texture preservation, although responses depend on fruit type and storage conditions [29, 30]. Cell-wall enzyme activities were not measured in the present experiment, so these mechanisms remain interpretations of the observed firmness response.

Among the three-factor combinations, 1.5 mM MeJA with 15 mM GABA after 30 days produced a firmness value of 15.57 lb. This was among the highest values and shared a significance grouping with several other combinations. The untreated combination after 120 days had the lowest numerical firmness, 9.20 lb. These findings support treatment-related differences while also demonstrating the substantial influence of storage duration.

**Table 1.** *Effect of methyl jasmonate (MeJA), γ-aminobutyric acid (GABA), storage periods, and their interactions on firmness (lb) of Granny Smith apples stored at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | Storage period | | | MeJA × GABA | MeJA mean |
|---|---|---|---|---|---|---|
| | | 30 days | 60 days | 120 days | | |
| 0 | 0 | 13.48 b-g | 11.83 j-n | 9.20 r | 11.51 f | 12.04 c |
| | 5 | 13.83 b-f | 12.17 h-l | 10.43 o-q | 12.14 de | |
| | 10 | 14.20 b-d | 12.17 h-l | 10.75 n-p | 12.37 c-e | |
| | 15 | 13.60 b-f | 12.00 i-m | 10.85 m-p | 12.15 de | |
| 0.75 | 0 | 13.73 b-f | 12.00 i-m | 11.05 l-p | 12.26 de | 12.54 b |
| | 5 | 14.72 ab | 12.33 g-k | 10.02 p-r | 12.36 c-e | |
| | 10 | 14.42 a-c | 12.83 e-j | 11.23 k-o | 12.83 a-d | |
| | 15 | 14.02 b-e | 12.83 e-j | 11.27 k-o | 12.71 b-e | |
| 1.5 | 0 | 13.92 b-e | 12.62 f-j | 9.60 q-r | 12.04 ef | 12.68 b |
| | 5 | 15.52 a | 12.83 e-j | 9.63 q-r | 12.66 b-e | |
| | 10 | 14.55 a-c | 11.95 i-n | 11.20 k-o | 12.57 b-e | |
| | 15 | 15.57 a | 13.83 b-f | 10.95 l-p | 13.45 a | |
| 2.5 | 0 | 14.50 a-c | 13.50 b-g | 10.85 m-p | 12.95 a-c | 13.01 a |
| | 5 | 14.02 b-e | 13.32 c-h | 12.08 i-l | 13.14 ab | |
| | 10 | 14.32 b-d | 13.12 d-i | 11.98 i-m | 13.14 ab | |
| | 15 | 14.50 a-c | 12.33 g-k | 11.63 j-o | 12.82 b-d | |
| Storage-period mean | | 14.31 a | 12.60 b | 10.80 c | | |
| MeJA*Storage period | 0 | 13.78 c | 12.04 fg | 10.31 i | GABA mean | |
| | 0.75 | 14.22 bc | 12.50 ef | 10.89 h | | |
| | 1.5 | 14.89 a | 12.81 de | 10.34 i | | |
| | 2.5 | 14.33 b | 13.07 d | 11.64 g | | |
| GABA*Storage period | 0 | 13.91 b | 12.49 c | 10.18 e | 12.19 b | |
| | 5 | 14.52 a | 12.66 c | 10.54 e | 12.57 a | |
| | 10 | 14.37 ab | 12.52 c | 11.29 d | 12.73 a | |
| | 15 | 14.42 ab | 12.75 c | 11.18 d | 12.78 a | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The results in Table 1 therefore indicate that maintaining texture requires both an effective treatment and control of storage duration; the highest marginal treatment mean does not imply the absence of softening at 120 days.

### 3.2. FRUIT WEIGHT LOSS

The data in Table 2 show that weight loss decreased as MeJA concentration increased, with 2.5 mM MeJA producing the lowest main-effect mean. GABA at 5 and 15 mM also produced significantly lower main-effect means than the untreated GABA level; the 10 mM mean shared letters with both the untreated and treated groups. Storage duration had a clear effect, as mean weight loss increased from 1.28% after 30 days to 2.23% after 60 days and 3.68% after 120 days. Therefore, treatment reduced the extent of mass loss without eliminating the accumulation of losses over time.

Weight loss arises primarily from water transfer to the surrounding atmosphere, with an additional contribution from respiratory use of stored substrates. The magnitude of the response depends on fruit-surface properties, storage temperature, humidity, and packaging conditions [3]. MeJA-associated reductions in weight loss have also been reported in Nanguo pears [5]. GABA dipping reduced weight loss and maintained quality in Hindi-Besennara mangoes, supporting its evaluation as a treatment affecting postharvest deterioration [31]. Related work on Orlando tangelo considered antioxidant protection and chilling injury [16], while loquat research reported storage responses to GABA and L-cysteine treatments [32]. These studies provide comparisons across fruit systems, but they do not demonstrate the rate of transpiration or respiration in the apples examined here.

The combination of 2.5 mM MeJA and 5 mM GABA after 30 days was among the combinations with the lowest weight loss. Conversely, the untreated MeJA–GABA combination after 120 days recorded the greatest numerical loss, 4.57%. The overall pattern indicates that treatment concentration and exposure time in storage should be considered together when evaluating the practical value of the dipping treatments.

**Table 2.** *Effect of methyl jasmonate (MeJA), $\gamma$-aminobutyric acid (GABA), storage periods, and their interactions on fruit weight loss (%) of Granny Smith apples stored at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | Storage period | | | MeJA × GABA | MeJA mean |
|---|---|---|---|---|---|---|
| | | 30 days | 60 days | 120 days | | |
| 0 | 0 | 1.77 o-s | 3.06 g-i | 4.57 a | 3.13 a | 2.85 a |
| | 5 | 1.37 s-w | 2.37 j-n | 4.01 b-d | 2.59 c | |
| | 10 | 1.50 q-v | 2.49 j-m | 4.13 a-c | 2.71 bc | |
| | 15 | 1.63 o-t | 2.81 h-j | 4.47 ab | 2.97 ab | |
| 0.75 | 0 | 1.49 q-v | 2.38 j-n | 3.92 c-e | 2.59 c | 2.62 b |
| | 5 | 1.57 p-u | 2.55 j-l | 4.19 a-c | 2.77 bc | |
| | 10 | 1.69 o-s | 2.63 ij | 4.28 a-c | 2.87 b | |
| | 15 | 1.36 s-w | 2.04 m-p | 3.39 fg | 2.27 d | |
| 1.5 | 0 | 1.14 t-x | 2.14 k-o | 3.57 d-f | 2.28 d | 2.16 c |
| | 5 | 1.08 u-x | 2.07 l-p | 3.50 e-g | 2.22 de | |
| | 10 | 0.98 wx | 1.82 o-s | 3.08 g-i | 1.96 e | |
| | 15 | 1.06 v-x | 2.01 m-p | 3.45 fg | 2.17 de | |
| 2.5 | 0 | 1.01 v-x | 1.88 n-r | 3.24 f-h | 2.04 de | 1.95 d |
| | 5 | 0.83 x | 1.45 r-w | 2.58 jk | 1.62 f | |
| | 10 | 0.98 wx | 1.98 n-q | 3.18 f-h | 2.05 de | |
| | 15 | 1.07 v-x | 1.92 n-r | 3.32 fg | 2.11 de | |
| Storage-period mean | | 1.28 c | 2.23 b | 3.68 a | GABA mean | |
| MeJA*Storage period | 0 | 1.57 h | 2.68 e | 4.29 a | | |
| | 0.75 | 1.53 h | 2.40 f | 3.95 b | | |
| | 1.5 | 1.07 i | 2.01 g | 3.40 c | | |
| | 2.5 | 0.97 i | 1.81 g | 3.08 d | | |
| GABA*Storage period | 0 | 1.35 e | 2.36 c | 3.82 a | 2.51 a | |
| | 5 | 1.21 e | 2.11 d | 3.57 b | 2.30 b | |
| | 10 | 1.29 e | 2.23 cd | 3.67 ab | 2.39 ab | |
| | 15 | 1.28 e | 2.20 cd | 3.66 ab | 2.38 b | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The pattern in Table 2 suggests that the principal benefit of the treatments was a reduction in accumulated loss. Initial fruit mass, bag perforation, and storage humidity remain relevant when translating these percentages to another storage system.

### 3.3. ASCORBIC ACID CONTENT

The results in Table 3 show that 2.5 mM MeJA produced a significantly greater mean ascorbic acid content than the untreated MeJA level, whereas the intermediate concentrations shared significance letters with both groups. GABA at 10 mM produced the highest main-effect mean and differed from the other GABA levels. The storage response was not a continuous decrease: mean ascorbic acid content increased from 1.12 mg per 100 mL after 30 days to 1.38 mg per 100 mL after 60 days, before decreasing to 1.01 mg per 100 mL after 120 days. This distinction is necessary when describing the temporal response in the abstract and conclusion.

MeJA can influence ascorbate accumulation through changes in biosynthetic regulation. Wolucka et al. [33] demonstrated stimulation of vitamin C biosynthesis in plant cell suspensions, although this experimental system differs from stored apple fruit. GABA-associated enhancement of antioxidant-system activity has also been reported in cornelian cherries [34]. Such findings offer plausible explanations involving biosynthesis, recycling, and oxidative consumption, but the present measurements do not identify which of these processes determined the apple response. In particular, ascorbate peroxidase, glutathione reductase, and ascorbate oxidase were not measured, and their activities should not be presented as observed mechanisms.

The combination of 2.5 mM MeJA and 15 mM GABA after 60 days was among the combinations with the greatest ascorbic acid content. Untreated fruit after 30 and 120 days both recorded 0.79 mg per 100 mL, the lowest numerical values in the table. These findings suggest that treatment effects interacted with the stage of storage, rather than producing an identical degree of preservation at every sampling interval.

**Table 3.** *Effect of methyl jasmonate (MeJA), $\gamma$-aminobutyric acid (GABA), storage periods, and their interactions on ascorbic acid content (mg per 100 mL of juice) of Granny Smith apples stored at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | Storage period | | | MeJA × GABA | MeJA mean |
|---|---|---|---|---|---|---|
| | | 30 days | 60 days | 120 days | | |
| 0 | 0 | 0.79 g | 1.01 d-g | 0.79 g | 0.86 c | 1.12 b |
| | 5 | 1.08 c-g | 1.37 a-c | 1.01 d-g | 1.15 ab | |
| | 10 | 1.37 a-c | 1.44 ab | 1.08 c-g | 1.30 a | |
| | 15 | 1.08 c-g | 1.30 a-d | 1.08 c-g | 1.15 ab | |
| 0.75 | 0 | 1.08 c-g | 1.37 a-c | 0.94 e-g | 1.13 ab | 1.17 ab |
| | 5 | 1.08 c-g | 1.37 a-c | 1.08 c-g | 1.18 ab | |
| | 10 | 1.15 b-f | 1.44 ab | 1.08 c-g | 1.22 ab | |
| | 15 | 1.15 b-f | 1.37 a-c | 0.94 e-g | 1.15 ab | |
| 1.5 | 0 | 1.15 b-f | 1.44 ab | 1.08 c-g | 1.22 ab | 1.18 ab |
| | 5 | 1.01 d-g | 1.37 a-c | 0.86 fg | 1.08 b | |
| | 10 | 1.22 a-e | 1.44 ab | 1.15 b-f | 1.27 a | |
| | 15 | 1.08 c-g | 1.37 a-c | 0.94 e-g | 1.13 ab | |
| 2.5 | 0 | 1.22 a-e | 1.44 ab | 1.15 b-f | 1.27 a | 1.22 a |
| | 5 | 1.15 b-f | 1.37 a-c | 0.86 fg | 1.13 ab | |
| | 10 | 1.15 b-f | 1.44 ab | 1.08 c-g | 1.22 ab | |
| | 15 | 1.15 b-f | 1.51 a | 1.08 c-g | 1.25 ab | |
| Storage-period mean | | 1.12 b | 1.38 a | 1.01 c | GABA mean | |
| MeJA*Storage period | 0 | 1.08 de | 1.28 bc | 0.99 e | | |
| | 0.75 | 1.12 de | 1.39 ab | 1.01 e | | |
| | 1.5 | 1.12 de | 1.40 ab | 1.01 e | | |
| | 2.5 | 1.17 cd | 1.44 a | 1.04 de | | |
| GABA*Storage period | 0 | 1.06 de | 1.31 ab | 0.99 de | 1.12 b | |
| | 5 | 1.08 c-e | 1.37 a | 0.95 e | 1.13 b | |
| | 10 | 1.22 bc | 1.44 a | 1.10 c-e | 1.25 a | |
| | 15 | 1.12 cd | 1.39 a | 1.01 de | 1.17 b | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The temporal pattern in Table 3 demonstrates that sampling time materially affects the apparent ascorbic acid response. A result measured at 60 days should not be presented as the concentration retained at the end of storage.

### 3.4. TOTAL SOLUBLE SOLIDS

The main-effect means in Table 4 indicate that all MeJA and GABA levels shared the same significance letter for total soluble solids. Consequently, the numerical decreases associated with treatment cannot be described as statistically significant main effects. In contrast, the storage-period means increased significantly from 13.94% after 30 days to 14.52%

after 60 days and 15.56% after 120 days. This result identifies storage duration as the clearest source of variation in the reported marginal means for this quality attribute.

The concentration of soluble solids can rise through the conversion of starch into soluble sugars and through the concentration effect of water loss. Treatment-related changes may also reflect altered ripening and respiratory metabolism. GABA treatment maintained lower soluble solids in ripening mangoes in the study by Al-Qurashi and Awad [31]. Research on GABA-coated pomegranates provides evidence from a different treatment system, but a coating should not be assumed to have formed on the apples in the present experiment because only dipping solutions were described [35]. Accordingly, oxygen-barrier formation and modification of the internal atmosphere are not established explanations for these results.

Studies of MeJA-treated grapes and GABA-treated mangoes likewise show that soluble-solids responses must be interpreted with regard to fruit type, ripening stage, and storage conditions [36, 37]. Research on Fuji apples also demonstrates that MeJA can affect physicochemical quality, but this does not imply that every concentration causes the same response in Granny Smith apples [38]. The combination of 2.5 mM MeJA and 15 mM GABA after 30 days was among the combinations with the lowest soluble-solids values, whereas the untreated combination after 120 days recorded 16.00%, the greatest numerical value. These individual comparisons should be distinguished from the non-significant treatment main effects.

**Table 4.** *Effect of methyl jasmonate (MeJA), γ-aminobutyric acid (GABA), storage periods, and their interactions on total soluble solids (%) of Granny Smith apples stored at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | Storage period | | | MeJA × GABA | MeJA mean |
|---|---|---|---|---|---|---|
| | | 30 days | 60 days | 120 days | | |
| 0 | 0 | 14.67 b-e | 15.00 a-d | 16.00 a | 15.22 a | 14.81 a |
| | 5 | 13.67 ef | 14.33 c-f | 15.67 ab | 14.56 b | |
| | 10 | 13.67 ef | 14.67 b-e | 15.67 ab | 14.67 ab | |
| | 15 | 14.00 d-f | 14.67 b-e | 15.67 ab | 14.78 ab | |
| 0.75 | 0 | 14.00 d-f | 14.33 c-f | 15.33 a-c | 14.56 b | 14.67 a |
| | 5 | 13.67 ef | 14.67 b-e | 15.67 ab | 14.67 ab | |
| | 10 | 13.67 ef | 14.67 b-e | 15.67 ab | 14.67 ab | |
| | 15 | 14.00 d-f | 14.67 b-e | 15.67 ab | 14.78 ab | |
| 1.5 | 0 | 14.00 d-f | 14.33 c-f | 15.33 a-c | 14.56 b | 14.69 a |
| | 5 | 14.00 d-f | 14.67 b-e | 15.67 ab | 14.78 ab | |
| | 10 | 13.67 ef | 14.67 b-e | 15.67 ab | 14.67 ab | |
| | 15 | 14.33 c-f | 14.67 b-e | 15.33 a-c | 14.78 ab | |
| 2.5 | 0 | 14.33 c-f | 14.33 c-f | 15.33 a-c | 14.67 ab | 14.53 a |
| | 5 | 14.00 d-f | 14.33 c-f | 15.33 a-c | 14.56 b | |
| | 10 | 14.00 d-f | 14.33 c-f | 15.33 a-c | 14.56 b | |
| | 15 | 13.33 f | 14.00 d-f | 15.67 ab | 14.33 b | |
| Storage-period mean | | 13.94 c | 14.52 b | 15.56 a | GABA mean | |
| MeJA*Storage period | 0 | 14.00 c | 14.67 b | 15.75 a | | |
| | 0.75 | 13.83 c | 14.58 b | 15.58 a | | |
| | 1.5 | 14.00 c | 14.58 b | 15.50 a | | |
| | 2.5 | 13.92 c | 14.25 bc | 15.42 a | | |
| GABA*Storage period | 0 | 14.25 bc | 14.50 b | 15.50 a | 14.75 a | |
| | 5 | 13.83 c | 14.50 b | 15.58 a | 14.64 a | |
| | 10 | 13.75 c | 14.58 b | 15.58 a | 14.64 a | |
| | 15 | 13.92 c | 14.50 b | 15.58 a | 14.67 a | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The comparisons in Table 4 distinguish a clear storage-related increase from non-significant treatment main effects. Lower soluble-solids values should also be interpreted alongside acidity and texture rather than treated automatically as an improvement in eating quality.

## 3.5. TITRATABLE ACIDITY

The data in Table 5 show numerically greater MeJA main-effect means at 1.5 and 2.5 mM than at 0 mM, but all four MeJA means share the letter a. Thus, the reported mean-separation results do not support a statistically significant MeJA main effect on titratable acidity. For GABA, the 5 and 15 mM means differed significantly from the untreated mean, whereas 10 mM shared letters with both groups. Mean acidity decreased significantly with storage duration, from 0.412% after 30 days to 0.388% after 60 days and 0.344% after 120 days.

Maintenance of organic acids can contribute to the retention of characteristic apple flavour during storage. MeJA-

treated Nanguo pears retained higher titratable acidity in research linking quality preservation with energy metabolism [5]. In apples, Han et al. [17] reported that GABA altered malate-related metabolism and ethylene synthesis. Their findings support a possible relationship between GABA and the balance of acid synthesis and degradation, rather than the contradictory suggestion that greater respiratory consumption itself causes acid preservation. The respiratory use of organic acids generally contributes to their depletion as stored fruit continue to ripen and senesce.

Related research on stored pomegranates and GABA-treated persimmons provides useful comparisons for storage-associated changes in quality [39, 40]. However, those species and treatment conditions differ from those of the present experiment. The 2.5 mM MeJA–15 mM GABA combination after 30 days was among the combinations with the greatest titratable acidity, while untreated fruit after 120 days had the lowest numerical value, 0.326%. The individual combination results therefore support qualified treatment comparisons without overriding the non-significant MeJA marginal comparison.

**Table 5.** *Effect of methyl jasmonate (MeJA), γ-aminobutyric acid (GABA), storage periods, and their interactions on titratable acidity (%) of Granny Smith apples stored at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | Storage period | | | MeJA × GABA | MeJA mean |
|---|---|---|---|---|---|---|
| | | 30 days | 60 days | 120 days | | |
| 0 | 0 | 0.402 a-e | 0.362 fg | 0.326 h | 0.363 c | 0.377 a |
| | 5 | 0.420 ab | 0.398 a-e | 0.344 gh | 0.387 ab | |
| | 10 | 0.411 a-d | 0.380 ef | 0.344 gh | 0.378 bc | |
| | 15 | 0.415 a-c | 0.384 d-f | 0.344 gh | 0.381 ab | |
| 0.75 | 0 | 0.411 a-d | 0.384 d-f | 0.335 gh | 0.377 bc | 0.380 a |
| | 5 | 0.406 a-e | 0.384 d-f | 0.362 fg | 0.384 ab | |
| | 10 | 0.411 a-d | 0.384 d-f | 0.348 gh | 0.381 ab | |
| | 15 | 0.406 a-e | 0.389 c-f | 0.335 gh | 0.377 bc | |
| 1.5 | 0 | 0.411 a-d | 0.398 a-e | 0.344 g-h | 0.384 ab | 0.385 a |
| | 5 | 0.415 a-c | 0.389 c-f | 0.335 gh | 0.380 ab | |
| | 10 | 0.415 a-c | 0.402 a-e | 0.348 gh | 0.389 ab | |
| | 15 | 0.415 a-c | 0.393 b-e | 0.348 gh | 0.386 ab | |
| 2.5 | 0 | 0.415 a-c | 0.384 d-f | 0.335 gh | 0.378 bc | 0.385 a |
| | 5 | 0.411 a-d | 0.393 b-e | 0.348 gh | 0.384 ab | |
| | 10 | 0.406 a-e | 0.389 c-f | 0.344 gh | 0.380 ab | |
| | 15 | 0.424 a | 0.402 a-e | 0.362 fg | 0.396 a | |
| Storage-period mean | | 0.412 a | 0.388 b | 0.344 c | GABA mean | |
| MeJA*Storage period | 0 | 0.412 a | 0.381 c | 0.339 d | | |
| | 0.75 | 0.409 a | 0.385 bc | 0.345 d | | |
| | 1.5 | 0.414 a | 0.395 b | 0.344 d | | |
| | 2.5 | 0.414 a | 0.392 bc | 0.347 d | | |
| GABA*Storage period | 0 | 0.410 a | 0.382 b | 0.335 c | 0.376 b | |
| | 5 | 0.413 a | 0.391 b | 0.347 c | 0.384 a | |
| | 10 | 0.411 a | 0.389 b | 0.346 c | 0.382 ab | |
| | 15 | 0.415 a | 0.392 b | 0.347 c | 0.385 a | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The results in Table 5 support acidity preservation for selected GABA comparisons, while the MeJA marginal differences remain numerical. This distinction prevents the conclusion from overstating the evidence supplied by the original mean-separation test.

## 3.6. TOTAL PHENOLIC CONTENT

The results in Table 6 indicate small numerical increases in total phenolic content across the MeJA treatments, but all MeJA main-effect means share the same significance letter. The GABA main-effect means also share the same letter, including the numerically greatest mean at 15 mM. These main effects therefore cannot be described as statistically significant. The storage-period mean at 60 days, 5.23 mg per 100 g of juice, was greater than the 30-day mean of 5.02 mg per 100 g, whereas the 120-day mean of 5.08 mg per 100 g shared significance letters with both intervals.

Jasmonates can affect secondary metabolism and the accumulation of phenolic compounds, as discussed by Asghari [8]. GABA-associated quality responses in persimmons have also been studied in relation to cold-storage stress [40]. Accumulation of phenolics under temperature stress has been reported in tomato and watermelon plants [41], while research on citrus fruit identified relationships between phenylalanine ammonia-lyase, antioxidant enzymes, and chilling tolerance [42]. These comparisons suggest possible stress-response pathways, but neither phenylalanine ammonia-lyase

nor polyphenol oxidase was measured in the present apples. Consequently, increased synthesis and reduced oxidation remain possible explanations rather than experimentally demonstrated causes.

A more directly relevant postharvest comparison is the study by Supapvanich et al. [43], which evaluated hot-water and MeJA immersion in guava fruit and reported changes in quality and bioactive compounds. The guava findings provide a crop-specific comparison, although the additional hot-water treatment and different storage conditions limit direct extrapolation to apples. In the present dataset, 0.75 mM MeJA with 15 mM GABA after 120 days produced the highest numerical phenolic content, while 0.75 mM MeJA without GABA at the same interval produced the lowest numerical value. The significance groupings indicate that not every numerical difference between combinations was significant.

**Table 6.** *Effect of methyl jasmonate (MeJA), γ-aminobutyric acid (GABA), storage periods, and their interactions on total phenolic content (mg per 100 g of juice) of Granny Smith apples stored at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | Storage period | | | MeJA × GABA | MeJA mean |
|---|---|---|---|---|---|---|
| | | 30 days | 60 days | 120 days | | |
| 0 | 0 | 5.00 b | 5.20 b | 4.97 b | 5.06 b | 5.06 a |
| | 5 | 5.02 b | 5.23 b | 4.98 b | 5.08 b | |
| | 10 | 4.98 b | 5.20 b | 4.94 b | 5.04 b | |
| | 15 | 5.01 b | 5.23 b | 4.97 b | 5.07 b | |
| 0.75 | 0 | 4.92 b | 5.14 b | 4.88 b | 4.98 b | 5.13 a |
| | 5 | 4.95 b | 5.16 b | 4.90 b | 5.00 b | |
| | 10 | 4.95 b | 5.16 b | 4.90 b | 5.00 b | |
| | 15 | 4.94 b | 5.15 b | 6.52 a | 5.53 a | |
| 1.5 | 0 | 5.05 b | 5.23 b | 5.00 b | 5.09 ab | 5.11 a |
| | 5 | 5.07 b | 5.27 b | 5.03 b | 5.12 ab | |
| | 10 | 5.07 b | 5.29 b | 5.02 b | 5.13 ab | |
| | 15 | 5.05 b | 5.27 b | 4.95 b | 5.09 ab | |
| 2.5 | 0 | 5.08 b | 5.27 b | 5.03 b | 5.13 ab | 5.15 a |
| | 5 | 5.09 b | 5.31 b | 5.06 b | 5.15 ab | |
| | 10 | 5.10 b | 5.31 b | 5.03 b | 5.15 ab | |
| | 15 | 5.09 b | 5.30 b | 5.08 b | 5.16 ab | |
| Storage-period mean | | 5.02 b | 5.23 a | 5.08 ab | GABA mean | |
| MeJA*Storage period | 0 | 4.94 a | 5.15 a | 5.30 a | | |
| | 0.75 | 5.00 a | 5.22 a | 4.96 a | | |
| | 1.5 | 5.06 a | 5.27 a | 5.00 a | | |
| | 2.5 | 5.09 a | 5.30 a | 5.05 a | | |
| GABA*Storage period | 0 | 5.01 ab | 5.21 ab | 4.97 b | 5.06 a | |
| | 5 | 5.03 ab | 5.24 ab | 4.99 ab | 5.09 a | |
| | 10 | 5.02 ab | 5.24 ab | 4.97 b | 5.08 a | |
| | 15 | 5.02 ab | 5.24 ab | 5.38 a | 5.21 a | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The pattern in Table 6 is consistent with a variable phenolic response across combinations and storage intervals. It does not support claiming that either compound uniformly increased phenolic content throughout the experiment.

## 3.7. SUPEROXIDE DISMUTASE ACTIVITY

The results in Table 7 describe superoxide dismutase activity after 120 days of storage. MeJA at 1.5 and 2.5 mM produced main-effect means in the highest significance group, with both exceeding the untreated MeJA mean. Although 1.5 mM gave the greatest numerical mean, it was not significantly different from 2.5 mM. For GABA, 5 mM produced a greater mean than 0 and 15 mM, while the 10 mM mean shared letters with both significance groups. These comparisons indicate that the enzyme response did not simply increase in direct proportion to GABA concentration.

MeJA-associated changes in antioxidant defence have been discussed for postharvest fruit [10], and GABA-related antioxidant responses have been reported in mangoes [37]. Chen et al. [12] also observed increased antioxidant and defence enzyme activities in treated pear fruit. These findings support the interpretation that antioxidant regulation may contribute to quality preservation. However, enzyme activity alone does not establish increased expression of particular apple genes, greater endogenous proline accumulation, or enhanced membrane integrity, because those variables were not measured here. The present evidence is limited to the reported activity assay and its treatment comparisons.

The combination of 1.5 mM MeJA and 10 mM GABA produced the greatest numerical activity, 10.89 in the reported units, while the untreated MeJA–GABA combination produced the lowest value, 6.21. The former shared a significance letter with the 2.5 mM MeJA–5 mM GABA combination. Therefore, the results identify a group of strongly responding

combinations rather than a uniquely superior treatment for every enzyme-related comparison.

**Table 7.** *Effect of methyl jasmonate (MeJA), γ-aminobutyric acid (GABA), and their interactions on superoxide dismutase activity (*$\mathrm{unit\,min^{-1}\,mg^{-1}}$*) of Granny Smith apples stored for 120 days at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | | | | MeJA mean |
|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | |
| 0 | 6.21 f | 7.16 e | 7.26 e | 7.60 e | 7.06 c |
| 0.75 | 9.90 bc | 9.08 cd | 7.57 e | 7.80 e | 8.59 b |
| 1.5 | 7.71 e | 9.89 bc | 10.89 a | 9.49 b-d | 9.49 a |
| 2.5 | 9.17 b-d | 10.10 ab | 8.81 d | 9.05 cd | 9.28 a |
| GABA mean | 8.24 b | 9.06 a | 8.63 ab | 8.49 b | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The endpoint comparison in Table 7 supports a treatment-associated antioxidant response after prolonged storage. Because earlier enzyme measurements are not supplied, it does not establish the trajectory of superoxide dismutase activity between 30 and 120 days.

## 3.8. CATALASE ACTIVITY

The findings in Table 8 show that catalase activity after 120 days was numerically greatest at 2.5 mM MeJA. This main-effect mean differed from 0 and 0.75 mM but shared a significance letter with 1.5 mM. GABA at 15 mM produced a greater main-effect mean than the untreated level, while the 5 and 10 mM means shared letters with both groups. Consequently, these results support increased catalase activity for selected comparisons without establishing significant differences among all adjacent treatment concentrations.

Wang et al. [44] reported changes in antioxidant constituents and antioxidant enzyme activities following MeJA treatment of blueberry fruit. GABA-associated enhancement of antioxidant-system activity was also reported in cornelian cherries [34], and work on apples examined the relationships between GABA treatment, reactive oxygen species metabolism, and disease resistance [18]. Together, these studies provide a plausible context in which maintained catalase activity could assist hydrogen peroxide detoxification. Nevertheless, the present experiment did not measure reactive oxygen species concentration, membrane lipid peroxidation, or disease incidence, so improved activity cannot be equated directly with demonstrated protection against those outcomes.

The combination of 2.5 mM MeJA and 15 mM GABA produced the highest numerical catalase activity, 10.50 in the reported units. The combination of 0 mM MeJA and 15 mM GABA produced the lowest numerical value, 8.03. Several other combinations shared letters with the highest value, which limits claims of unique superiority. The contrast between the GABA marginal mean and individual combinations also emphasizes that a concentration giving a favourable average response may perform differently depending on the accompanying MeJA treatment.

**Table 8.** *Effect of methyl jasmonate (MeJA), γ-aminobutyric acid (GABA), and their interactions on catalase activity (*$\mathrm{mmol\,min^{-1}\,mg^{-1}}$*) of Granny Smith apples stored for 120 days at* $1 \pm 1\,^{\circ}\mathrm{C}$.

| MeJA (mM) | GABA (mM) | | | | MeJA mean |
|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | |
| 0 | 8.46 ef | 8.86 c-f | 8.87 c-f | 8.03 f | 8.55 c |
| 0.75 | 8.93 c-f | 9.64 a-d | 8.61 d-f | 9.75 a-c | 9.23 b |
| 1.5 | 9.22 b-e | 9.10 b-e | 9.09 b-e | 10.03 ab | 9.36 ab |
| 2.5 | 9.43 b-e | 9.15 b-e | 9.92 a-c | 10.50 a | 9.75 a |
| GABA mean | 9.01 b | 9.19 ab | 9.12 ab | 9.57 a | |

Within the relevant main-effect or interaction comparison, means sharing one or more letters are not significantly different according to Duncan's multiple range test at $P = 0.05$. Numerical values and significance letters are retained as reported.

The endpoint results in Table 8, considered together with Table 7, indicate that the most responsive treatment combination differed between catalase and superoxide dismutase. A single optimum for all antioxidant measurements is therefore not established.

## 3.9. SCOPE OF THE FINDINGS

The reported data support treatment-related differences in selected quality attributes, but they do not establish an optimum that is simultaneously superior for every response. Firmness, weight loss, acidity, ascorbic acid, soluble solids, phenolic content, and antioxidant enzymes represent complementary aspects of quality. In particular, the non-significant main effects for soluble solids and phenolics should remain visible when the overall performance of the treatments is

evaluated. The endpoint enzyme measurements provide additional information after 120 days, but they cannot substitute for measurements of chilling injury, decay, sensory acceptability, or commercial shelf life after removal from cold storage.

The interpretation is also limited by details absent from the supplied experimental record, including experimental-unit size, the exact procedure used for combined treatments, and the normalization of enzyme activity. The interpretation is based on the reported means and their significance groupings, with three replicates per treatment. Additional methodological information is necessary to assess reproducibility and to distinguish variation among fruit, experimental units, and storage intervals. Independent confirmation of the treatment procedure and statistical analysis is needed before recommending a particular combination for commercial practice. Subsequent studies should include these methodological details and evaluate whether the observed differences remain useful across harvest seasons, orchards, and post-storage marketing conditions.

## 4. CONCLUSION

Postharvest MeJA and GABA dipping treatments were associated with preservation of selected quality attributes of Granny Smith apples during cold storage. The clearest MeJA responses were greater firmness, lower weight loss, and improved ascorbic acid retention at the highest concentration, together with increased antioxidant enzyme activities at the 120-day endpoint. GABA responses depended on concentration and quality attribute: treated fruit maintained greater firmness, while particular concentrations reduced weight loss or maintained acidity and ascorbic acid. Main effects on total soluble solids and total phenolic content were not significant according to the reported mean-separation results, and the MeJA main effect on titratable acidity was also non-significant. Storage duration remained influential, with progressive softening, increasing weight loss, declining acidity, and increasing soluble solids. These findings support further evaluation of MeJA and GABA as postharvest dipping treatments, while indicating that a universally superior combination and a commercial recommendation cannot be established from the reported measurements alone.

**Acknowledgments**

The first author expresses sincere gratitude to the supervisor, Prof. Dr. Sarfaraz Fatah Ali Al-Bamarny, for the guidance, encouragement, and support throughout this study. Appreciation is also extended to the College of Agricultural Engineering Sciences at the University of Duhok for providing the facilities and assistance necessary to conduct the research. The first author is grateful to the family for their patience, understanding, and continued encouragement during the completion of this work.

**Author Contributions**

All authors contributed equally to this study, read and approved the final manuscript, and agreed to its submission for publication.

**Conflict Of Interest**

The authors declare no conflicts of interest related to this research.

**Data Availability Statement**

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

**Funding Information**

This research received no external funding from public, commercial, or nonprofit funding agencies.

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