

Dynamics of mineral nutrients in apple fruit cultivars during cold storage

Dinamika mineralnih hranljivih materija u sortama jabuke tokom čuvanja u hladnjači

Boris RILAK¹ (✉), Žaklina KARAKLAJIĆ-STAJIĆ¹, Mira MILINKOVIĆ², Ivan P. GLIŠIĆ³, Jelena TOMIĆ¹, Svetlana M. PAUNOVIĆ¹, Tatjana ANĐELIĆ¹

¹ Fruit Research Institute, Department for Technology of Fruit Growing, Kralja Petra I 9, Čačak, Republic of Serbia

² Institute of Soil Science, Teodora Drajzera 7, 11000 Belgrade, Republic of Serbia

³ University of Kragujevac, Faculty of Agronomy, Čačak, Republic of Serbia

✉ Corresponding author: brilak@institut-cacak.org

Received: July 3, 2025; accepted: February 15, 2026

ABSTRACT

Apples are widely consumed and rich in phytochemicals beneficial to human health. This study examines changes in mineral content of five apple cultivars ('Golden Delicious Reinders', 'Red Chief', 'Granny Smith', 'Gloster', and 'Morren's Jonagored') during cold storage. Mineral compositions, including macro- [calcium (Ca), potassium (K), and magnesium (Mg)], and microelements [cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), chromium (Cr), nickel (Ni), zinc (Zn), and lead (Pb)], were determined using atomic absorption spectrophotometry during harvest and different periods of cold storage, which is the dominant storage method in Serbia. The content of K, Ca, and Mg followed a regular accumulation pattern, with the highest levels observed after 120 days of storage. Cultivar/year interactions significantly affected the K/Ca and K+Mg/Ca ratios. Cu and Fe concentrations were highest in 'Gloster' at harvest, while the lowest levels were found after 120 days of storage in the second year and in 'Granny Smith', respectively. Zn levels were highest in 'Morrens Jonagored' after 60 days, and Mn peaked in 'Gloster'. Pb concentrations increased during storage across all cultivars. This highlights the importance of monitoring nutrient levels to prevent quality issues during storage.

Keywords: apple fruit, mineral nutrition, storage physiology, K/Ca ratio, fruit quality

ABSTRAKT

Jabuka je široko konzumirano voće bogato fitohemikalijama koje imaju povoljan uticaj na ljudsko zdravlje. U ovoj studiji proučavane su promene u mineralnom sastavu ploda pet sorti jabuke ('Golden Delicious Reinders', 'Red Chief', 'Granny Smith', 'Gloster' i 'Morren's Jonagored') tokom čuvanja u hladnjači. Mineralni sastav, koji podrazumeva sadržaj makroelemenata [kalcijum (Ca), kalijum (K) i magnezijum (Mg)] i mikroelemenata [kobalt (Co), bakar (Cu), gvožđe (Fe), mangan (Mn), hrom (Cr), nikl (Ni), cink (Zn) i olovo (Pb)], određivan je pomoću atomske apsorpcione spektrofotometrije u vreme berbe i tokom različitih perioda skladištenja u hladnjači, kao dominantnog načina čuvanja u Srbiji. Sadržaji K, Ca i Mg odlikovali su se utvrđenim obrazcem akumulacije, a najviše vrednosti zabeležene su nakon 120 dana čuvanja. Interakcijski efekat sorte i godine značajno je uticao na odnose K/Ca i (K+Mg)/Ca. Najviše koncentracije Cu i Fe utvrđene su kod sorti 'Gloster' pri berbi, a najniži nivoi zabeleženi su u drugoj godini posle 120 dana čuvanja kod sorte 'Granny Smith'. U pogledu Zn najviša koncentracija utvrđena je kod sorte 'Morren's Jonagored' nakon 60 dana, a Mn kod sorte jabuke 'Gloster'. Koncentracije Pb povećavale su se tokom perioda skladištenja kod svih ispitivanih sorti jabuke. Dobijeni rezultati ukazuju na značaj utvrđivanja dinamike hranljivih materija u plodu jabuke u cilju prevencije lošijeg kvaliteta tokom skladištenja u hladnjači.

Ključne reči: jabuka, mineralna ishrana, fiziologija čuvanja, odnos K/Ca, kvalitet ploda

INTRODUCTION

In 2020, apples (*Malus × domestica* Borkh.) ranked as the third most-produced fruit globally, with an annual production of 86.4 million tons (Shahbandeh, 2022). With an average consumption of approximately 13 kg per person annually, apples are highly popular in Europe (AMI, 2021). Apples are recognized for their strong nutritional profile, contributing to increasing awareness of their health benefits (Ferreira and Ribeiro, 2024). In the EU, major apple producers include Poland, Italy, France, and Germany, with dominant cultivars such as 'Golden Delicious' (21%), 'Gala' (11%), and 'Idared' (9%) (Jakobek et al., 2020). In Serbia, common cultivars include 'Idared', 'Gala', 'Golden Delicious', 'Red Delicious', 'Jonagold', 'Braeburn', 'Granny Smith', and 'Fuji' (Magazin et al., 2022).

Minerals, both macronutrients and micronutrients, are crucial for human health, supporting various biological functions (Acham et al., 2018). Deficiencies in these minerals can lead to organ damage, metabolic imbalances, and even fatal outcomes (Cozma et al., 2022). Fruits, including apples, play an essential role in human nutrition by providing beneficial phytochemicals and vital minerals (Rehman et al., 2014). Apples are rich in essential nutrients, contributing to the reduction of chronic diseases and obesity (Mozaffarian, 2016), and serve as a significant source of minerals for human health.

When purchasing fruit, consumers initially assess external qualities such as size, shape, and color. Internal qualities, such as flesh texture and flavor, are evaluated post-purchase, influencing future decisions, particularly when linked to health benefits (Musacchi and Serra, 2018). Mineral composition, along with other metabolites, is a significant factor in the chemical quality of fruit, affecting both its preservation and its health benefits. The human body requires approximately 20 essential minerals, divided into macrominerals (needed in quantities over 100 mg per day) and microminerals (required in smaller amounts). Both are essential for maintaining physiological functions (Spada et al., 2010). These nutrients support vital processes like hematopoiesis, tissue

respiration, immune reactions, and reproduction (Struk et al., 2024). Previous studies on apples have focused on their chemical composition, including macronutrients, micronutrients, and bioactive compounds, as well as their postharvest physiology and storage behavior. Research has also investigated the effects of cultivar, growing conditions, and storage methods on fruit quality, shelf life, and nutritional value (Nachtigall and Dechen, 2006; Nour et al., 2010; Gago et al., 2016; Skordas et al., 2018). Despite these studies, there is limited information on the combined effects of cultivar, growing year, and storage period on both macro- and microelement content in apple fruit, particularly in Serbian apple cultivars. This gap highlights the need for comprehensive studies like the present work. Apples are integral to many diets and offer therapeutic benefits, such as promoting gastric secretion and absorption, toxin elimination, and a diuretic effect. The World Health Organization (WHO, 2003) recommends a daily intake of 400 g of fresh fruits and vegetables to prevent non-communicable diseases, including cardiovascular diseases and certain cancers. The nutrient content of fruit is influenced by factors such as soil mineral composition, irrigation water quality, weather, agricultural practices, and cultivar type (Turra et al., 2011). However, limited data exist on the dynamics of mineral content in apples during cold storage.

The main objective of this study was to evaluate the effects of cultivar, growing year, and storage period on the macro- (Ca, K, Mg) and microelement (Co, Cu, Fe, Mn, Cr, Ni, Zn, Pb) composition of apple fruit. A secondary objective was to calculate the K/Ca, K+Mg/Ca, and Ca/Mg ratios to assess their potential impact on post-harvest fruit quality and storage stability.

MATERIAL AND METHODS

Plant material and experimental design

The investigation was conducted over a two-year period (2019–2020) in the experimental trial of five apple cultivars ('Golden Delicious Reinders', 'Red Chief', 'Granny Smith', 'Gloster', and 'Morren's Jonagored') all grafted onto M9 rootstock. The orchard was established in

2006 and is located at Donja Trepča (43° 53' N latitude, 20° 25' E longitude, 223 m altitude) near Čačak, Western Serbia. Trees were planted at a density of 2,000 trees per hectare with a spacing of 4 × 1.25 m, except for 'Red Chief', which was planted at a higher density of 2,500 trees per hectare with a spacing of 4 × 1.0 m and trained using the spindle bush system. Soil management followed integrated production principles, including grass cover between rows and weed-free zones within rows. Disease and pest control adhered to standard protocols recommended for commercial apple orchards. According to records from the Republic Hydrometeorological Service of Serbia, the weather conditions in Čačak, both for the experimental years, were characterized by a mean growing season temperature of 16.05 °C and total rainfall of 80.55 mm (Table 1).

The soil in the apple orchard was classified as vertisol, with a moderate organic matter content of 2.92% and nitrogen (N) content of 0.18%. The soil exhibited a slightly acidic reaction, with pH values measured in KCl 0.01 mol/L. The available phosphorus (P) content was sufficient, at 21.26 mg/100 g, while the available potassium (K) was high, at 45.40 mg/100 g. These soil characteristics satisfy the agro-environmental requirements for

apple cultivation as described by Kljajić et al. (2023). The experiment was conducted using a randomized block design with four replications per treatment. Specific protective measures were applied to all apple trees according to national and international standards (Magazin et al., 2022; Rilak et al., 2023). Fertilization, pruning, and irrigation were conducted according to cultivar-specific recommendations.

Treatments

The study was conducted using a three-factor factorial experimental design with the following factors: apple cultivar ('Golden Delicious Reinders', 'Red Chief', 'Granny Smith', 'Gloster', and 'Morrens Jonagored'), year of study (2018 and 2019), and storage period (0, 60, and 120 days). After harvest, apple fruits were transported to the laboratory of the Fruit Research Institute, Čačak, and randomly assigned to three storage treatments: 1) immediate analysis at harvest, 2) cold storage for 60 days, and 3) cold storage for 120 days. Data were analyzed using three-way ANOVA to evaluate the effects of individual factors and their interactions on fruit mineral composition and quality parameters.

Table 1. Mean monthly growing season temperatures and rainfall in Čačak (2019–2020)

Month	Air temperature (°C)			Rainfall (mm)		
	2019	2020	LTA* VP*	2019	2020	LTA* VP*
March	7.6	8.0	6.1	29.0	88.6	77.2
April	10.8	12.1	10.7	67.0	36.9	75.6
May	11.9	15.7	14.7	118.8	84.4	98.9
June	20.4	19.7	18.9	236.0	147.3	78.7
July	20.7	21.9	21.2	45.4	127.7	50.4
August	21.3	22.3	21.2	61.6	117.7	41.7
September	17.3	19.4	16.5	20.8	7.5	60.0
October	14.9	13.1	10.5	16.4	101.9	59.2
Mean of growing season	15.6	16.5	15.0	595.0	712.0	541.7

* Long-term average (55-year average, i.e. 1965–2020 period)

Table 2. Overview of the sampling dates of the examined apple cultivars by year

Cultivar	Growing year	Storage period (days)		
		0	60	120
'Golden Delicious Reinders'	2018/19	30 th of September	2 nd of December	30 th of January
	2019/20	24 th of September	24 th of November	26 th of January
'Granny Smith'	2018/19	30 th of September	2 nd of December	30 th of January
	2019/20	24 th of September	24 th of November	25 th of January
'Red Chief'	2018/19	17 th of September	18 th of November	17 th of January
	2019/20	23 rd of September	23 rd of November	21 st of January
'Gloster'	2018/19	1 st of September	15 th of November	15 th of January
	2019/20	17 th of September	18 th of November	17 th of January
'Morren's Jonagored'	2018/19	11 th of September	15 th of November	15 th of January
	2019/20	26 th of September	26 th of November	24 th of January

The cold storage conditions were 0.5–2.5 °C, high relative humidity (90–92%), an O₂ content of approximately 21%, CO₂ at around 0.03%, and N at about 78%. Sampling times for the investigated apple cultivars are shown in Table 2.

Mineral fruit quality analysis

Apple fruit samples for the determination of mineral content were collected from all the experimental treatments during the 2018 and 2019 growing seasons, at the stage of commercial maturity, as identified by the iodine-starch test. Fruits of uniform size, free from visible damage and infections, were randomly selected from the same pool of trees and transported to the laboratory of the Fruit Research Institute (Rilak et al., 2023). A total of 120 fruits from each examined cultivar were sampled, with 4 replications (30 fruits per replication) per treatment. Chemical analyses were performed on 100 g samples of apple fruit from each cultivar, with each replication consisting of 25 g (4 replications in total). Each chemical analysis was performed in four replications per cultivar and treatment to ensure statistical reliability. All mineral concentrations are expressed in mg/kg of fresh

weight (FW). The homogenized fruit samples were digested following standard protocols to avoid contamination, and all glassware was acid-washed prior to use. The procedure follows previously established methods (Morais et al., 2017) and allows for accurate determination of macro- and microelements in apple fruit. The analyses were conducted at the stage of physiological maturity, as well as after two storage periods (60 and 120 days).

For mineral determination, the fruits were washed with deionized water and homogenized. A 25 g sample of fruit was decontaminated with a 10% nitric acid solution and then subjected to digestion by drying at 600 °C for 4 hours. Subsequently, 5 mL of 3N HCl was added to the sample and heated until the ash was completely dissolved. The sample was then filtered and diluted to a final volume of 50 mL with deionized water. The content of macro, microminerals, and Pb were determined according to Morais et al. (2017) using atomic absorption spectrophotometry (Perkin-Elmer, PinAAcle 500, USA). The results expressed in mg/kg of fresh weight (mg/kg FW). The ratios of K/Ca, K+Mg/Ca, and Ca/Mg were calculated.

Statistical analysis

The data were presented as mean \pm standard error of the mean (SE). Differences between means were compared by Duncan's Multiple Range test in three-way analysis of variance (ANOVA) using the MSTAT-C statistical computer package (Michigan State University, East Lansing, MI, USA). Differences at $P \leq 0.05$ were considered significant.

RESULTS AND DISCUSSION

The contents of the macroelements (Ca, Mg, and K) and their ratios (K/Ca, K+Mg/Ca, Ca/Mg) of assessed apple cultivars during different storage periods are shown in Table 3.

Analysis of variance revealed that the content of all tested macronutrients (K, Ca, Mg) in apple fruits significantly depended on the cultivar, growing year, and storage period (experimental factors). The K/Ca and K+Mg/Ca ratios were influenced mainly by cultivar and growing year, while the Ca/Mg ratio was largely unaffected by storage conditions (Figure 1, Table 3). Cultivar/year interactions caused significant variations in all macronutrient contents and their ratios, except for Mg during storage, indicating that environmental conditions and genetic factors jointly affect nutrient accumulation. Storage period influenced the highest K, K/Ca, and K+Mg/Ca values after 60 days, whereas Ca and Mg concentrations showed cultivar-specific trends.

Among the cultivars, 'Red Chief' had the highest K and Mg contents, whereas 'Morrens Jonagored' showed the lowest K and Ca levels. 'Golden Delicious Reinders' exhibited the highest Ca and Ca/Mg ratio, while 'Granny Smith' had the highest K+Mg/Ca ratio. On average, nutrient levels followed the order $K > Mg > Ca$, consistent with findings by Nachtigall and Dechen (2006). Mg concentrations were within commonly reported ranges for apple fruit, showing cultivar- and environment-dependent variation rather than nutritional excess (Nour et al., 2010). K excess is rare but may reduce Ca and Mg availability, affecting storage quality (Mratinić and Đurović, 2015).

Ca content is critical for postharvest quality, as low Ca increases susceptibility to physiological disorders and reduces storage potential (Marcelle, 1995; Wojcik, 2004). In this study, Ca ranged from 24.50 to 39.05 mg/kg FW (≈ 0.0025 – 0.0039% FW), below the 0.05% threshold suggested for extended storage (Mičić et al., 2005). Antagonistic interactions between K, Mg, and Ca may further influence fruit quality and susceptibility to bitter pit (Gransee and Führs, 2013; Bramlage et al., 1980; Hahn et al., 2022).

Overall, macronutrient contents depended on cultivar properties, agro-ecological conditions, fertilization practices, and storage duration, highlighting the need to consider these factors when predicting apple storage performance and nutritional value (Zavalloni et al., 2001; Johnston et al., 2002; Wicklund et al., 2021). Apples provide dietary K, Ca, and Mg, supporting muscle and nerve function, bone health, and enzymatic activity, while their fiber and bioactive compounds contribute to general nutritional value rather than strong therapeutic effects (Campeanu et al., 2009; Rilak et al., 2025). Literature reports Ca content in apples ranging from 2 to 202.7 mg/100 g (Morais et al., 2017; Maeaba and Prasad, 2023).

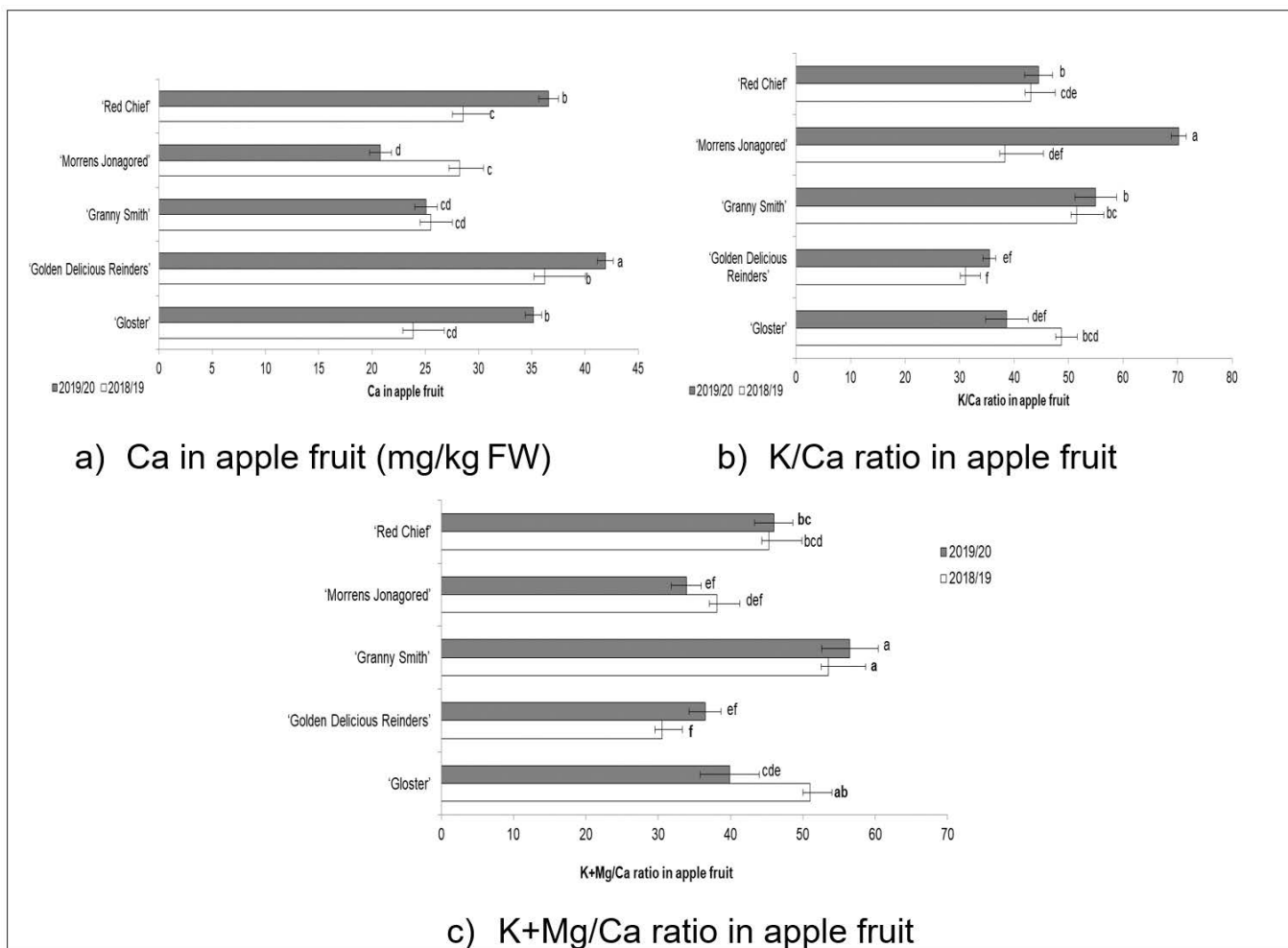
When considering cultivar differences, the highest K content was recorded in the 'Red Chief' cultivar after 120 days of storage in the second growing year (1,713.38 mg/kg FW), while the lowest value was observed in 'Morrens Jonagored' (1,444.45 mg/kg FW) (Figure 3). In contrast, Milinković et al. (2018) reported the lowest K content in 'Granny Smith' and the highest in 'Morrens Jonagored' under Čačak agroecological conditions, indicating a strong influence of environmental factors and year-to-year variability.

Regarding Mg, the highest Mg content was recorded in 'Red Chief' after 60 days of storage in the first growing year (67.98 mg/kg FW), whereas the lowest value was observed at the end of storage (120 days) in the second growing year (25.37 mg/kg FW) (Figure 4). These results confirm the combined influence of cultivar characteristics and storage duration on Mg dynamics.

Table 3. Content of macroelements (K, Ca, Mg) content in apple fruits (mean \pm SE, mg/kg FW)

Treatment	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	K/Ca	K+Mg/Ca	Ca/Mg
Cultivar (A)						
'Gloster'	1218.15 \pm 39.86 ^{cd}	29.53 \pm 2.00 ^b	47.00 \pm 2.73 ^c	43.67 \pm 2.67 ^b	45.42 \pm 2.81 ^b	0.69 \pm 0.08 ^{ab}
'Golden Delicious Reinders'	1266.23 \pm 43.60 ^{bc}	39.05 \pm 2.01 ^a	47.41 \pm 3.18 ^c	33.28 \pm 1.53 ^c	33.52 \pm 1.86 ^c	0.92 \pm 0.11 ^a
'Granny Smith'	1297.15 \pm 41.85 ^b	25.29 \pm 1.10 ^c	45.58 \pm 3.41 ^c	53.22 \pm 3.09 ^a	55.04 \pm 3.15 ^a	0.62 \pm 0.06 ^{bc}
'Morrens Jonagored'	1204.78 \pm 38.58 ^d	24.50 \pm 1.50 ^c	51.90 \pm 2.90 ^b	54.27 \pm 5.22 ^a	36.00 \pm 1.92 ^c	0.49 \pm 0.04 ^c
'Red Chief'	1375.73 \pm 51.29 ^a	32.56 \pm 1.65 ^b	57.36 \pm 2.30 ^a	43.79 \pm 2.52 ^b	45.63 \pm 2.58 ^b	0.59 \pm 0.05 ^{bc}
Growing year (B)						
2018/2019	1166.65 \pm 23.15 ^b	28.47 \pm 0.77 ^b	55.78 \pm 1.28 ^a	42.52 \pm 1.63 ^b	43.70 \pm 1.84 ^a	0.52 \pm 0.02 ^b
2019/2020	1378.17 \pm 23.95 ^a	31.91 \pm 1.67 ^a	43.92 \pm 2.06 ^b	48.77 \pm 2.77 ^a	42.55 \pm 2.05 ^a	0.80 \pm 0.06 ^a
Storage period (C)						
0 days	1294.18 \pm 29.64 ^a	32.31 \pm 1.94 ^a	52.76 \pm 1.78 ^a	43.69 \pm 2.60 ^a	41.57 \pm 2.28 ^a	0.67 \pm 0.08 ^a
60 days	1318.44 \pm 30.85 ^a	29.75 \pm 1.54 ^{ab}	52.19 \pm 2.57 ^a	47.66 \pm 2.67 ^a	45.50 \pm 2.28 ^a	0.61 \pm 0.04 ^a
120 days	1204.67 \pm 40.06 ^b	28.51 \pm 1.23 ^b	44.59 \pm 2.41 ^b	45.59 \pm 3.22 ^a	42.30 \pm 2.56 ^a	0.70 \pm 0.05 ^a
ANOVA						
A	*	*	*	*	*	*
B	*	*	*	*	ns	*
C	*	*	*	ns	ns	ns
A \times B	*	*	ns	*	*	*
A \times C	*	ns	*	ns	ns	*
B \times C	*	*	*	*	*	ns
A \times B \times C	*	ns	*	ns	ns	*

Values within each column followed by the same small letter are not significantly different at $P \leq 0.05$ by Duncan's Multiple Range test; * in column indicates significant differences at $P \leq 0.05$ by Duncan's Multiple Range test; ns: not significant.



Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 1. Interaction effects (AxB); 1.a) Ca in apple fruit; 1.b) K/Ca ratio in apple fruit; 1.c) K+Mg/Ca ratio in apple fruit

Ca content and related ratios showed pronounced variation depending on evaluation date and growing year. The highest Ca content was observed at harvest (0 days) in the second growing year (36.79 mg/kg FW), while the lowest was recorded after 120 days of storage in the same year (26.03 mg/kg FW). Consequently, the K/Ca ratio increased during storage, reaching its maximum after 120 days in the second growing year (56.52), whereas the lowest value was observed at harvest in the first growing year (34.66). Similarly, the K+Mg/Ca ratio reached its highest value after 60 days of storage (51.27), while the lowest value was recorded after 120 days in the first growing year (34.66).

Year effects were also evident in mineral balance. The K/Ca ratio was generally higher in the second growing year for all cultivars except 'Gloster'. In contrast, the K+Mg/Ca ratio showed higher values in the first growing year for 'Gloster' (35.18), 'Granny Smith' (25.52), and 'Morrens Jonagored' (28.22), indicating differences in nutrient equilibrium between seasons.

The observed K/Ca and K+Mg/Ca ratios were higher than those reported by Doryanizadeh et al. (2017) for apples stored at 0 °C and 90% relative humidity. As previously noted, low Ca content combined with high K levels, due to their antagonistic relationship, may increase susceptibility to bitter pit (Wińska-Krysiak and Łata,

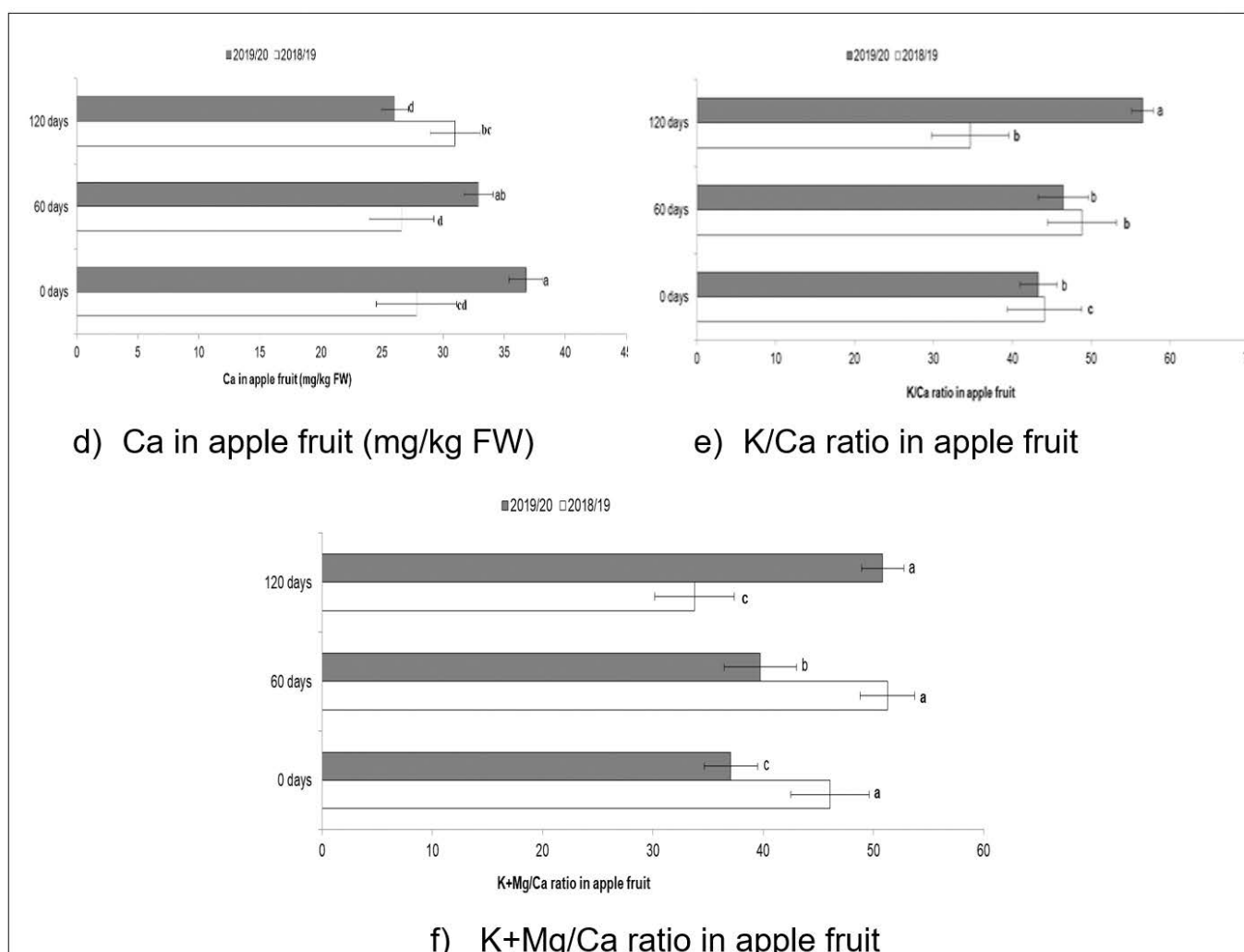
2010). These findings support earlier reports highlighting strong cultivar and environmental effects on fruit mineral composition (Habte et al., 2017).

Figure 2 shows the significant interaction effect of growing year/storage period on Ca content, K/Ca ratio, and K+Mg/Ca ratio in apple fruit.

Analysis of variance revealed significant effects of cultivar, growing year, and storage period on the concentrations of Cu, Fe, Zn, Mn, Ni, Co, Cr, and Pb (Table 4). A significant three-way interaction (cultivar/year/storage period) was observed for all microelements except Ni, where only the cultivar/storage period interaction was significant (Figure 6).

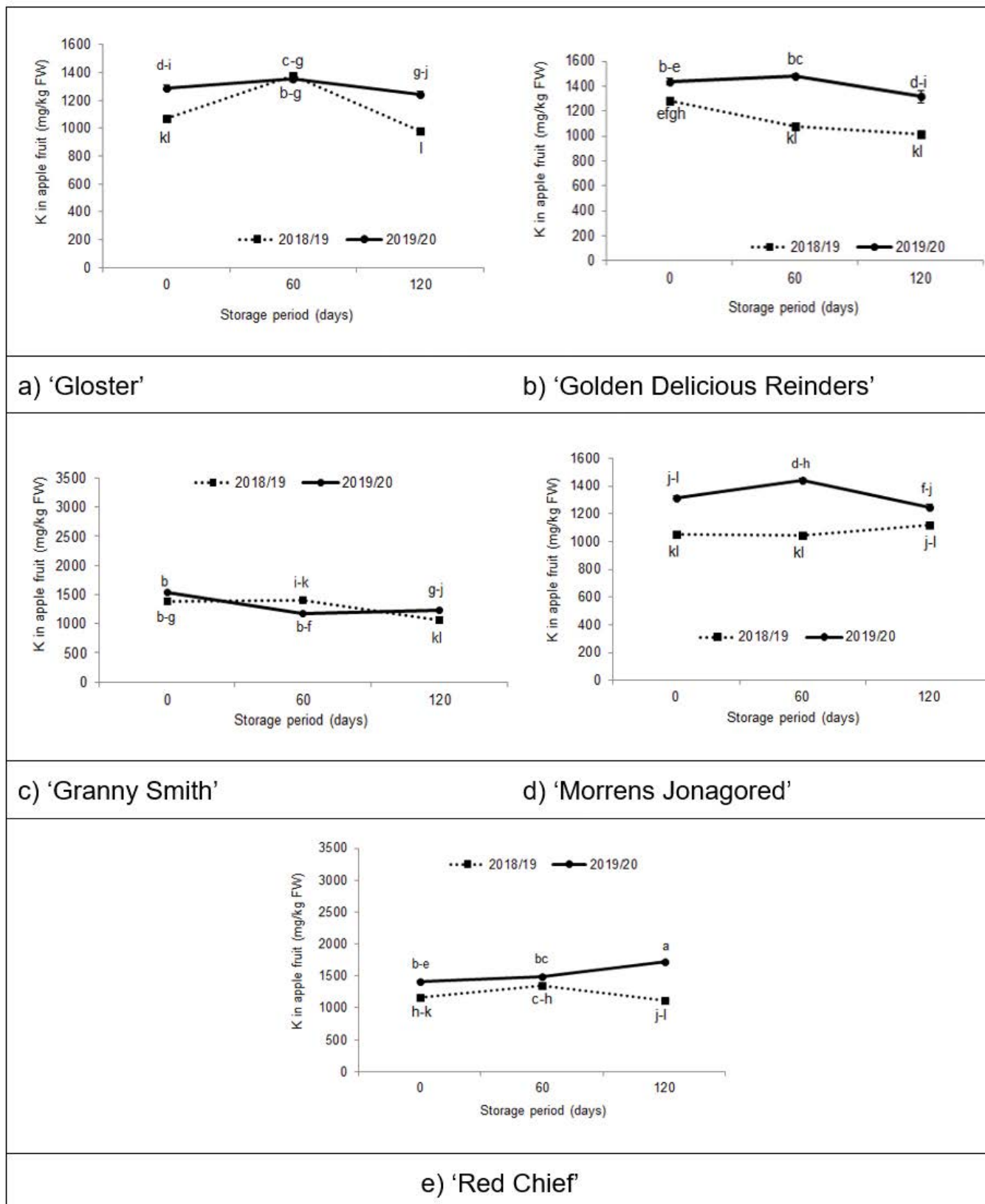
Among the studied cultivars, the highest Ni concentration was recorded in 'Gloster' after 60 days of storage (0.105 mg/kg FW), whereas the lowest value was observed in 'Golden Delicious Reinders' after 120 days of storage (0.010 mg/kg FW). Li et al. (2012) reported elevated Ni concentrations in Chinese apple fruit, with 1.4% of samples exceeding the safety limit of 0.3 mg/kg, indicating the importance of monitoring trace elements in fruit.

The Ca/Mg ratio differed significantly among cultivars and years, with the highest value recorded in 'Golden Delicious Reinders' during the second growing year (1.56) and the lowest in 'Morrens Jonagored' (0.31).



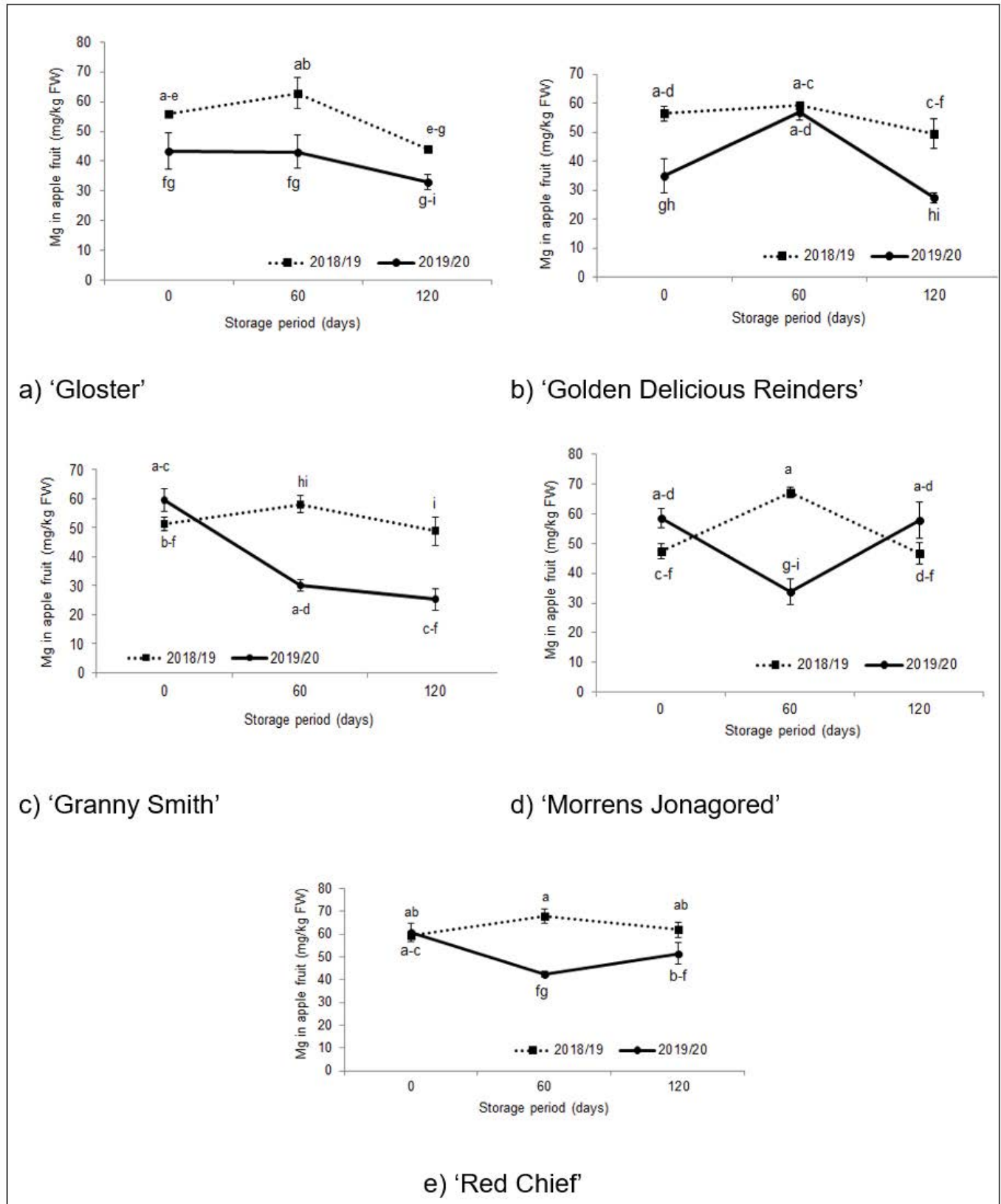
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (Results as mean \pm SE).

Figure 2. Interaction effects (B×C); 2.a) Ca in apple fruit; 2.b) K/Ca ratio in apple fruit; 2. c) K+Mg/Ca ratio in apple fruit



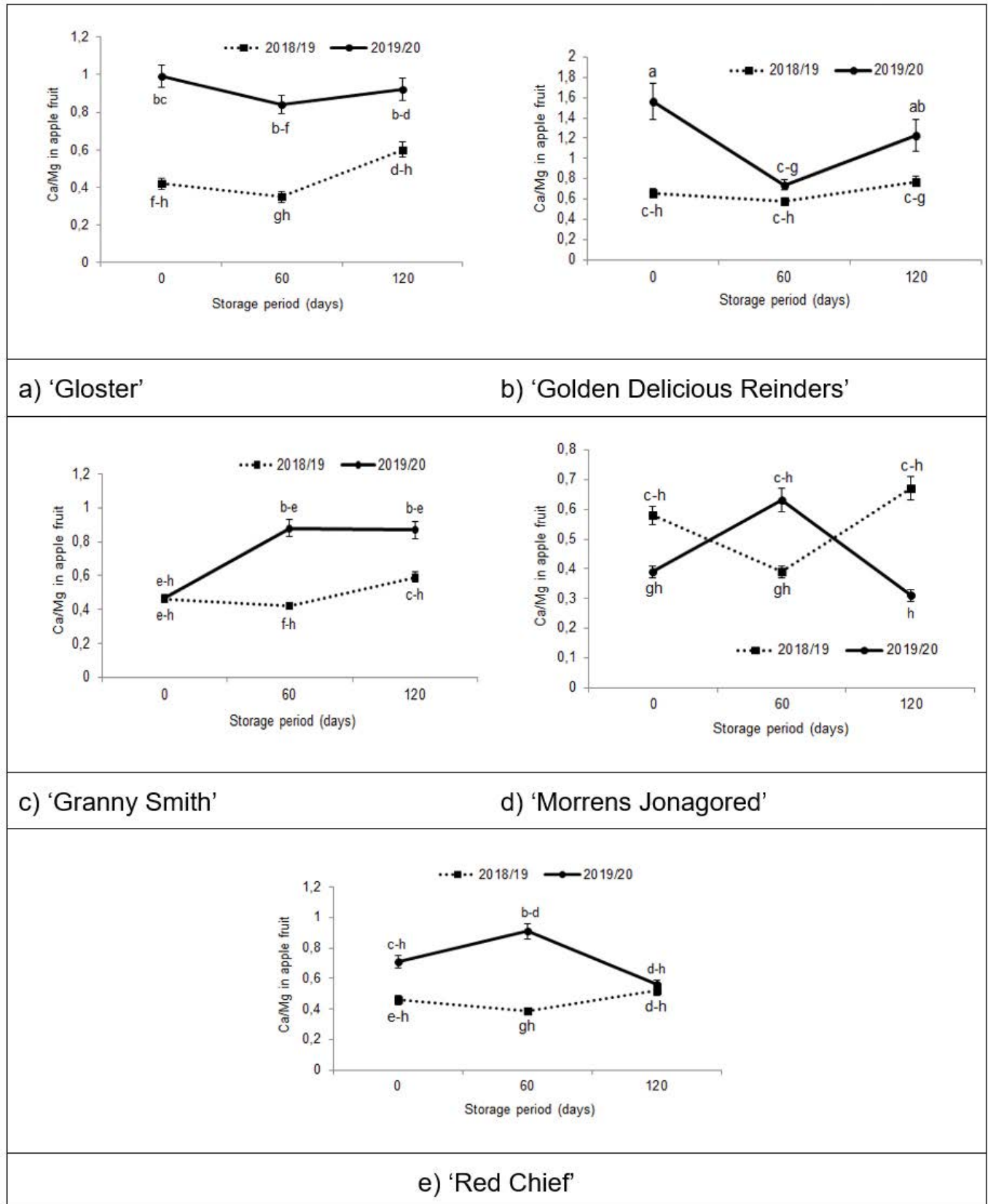
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 3. K content in apple fruit (A×B×C). 3.a) 'Gloster'; 3.b) 'Golden Delicious Reinders'; 3.c) 'Granny Smith'; 3.d) 'Morrens Jonagored'; 3.e) 'Red Chief'



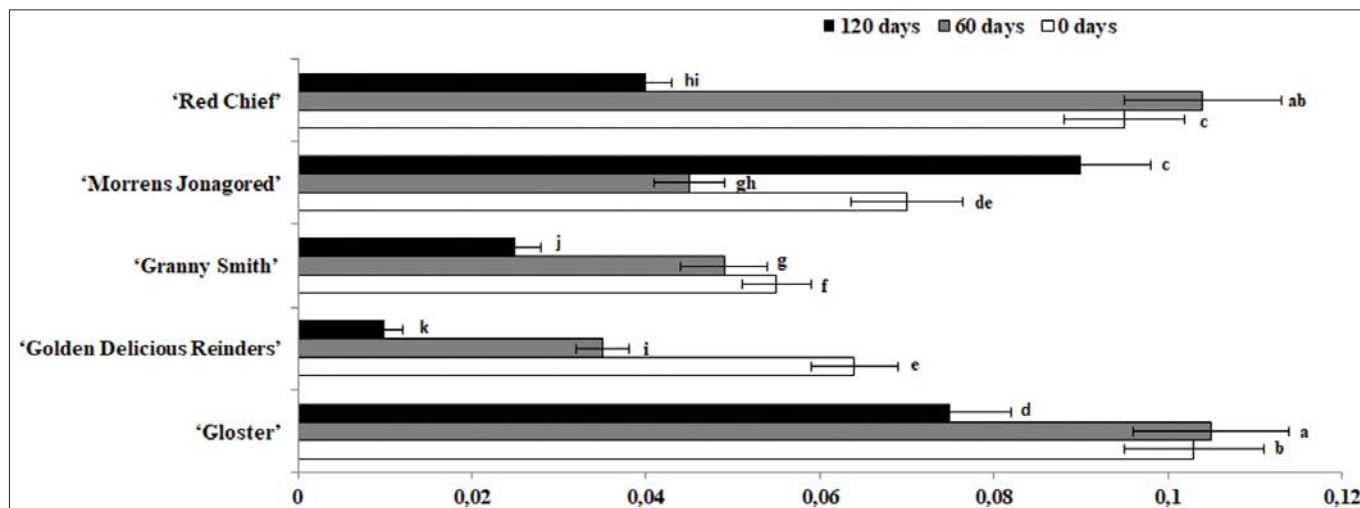
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 4. Mg content in apple fruit (A×B×C). 4.a) 'Gloster'; 4.b) 'Golden Delicious Reinders'; 4.c) 'Granny Smith'; 4.d) 'Morrens Jonagored'; 4.e) 'Red Chief'



Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 5. Ca/Mg value in apple fruit (A×B×C). 5.a) 'Gloster'; 5.b) 'Golden Delicious Reinders'; 5.c) 'Granny Smith'; 5.d) 'Morrens Jonagored'; 5.e) 'Red Chief'



Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 6. Ni concentration in apple fruit (AxC). 6.a) 'Gloster'; 6.b) 'Golden Delicious Reinders'; 6.c) 'Granny Smith'; 6.d) 'Morrens Jonagored'; 6.e) 'Red Chief'

Similar Mg/Ca ratios were reported for 'Fuji' apples grown in Southern Brazil (Amarante et al., 2017), highlighting the relevance of these ratios for assessing bitter pit susceptibility.

Previous studies have shown that Mg concentration may vary depending on peel color and cultivar. Doryanizadeh et al. (2017) observed lower Mg content in dark red apples compared to medium and light red cultivars, while Ahmed et al. (2025) reported higher Mg levels in 'Golden' and 'Starking' apples, attributing these differences to environmental and varietal factors.

Although trace elements are essential in small quantities, excessive intake may pose health risks. Therefore, their concentrations are interpreted relative to established food safety limits rather than categorized as sufficient or insufficient. Nutrient accumulation patterns in apple tissues remain incompletely understood (Mészáros et al., 2021). Additionally, postharvest treatments such as freezing may preserve micronutrient content and reduce degradation (Ali et al., 2012; Niyazova et al., 2024).

Figures 7–13 illustrate the interaction effects of cultivar, growing year, and storage period on microelement concentrations in apple fruit. For Cu, the highest concentration (0.26 mg/kg FW) was recorded in 'Gloster' fruit

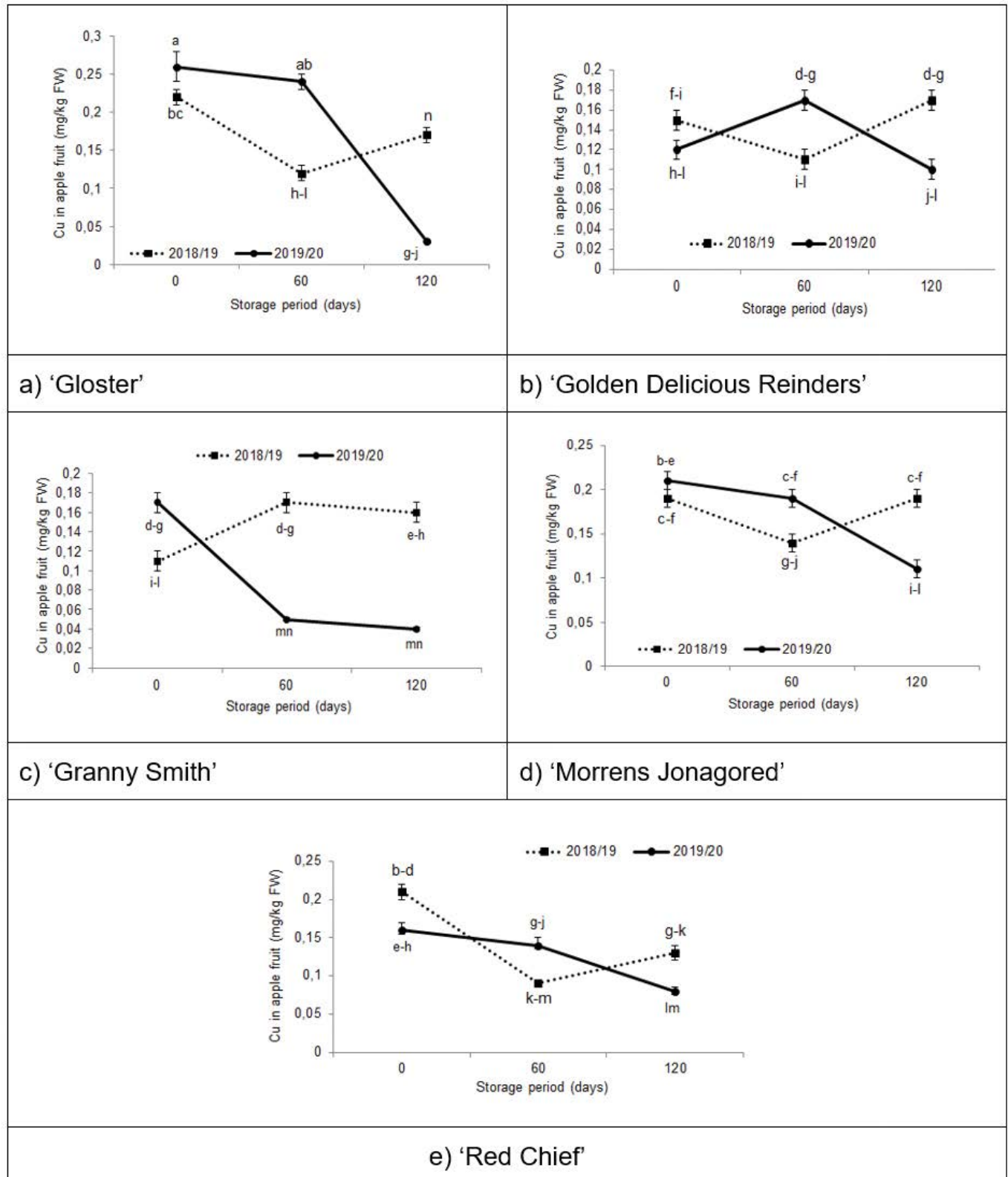
at harvest (initial evaluation), whereas the lowest value (0.03 mg/kg FW) was observed after 120 days of storage in the second growing year. These results indicate a decrease in Cu concentration during storage, which may be associated with metabolic changes occurring during fruit ripening and senescence. The Cu concentrations obtained in the present study were lower than those reported by Park et al. (2011) for apples grown in southern Korea, suggesting that differences in agro-ecological conditions and production practices may influence microelement accumulation.

The highest Fe concentration was recorded in 'Gloster' fruit at harvest (initial evaluation) in the first growing year (3.15 mg/kg FW), whereas the lowest value was observed in 'Granny Smith' after 60 and 120 days of storage (0.71 mg/kg FW). The results indicate a decline in Fe concentration during storage, which may be associated with physiological and metabolic changes occurring during fruit maturation and storage. Campeanu et al. (2009) emphasized the secondary role of Fe in plant development and its contribution to fruit quality, reporting higher FeO concentrations (1.996%–2.752%) in Romanian apple genotypes compared with the values obtained in the present study.

Table 4. Concentrations of microelements in apple fruits (mean \pm SE, mg/kg FW)

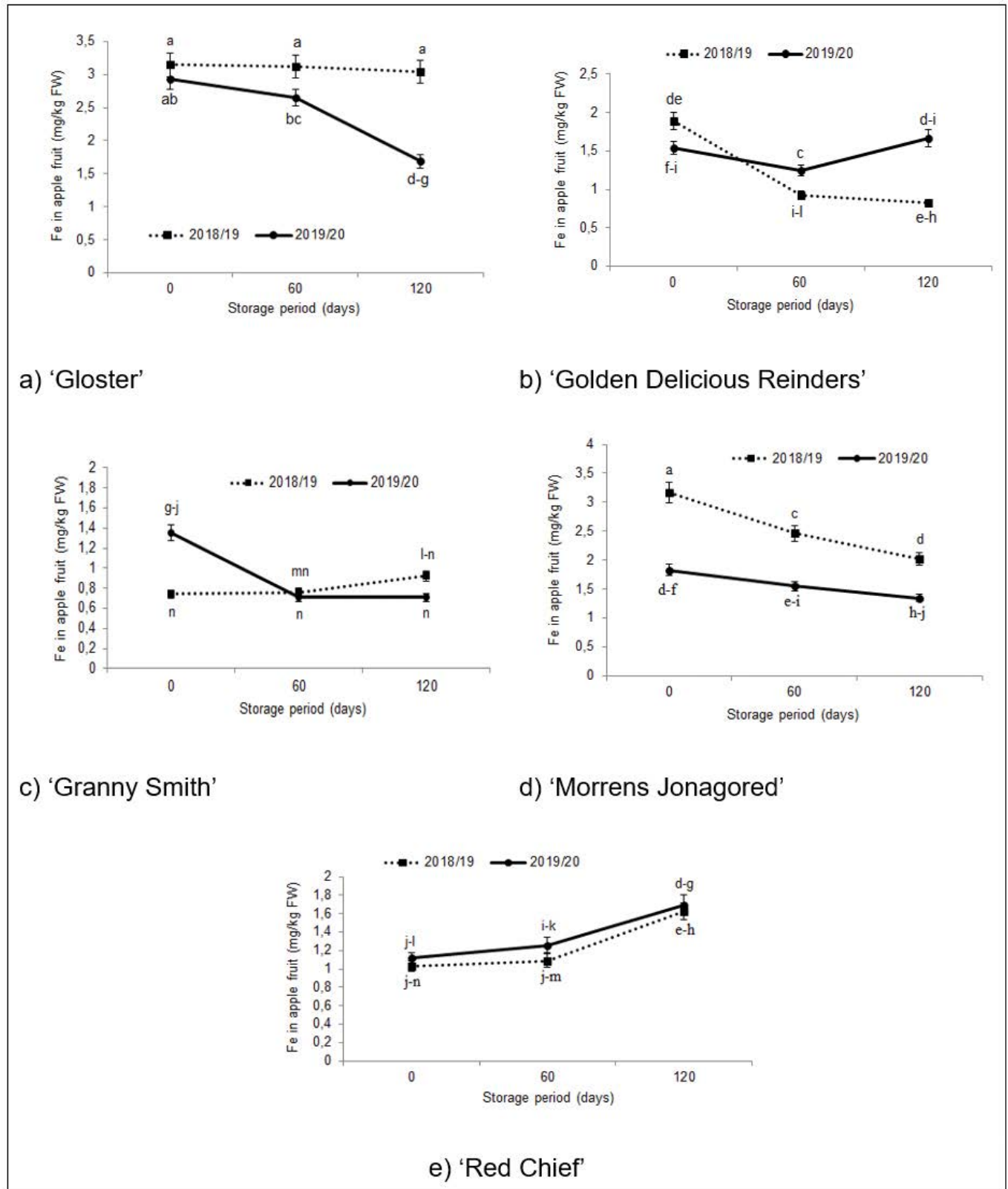
Treatment	Cu	Fe	Zn	Mn	Ni	Co	Cr	Pb
Cultivar (A)								
'Gloster'	0.17 \pm 0.02 ^a	2.77 \pm 0.14 ^a	0.32 \pm 0.04 ^b	0.48 \pm 0.07 ^a	0.10 \pm 0.01 ^a	0.033 \pm 0.01 ^a	0.11 \pm 0.01 ^a	0.32 \pm 0.04 ^a
'Golden Delicious Reinders'	0.14 \pm 0.01 ^b	1.35 \pm 0.10 ^c	0.20 \pm 0.02 ^d	0.36 \pm 0.02 ^b	0.04 \pm 0.01 ^e	0.018 \pm 0.01 ^e	0.07 \pm 0.01 ^{cd}	0.27 \pm 0.04 ^b
'Granny Smith'	0.12 \pm 0.01 ^c	0.87 \pm 0.06 ^d	0.42 \pm 0.01 ^a	0.34 \pm 0.03 ^b	0.05 \pm 0.01 ^d	0.020 \pm 0.01 ^d	0.09 \pm 0.01 ^b	0.37 \pm 0.04 ^b
'Morrens Jonagored'	0.17 \pm 0.01 ^a	2.06 \pm 0.15 ^b	0.31 \pm 0.04 ^b	0.35 \pm 0.01 ^b	0.07 \pm 0.01 ^c	0.027 \pm 0.01 ^b	0.06 \pm 0.01 ^d	0.27 \pm 0.04 ^b
'Red Chief'	0.14 \pm 0.01 ^b	1.30 \pm 0.07 ^c	0.27 \pm 0.01 ^c	0.36 \pm 0.02 ^b	0.08 \pm 0.01 ^b	0.021 \pm 0.01 ^c	0.08 \pm 0.01 ^c	0.32 \pm 0.02 ^a
Growing year (B)								
2018/2019	0.15 \pm 0.01 ^a	1.78 \pm 0.14 ^a	0.36 \pm 0.02 ^a	0.39 \pm 0.01 ^a	0.07 \pm 0.01 ^a	0.030 \pm 0.01 ^a	0.08 \pm 0.01 ^b	0.24 \pm 0.02 ^b
2019/2020	0.14 \pm 0.01 ^b	1.55 \pm 0.09 ^b	0.25 \pm 0.02 ^b	0.37 \pm 0.03 ^b	0.06 \pm 0.01 ^b	0.018 \pm 0.01 ^b	0.09 \pm 0.01 ^a	0.34 \pm 0.03 ^a
Storage period (C)								
0 days	0.18 \pm 0.01 ^a	1.86 \pm 0.16 ^a	0.35 \pm 0.03 ^a	0.43 \pm 0.04 ^a	0.08 \pm 0.01 ^a	0.023 \pm 0.01 ^b	0.04 \pm 0.01 ^c	0.14 \pm 0.01 ^c
60 days	0.14 \pm 0.01 ^b	1.58 \pm 0.15 ^b	0.31 \pm 0.03 ^b	0.40 \pm 0.02 ^b	0.07 \pm 0.01 ^b	0.021 \pm 0.01 ^c	0.09 \pm 0.01 ^b	0.26 \pm 0.02 ^b
120 days	0.12 \pm 0.01 ^c	1.55 \pm 0.12 ^b	0.24 \pm 0.02 ^c	0.30 \pm 0.01 ^c	0.05 \pm 0.01 ^c	0.028 \pm 0.01 ^a	0.12 \pm 0.01 ^a	0.48 \pm 0.02 ^a
ANOVA								
A	*	*	*	*	*	*	*	*
B	*	*	*	*	*	*	*	*
C	*	*	*	*	*	*	*	*
A \times B	*	*	*	*	ns	*	*	*
A \times C	*	*	*	*	*	*	*	*
B \times C	*	ns	*	*	ns	*	*	*
A \times B \times C	*	*	*	*	ns	*	*	*

Values within each column followed by the same small letter are not significantly different at $P \leq 0.05$ by Duncan's Multiple Range test; * in column indicates significant differences at $P \leq 0.05$ by Duncan's Multiple Range test, ns. not significant.



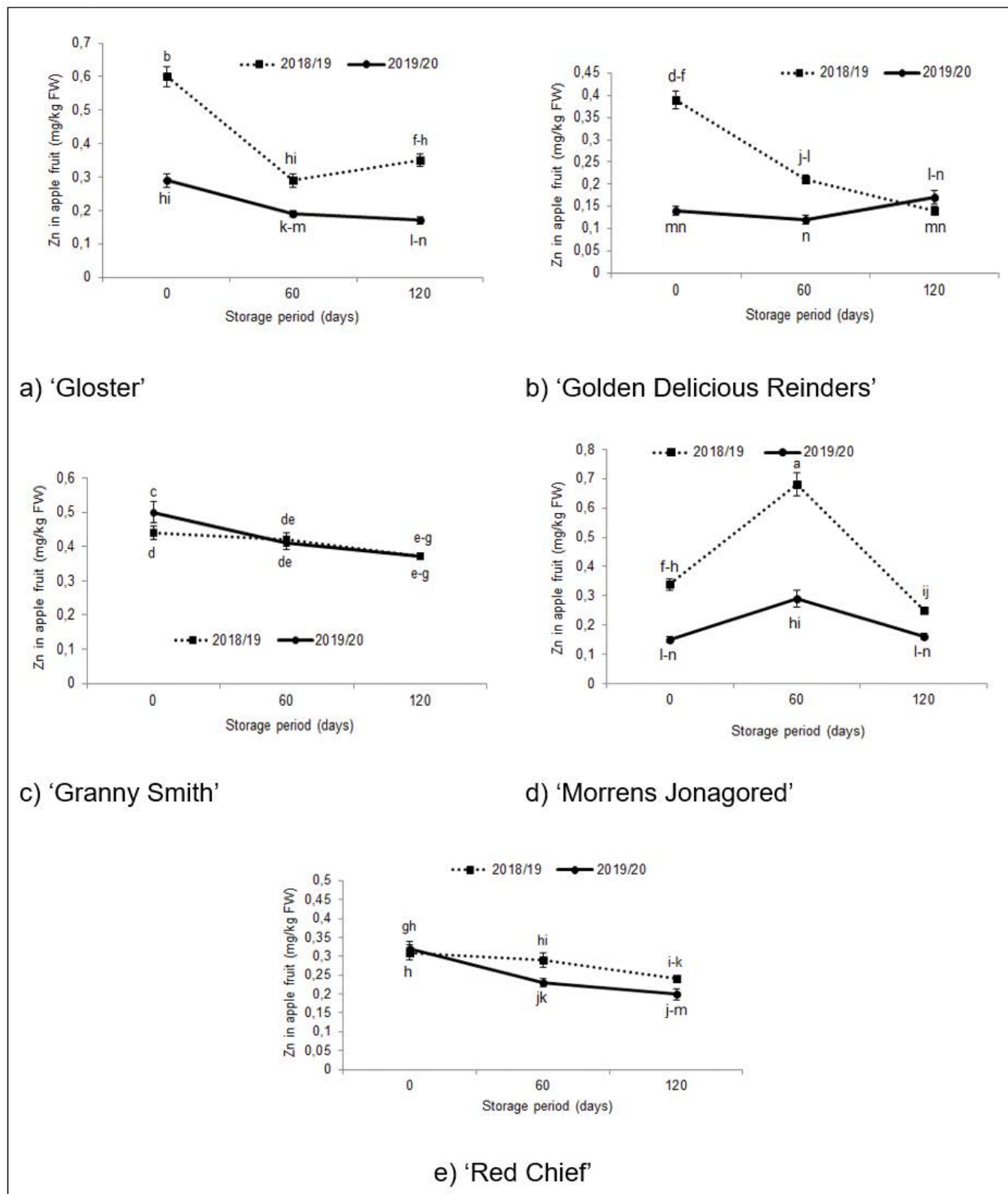
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 7. Cu concentration in apple fruit (A×B×C). 7.a) 'Gloster'; 7.b) 'Golden Delicious Reinders'; 7.c) 'Granny Smith'; 7.d) 'Morrens Jonagored'; 7.e) 'Red Chief'



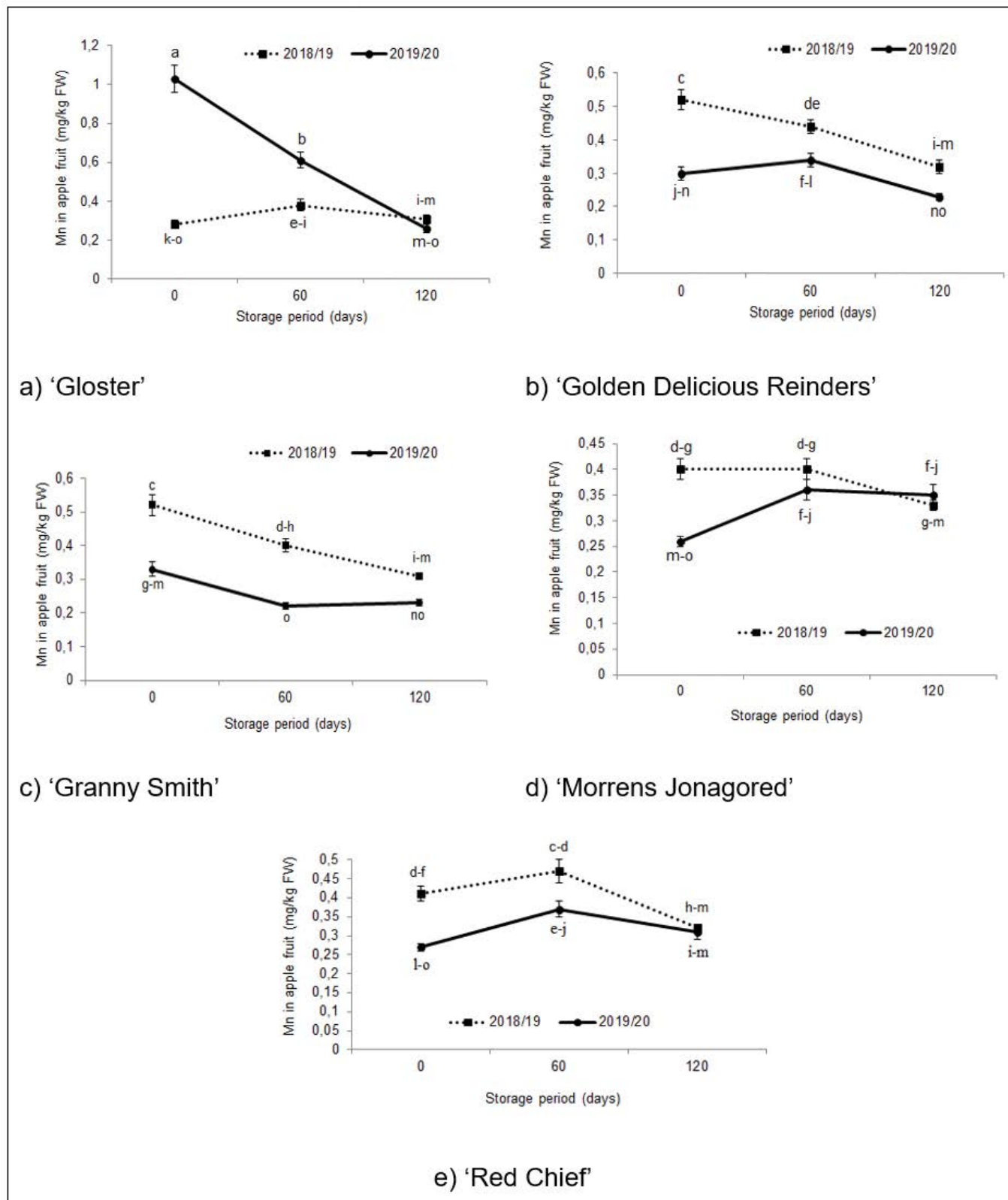
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 8. Fe concentration in apple fruit (A×B×C). 8.a) 'Gloster'; 8.b) 'Golden Delicious Reinders'; 8.c) 'Granny Smith'; 8.d) 'Morrens Jonagored'; 8.e) 'Red Chief'



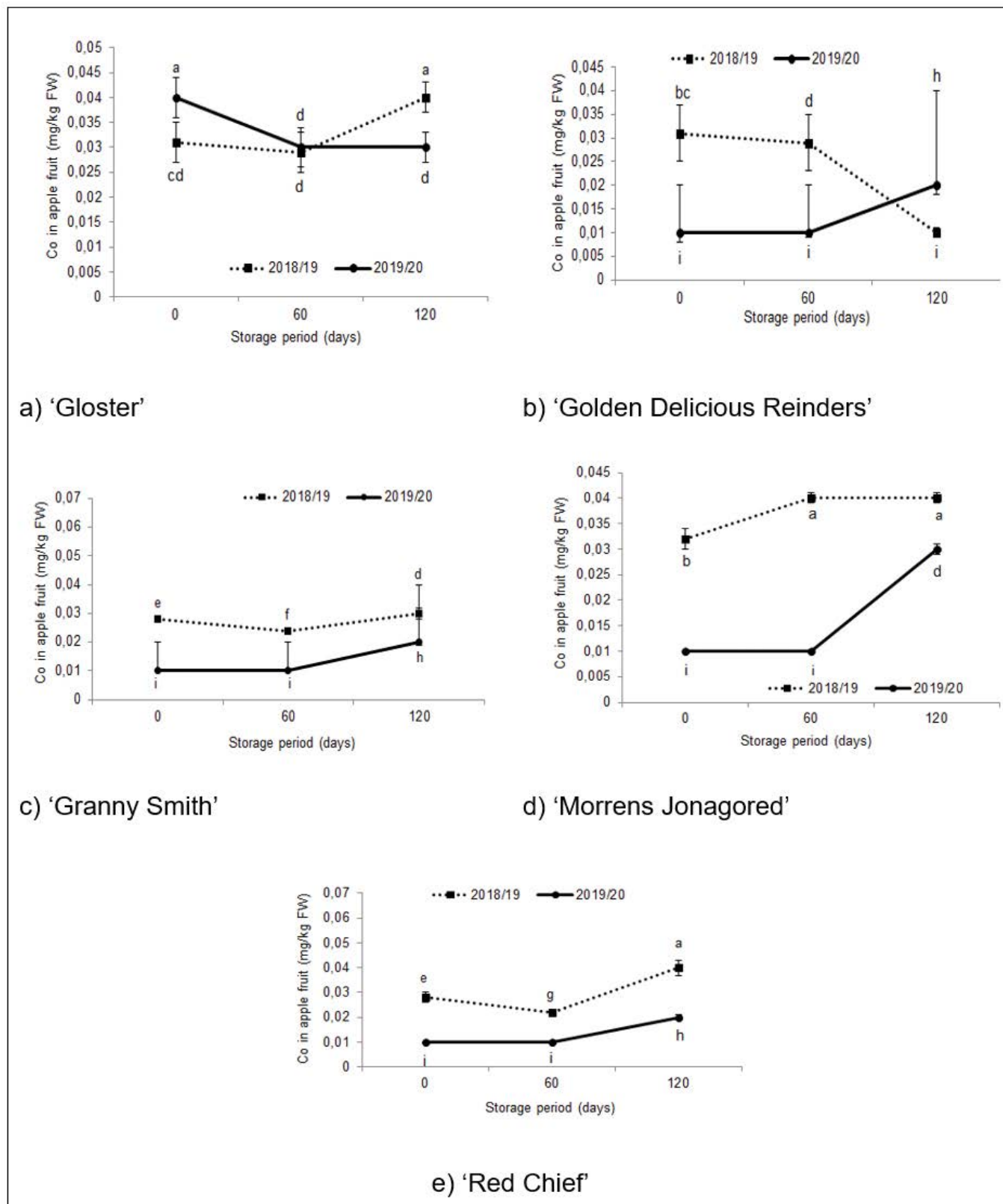
Values at each point followed by the same lowercase letter are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 9. Zn concentration in apple fruit (A×B×C). 9.a) 'Gloster'; 9.b) 'Golden Delicious Reinders'; 9.c) 'Granny Smith'; 9.d) 'Morrens Jonagored'; 9.e) 'Red Chief'



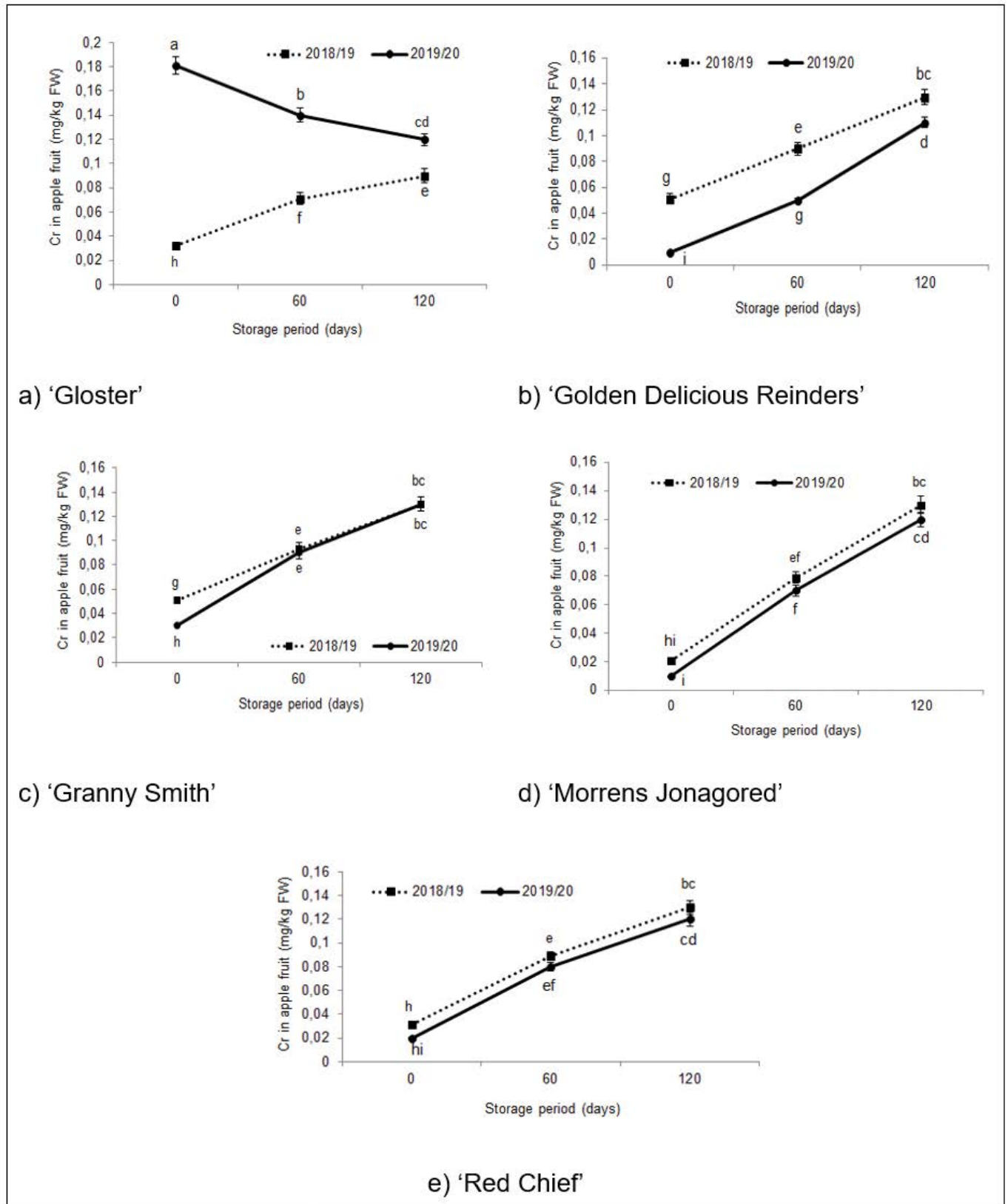
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE).

Figure 10. Mn concentration in apple fruit (A×B×C). 10.a) 'Gloster'; 10.b) 'Golden Delicious Reinders'; 10.c) 'Granny Smith'; 10.d) 'Morrens Jonagored'; 10.e) 'Red Chief'



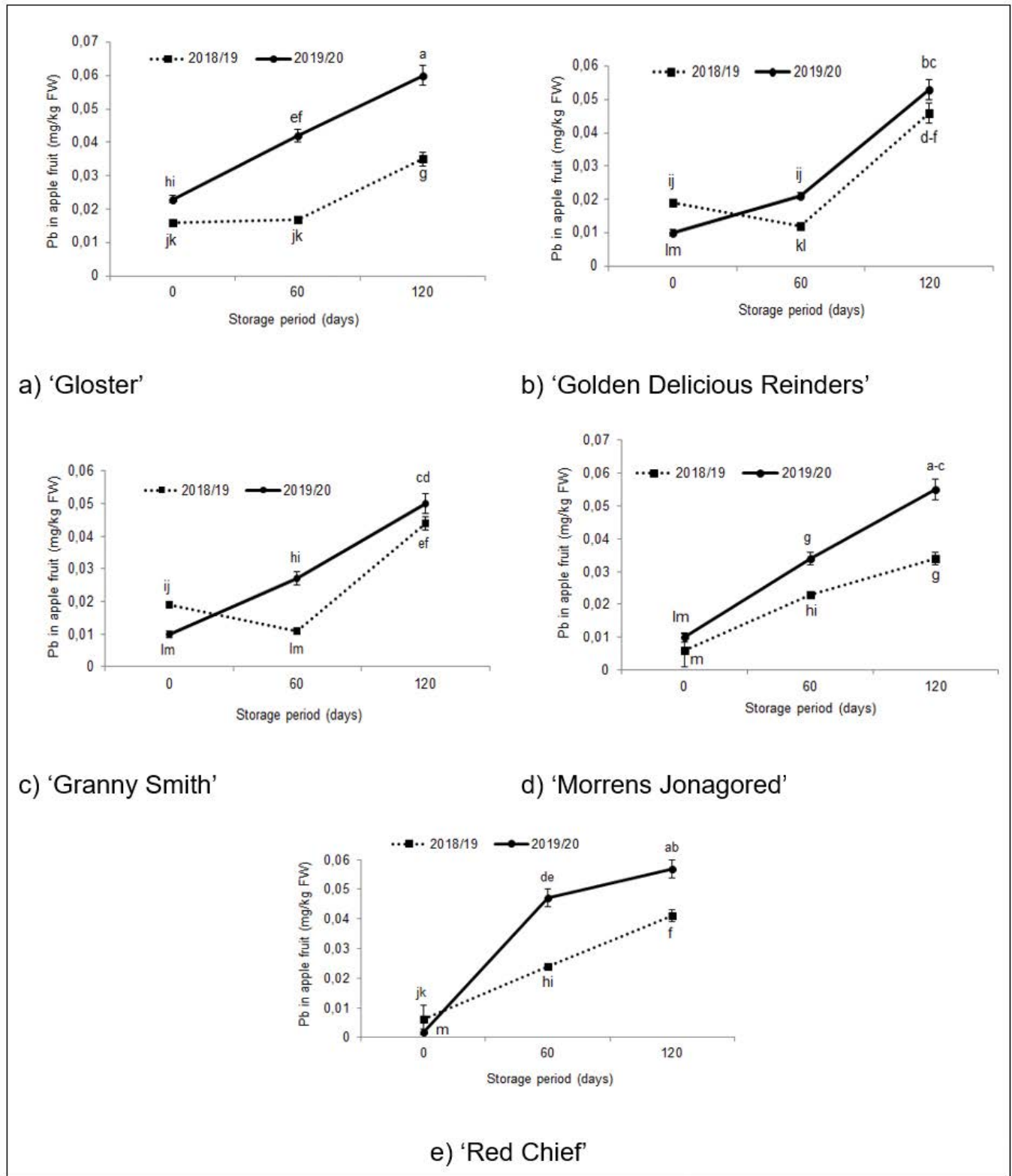
Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE)

Figure 11. Co concentration in apple fruit (A×B×C). 11.a) 'Gloster'; 11.b) 'Golden Delicious Reinders'; 11.c) 'Granny Smith'; 11.d) 'Morrens Jonagored'; 11.e) 'Red Chief'



Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (results as mean \pm SE)

Figure 12. Cr concentration in apple fruit (A×B×C). 12.a) 'Gloster'; 12.b) 'Golden Delicious Reinders'; 12.c) 'Granny Smith'; 12.d) 'Morrens Jonagored'; 12.e) 'Red Chief'



Values at each point followed by the same lowercase letter are not significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (Results as mean \pm SE).

Figure 13. Pb concentration in apple fruit (AxBxC). 13.a) 'Gloster'; 13.b) 'Golden Delicious Reinders'; 13.c) 'Granny Smith'; 13.d) 'Morrens Jonagored'; 13.e) 'Red Chief'

Similarly, Macit et al. (2021) reported higher Fe levels (5.75–14.17 mg/100 g FW) in Turkish apple cultivars, while Kistechok et al. (2024) observed increased Fe concentrations at the end of storage under different storage technologies, which contrasts with the decreasing trend observed in this study. Differences in Fe content among studies may be attributed to genotype, agro-ecological conditions, and cultivation practices, as previously reported by Brunetto et al. (2015).

After 60 days of cold storage, the highest Zn concentration was observed in 'Morrens Jonagored' fruit in the first growing year (0.68 mg/kg FW), whereas the lowest value was recorded in 'Golden Delicious Reinders' fruit in the second growing year (0.10 mg/kg FW). Compared with previous studies, the Zn concentrations recorded in the present study were lower than those reported by Aglar et al. (2016) and Skordas et al. (2018), who reported ranges of 1.1–10.3 mg/kg and 1.83–4.98 mg/kg FW, respectively. These differences further confirm the influence of cultivar characteristics, environmental conditions, and production practices on microelement accumulation in apple fruit.

The Mn concentration results (Figure 10) showed the highest Mn level in 'Gloster' fruit at harvest (initial evaluation) during the second growing year (1.03 mg/kg FW), whereas the lowest value was recorded in 'Granny Smith' fruit (0.22 mg/kg FW). Compared with the present results, Skordas et al. (2018) reported considerably higher Mn concentrations (2–9 mg/kg) in apples grown across different soil types in Central Greece, attributing these differences primarily to fertilization practices and intensive agrochemical use. The lower Mn levels observed in this study may therefore reflect differences in agro-ecological conditions and orchard management practices.

The highest Co concentration (0.04 mg/kg FW) was observed at the end of storage (120 days) in the first growing year in the cultivars 'Gloster', 'Morrens Jonagored', and 'Red Chief', while the lowest Co concentration (0.01 mg/kg FW) was mainly recorded in the second growing year at harvest and after 60 days of storage, except for 'Gloster'. The Co concentrations measured in

this study were comparable to those reported by Skordas et al. (2018), indicating that the observed values fall within ranges commonly reported for apple fruit.

The highest Cr concentration (0.18 mg/kg FW) was recorded in 'Gloster' fruit at harvest during the second growing year, whereas the lowest values (0.01 mg/kg FW) were observed in 'Golden Delicious Reinders' and 'Morrens Jonagored' under the same conditions. Compared with the present study, Wang et al. (2015) reported considerably higher Cr concentrations in the peel (2.25 mg/kg) and flesh (1.39 mg/kg) of 'Fuji' apples grown in China, suggesting potential health concerns at elevated levels. Jemaneh et al. (2021) also found higher Cr concentrations in green apples (6.15–10.40 mg/kg) than in red cultivars. In contrast, Skordas et al. (2018) reported average Cr concentrations below 1 mg/kg, which is consistent with the values obtained in the present study.

Regarding Pb, the interaction of cultivar, growing year, and storage period significantly affected its concentration. The highest Pb level (0.060 mg/kg FW) was recorded in 'Gloster' fruit after 120 days of storage in the second growing year, while the lowest value (0.006 mg/kg FW) was observed at harvest in 'Morrens Jonagored' and 'Red Chief' during the first year. A consistent increase in Pb concentration from harvest to the end of storage was observed across cultivars in both years. Nevertheless, Pb concentrations in this study were lower than those reported by Rusin et al. (2021) and remained close to the values published by Norton et al. (2015) for apples grown in Poland (0.009 mg/kg FW).

Elements such as Fe, Cu, Mn, and Zn are essential for human health; however, the concentrations measured in apples contribute only partially to recommended daily intake levels and should be interpreted primarily in terms of nutritional contribution rather than adequacy. Variability in trace element content among cultivars and storage periods reflects differences in genotype, environmental conditions, and postharvest dynamics, highlighting the importance of monitoring these elements to ensure both fruit quality and safety.

The findings of this study have practical implications for apple production and storage management. Since the content and ratios of K, Ca, and Mg, as well as microelements such as Fe, Cu, Zn, Mn, Co, Cr, and Pb, varied significantly among cultivars and evaluation dates, systematic monitoring of mineral composition is essential. Cultivars characterized by higher K/Ca ratios or lower Ca concentrations may exhibit increased susceptibility to physiological storage disorders, emphasizing the importance of balanced fertilization and adequate calcium management. In addition, maintaining Pb and Cr concentrations at low levels is crucial for food safety, particularly in markets relying on long-term storage or processed apple products.

CONCLUSION

Our study highlights the critical role of the mineral composition of apple fruits, particularly in terms of macroelements, in determining postharvest quality, storage potential, and nutritional value. Variations in macronutrient content were influenced by genotype, storage conditions under controlled atmosphere, and growing environment. K was the most abundant macroelement, followed by Mg and Ca, across all cultivars. The ratios of K/Ca, K+Mg/Ca, and Ca/Mg provided valuable insights into the fruits' nutritional dynamics during storage, closely linked to disorders like bitter pit and storage quality. The study revealed significant interactions between cultivar, storage duration, and growing year, affecting mineral composition. Cultivars such as 'Jonagold' and 'Granny Smith' exhibited higher nutrient content after prolonged cold storage. Maintaining a critical balance of macroelements, especially the antagonistic relationship between K and Ca, is crucial to reducing storage-related disorders. In terms of microelements, concentrations varied based on cultivar, growing year, and storage duration. Though generally low, monitoring microelements is essential due to potential heavy metal contamination, which could affect food safety and human health.

In conclusion, understanding the mineral composition, especially macroelement ratios and their interac-

tions, is vital for assessing apple postharvest behavior and storage potential. Future research should focus on nutrient imbalances and their impact on fruit quality, optimizing storage methods to maintain apple quality over time. Further investigation into the relationship between both macro and microelements and apple quality is essential for enhancing their nutritional profile for consumer health.

REFERENCES

- Acham, I. O., Ahemen, S., Ukeyima, M. T., Girgih, A. T. (2018) Tropical fruits: bioactive properties and health promoting benefits in chronic disease prevention and management. *Asian Food Science Journal*, 3 (1), 1-13. DOI: <https://doi.org/10.9734/AFSJ/2018/41853>
- Aglar, E., Yildiz, K., Ozkan, Y., Ozturk, B., Erdem, H. (2016) The effects of aminoethoxyvinylglycine and foliar zinc treatments on pre-harvest drops and fruit quality attributes of Jersey Mac apples. *Scientia Horticulturae*, 213 (3), 173-178. DOI: <https://doi.org/10.1016/j.scienta.2016.10.026>
- Ahmed, I.A.M., Özcan, M. M., Al Juhaimi, F., Albakry, Z. (2025) The monitoring of accumulations of elements in apple, pear, and quince fruit parts. *Biological Trace Element Research*, 203, 1202-1208. DOI: <https://doi.org/10.1007/s12011-024-04223-3>
- Ali, L., Alsanius, B. W., Rosberg, A. K., Svensson, B., Nielsen, T., Olsson, M. E. (2012) Effects of nutrition strategy on the levels of nutrients and bioactive compounds in blackberries. *European Food Research and Technology*, 234, 33-44. DOI: <https://doi.org/10.1007/s00217-011-1604-8>
- Amarante, C. V. T. D., Souza, A. G. D., Benincá, T. D. T., Steffens, C. A. (2017) Phenolic content and antioxidant activity of fruit of Brazilian genotypes of feijoa. *Pesquisa Agropecuária Brasileira*, 52, (12), 1223-1230. DOI: <https://doi.org/10.1590/S0100-204X2017001200011>
- AMI: European Statistics Handbook. 2021. Berlin: Agrar Markt Informations GmbH.
- Bramlage, W. J., Drake, M., Lord, W. J. (1980) The influence of mineral nutrition on the quality and storage performance of pome fruits in North America. *Acta Horticulturae*, 92, 29-40. DOI: <https://doi.org/10.17660/ActaHortic.1980.92.4>
- Brunetto, G., Melo, G. W., Toselli, M., Quartieri, M., Tagliavini, M. (2015) The role of mineral nutrition on yields and fruit quality in grapevine, pear and apple. *Revista Brasileira de Fruticultura*, 37, 1089-1104. DOI: <https://doi.org/10.1590/0100-2945-103/15>
- Campeanu, G., Neata, G., Darjanschi, G. (2009) Chemical composition of the fruits of several apple cultivars growth as biological crop. *Notulae Botanicae Horti Agrobotanici*, 37, (2), 161-164. DOI: <https://doi.org/10.15835/nbha3723465>
- Cozma, A., Velcioc, A., Popescu, S., Mihut, C., DumaCopcea, A., Rada, M. (2022) Determination of some essential mineral elements from different tropical fruits. In: Alapi, T., Berkecz, R., Ilisz, I., eds. *Proceedings of the 28th International Symposium on Analytical and Environmental Problems*. Szeged, Hungary: 98-100.
- Doryanizadeh, M., Ghasemnezhad, M., Sabouri, A. (2017) Estimation of postharvest quality of 'Red Delicious' apple fruits based on fruit nutrient elements composition. *Journal of Agricultural Science*, 9, (1), 164-173. DOI: <https://doi.org/10.5539/jas.v9n1p164>

- Ferreira, C., Ribeiro, C. (2024) Effect of storage conditions on phenolic composition, vitamin C and antioxidant activity of 'Golden Delicious' and 'Red Delicious' apples. *Postharvest biology and technology*, 210, (21), 112754.
DOI: <https://doi.org/10.1016/j.postharvbio.2023.112754>
- Gago, C. M., Guerreiro, A. C., Miguel, G., Panagopoulos, T., Da Silva, M. M., Antunes, M. D. (2016) Effect of calcium chloride and 1-MCP (Smartfresh™) postharvest treatment on 'Golden Delicious' apple cold storage physiological disorders. *Scientia Horticulturae*, 211, 440-448. DOI: <https://doi.org/10.1016/j.scienta.2016.09.017>
- Granssee, A., Fühns, H. (2013) Magnesium mobility in soils as challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant and Soil*, 368, 5-21.
DOI: <https://doi.org/10.1007/s11104-012-1567-y>
- Habte, G., Choi, J. Y., Nho, E. Y., Jamila, N., Khan, N., Hwang, I.M., Kim, K. S. (2017) Determination of essential and toxic elements in tropical fruit by microwave-assisted digestion and inductively coupled plasma-mass spectrometry. *Analytical Letters*, 50, 1025-1039.
DOI: <https://doi.org/10.1080/00032719.2016.1207655>
- Hahn, L., Suzin, D. L., Argenta, L. C., Tiecher, T. L., Thewes, F. R., Moura-Bueno, J. M., Brunetto, G. (2022) Calcium applications on 'Fuji Suprema' and 'Maxi Gala' apple trees: fruit quality at harvest and after cold storage. *Bragantia*, 81, e0522.
DOI: <https://doi.org/10.1590/1678-4499.20210063>
- Jakobek, L., Ištuk, J., Buljeta, I., Voća, S., Žlabur, J. Š., Babojević, M. S. (2020) Traditional, indigenous apple varieties, a fruit with potential for beneficial effects: their quality traits and bioactive polyphenol contents. *Foods*, 9, (52), 1-18.
DOI: <https://doi.org/10.3390/foods9010052>
- Jemaneh, D., Chandravanshi, B. (2021) Mineral contents of Ethiopian red and green apple fruits: A comparison with WHO/FAO standards. *International Journal of Environment Analytical Chemistry*, 7, (2), 112-122. DOI: <https://doi.org/10.5281/zenodo.4572213>
- Johnston, J. W., Hewett, E. W., Hertog, M. T. M. (2002) Postharvest softening of apple (*Malus domestica*) fruit: A review. *New Zealand Journal of Crop and Horticultural Science*, 30, 145-160.
DOI: <https://doi.org/10.1080/01140671.2002.9514210>
- Kistechok, A., Wrona, D., Krupa, T. (2024) Effect of storage conditions on the storability and nutritional value of new Polish apples grown in central Poland. *Agriculture*, 14, (1), 59.
DOI: <https://doi.org/10.3390/agriculture14010059>
- Kljajić, N., Paraušić, V., Vuković, P. (2023) Economic aspects of fruit production in Serbia on the example of apple orchards. *Ekonomika*, 69, (4), 41-53. DOI: <https://doi.org/10.5937/ekonomika2304041K>
- Li, Q., Chen, Y., Fu, H., Cui, Z., Shi, L., Wang, L., Liu, Z. (2012) Health risk of heavy metals in food crops grown on reclaimed tidal flat soil in the Pearl River Estuary, China. *Journal of Hazardous Materials*, 227, 148-154. DOI: <https://doi.org/10.1016/j.jhazmat.2012.05.023>
- Macit, İ., Aydın, E., Tas, A., Gundogdu, M. (2021) Fruit quality properties of the local apple varieties of Anatolia. *Sustainability*, 13, (11), 6127.
DOI: <https://doi.org/10.3390/su13116127>
- Maeaba, W., Prasad, S. (2023) Assessment of nutritional potential with respect to macroelements in the tropical fruits from Solomon Islands. *Journal of Food Composition and Analysis*, 118, 105187.
DOI: <https://doi.org/10.1016/j.jfca.2023.105187>
- Magazin, N., Milić, B., Keserović, Z. (2022) Production and assortment of apple in Serbia. *Plant Doctor*, 50, (6), 411-426.
DOI: <https://doi.org/10.5937/BiljLek2206411M>
- Marcelle, R. D. (1995) Mineral nutrition and fruit quality. *Acta Horticulture*, 383, 219-226.
DOI: <https://doi.org/10.17660/ActaHortic.1995.383.22>
- Mészáros, M., Hnátková, H., Čonka, P., Náměstek, J. (2021) Linking mineral nutrition and fruit quality to growth intensity and crop load in apple. *Agronomy*, 11, (3), 506.
DOI: <https://doi.org/10.3390/agronomy11030506>
- Mičić, N., Đurić, G., Cvetković, M. (2005) Sistemi gajenja i rezidba jabuke [The cultivation systems and pruning of apple trees]. Čačak: Grafika Jureš.
- Milinković, M., Lalević, B., Raičević, B., Paunović, S. M. (2018) Application of 1-methylcyclopropene in fruit of five apple cultivars grown in Serbia. *Journal of Applied Botany and Food Quality*, 91, 296-303.
DOI: <https://doi.org/10.5073/JABFQ.2018.091.038>
- Morais, D. R., Rotta, E. M., Sargi, S. C., Bonafe, E. G., Suzuki, R. M., Souza, N. E., Matsushita, M., Visentainer, J. V. (2017) Proximate composition, mineral contents and fatty acid composition of the different parts and dried peels of tropical fruits cultivated in Brazil. *Journal of the Brazilian Chemical Society*, 28, (2), 308-318.
DOI: <https://doi.org/10.5935/0103-5053.20160178>
- Mozaffarian, D. (2016) Dietary and policy priorities for cardiovascular disease, diabetes, and obesity: a comprehensive review. *Journal of the American Heart Association*, 133, (2), 187-225.
DOI: <https://doi.org/10.1161/CIRCULATIONAHA.115.018585>
- Mratinić, E., Đurović, D. (2015) Biološke osnove čuvanja voća [Biological bases of fruit preservation]. Belgrade-Bor: Partenon and Vibeko Agrar.
- Musacchi, S., Serra, S. (2018) Apple fruit quality: Overview on pre-harvest factors. *Scientia Horticulturae*, 234, 409-430.
DOI: <https://doi.org/10.1016/j.scienta.2017.12.057>
- Nachtigall, G. R., Dechen, A.R. (2006) Seasonality of nutrients in leaves and fruits of apple trees. *Scientia Agricola*, 63, (5), 493-501.
DOI: <https://doi.org/10.1590/S0103-90162006000500012>
- Niyazova, Sh. A., Khasanov, Sh. Sh., Dodayev, Q. O. (2024) Nutrient composition of fruits stored at cold temperatures for export. *International Journal of Science Education*, 7, (6), 645-652.
DOI: <https://doi.org/10.5281/zenodo.12675250>
- Norton, G. J., Deacon, C. M., Mestrot, A., Feldmann, J., Jenkins, P., Baskaran, C., Meharg, A. A. (2015) Cadmium and lead in vegetable and fruit produce selected from specific regional areas of the UK. *Science of the Total Environment*, 533, 520-527.
DOI: <https://doi.org/10.1016/j.scitotenv.2015.06.130>
- Nour, V., Trandafir, I., Ionica, M. E. (2010) Compositional characteristics of fruits of several apple (*Malus domestica* Borkh.) cultivars. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 38, (3), 228-233.
DOI: <https://doi.org/10.15835/nbha3834762>
- Park, B. J., Cho, J. Y. (2011) Assessment of copper and zinc in soils and fruit with the age of an apple orchard. *Journal of the Korean Society for Applied Biological Chemistry*, 54, 910-914.
DOI: <https://doi.org/10.1007/BF03253179>
- Rehman, N. U., Hussain, J., Ali, L., Khan, A. L., Mabood, F., Gillani, S. A., Al-Harrasi, A. (2014) Nutritional assessment and mineral composition of some selected edible vegetables. *European Journal of Medicinal Plants*, 4, (4), 444. DOI: <https://doi.org/10.9734/EJMP/2014/5271>
- Rilak, B., Glišić, I., Lukić, M., Milošević, T., Tomić, J., Milinković, M. (2023) Influence of pre-harvest calcium spray on fruit quality of apple cultivars during cold storage. *Horticultural Science*, 50, (4), 262-274. DOI: <https://doi.org/10.17221/127/2022-HORTSCI>
- Rilak, B., Glišić, I.P., Tomić, J., Paunović, S. M., Pešaković, M., Anđelić, T., Karaklajić-Stajić, Ž. (2025) Segregation of apple cultivars based on phytochemical properties following calcium chloride foliar application. *Applied Fruit Science/Erwerbs-Obstbau*, 67, 208.
DOI: <https://doi.org/10.1007/s10341-025-01426-3>

- Rusin, M., Domagalska, J., Rogala, D., Razzaghi, M., Szymala, I. (2021) Concentration of cadmium and lead in vegetables and fruits. *Scientific reports*, 11, (1), 11913. DOI: <https://doi.org/10.1038/s41598-021-91554-z>
- Shahbandeh, M. (2022) Global production of fruit by variety selected 2022. Statista. Accessed January 19: 2025, from <https://www.statista.com/statistics/264001/worldwide-production-of-fruit-by-variety/>
- Skordas, K., Papastergios, G., Kantiranis, N., Filippidis, A. (2018) Elemental content of apple leaves from Central Greece-potential sources and interrelations. *Fresenius Environmental Bulletin*, 27, (12), 8244-8252.
- Spada, P. D., Bortolin, G. V., Prá, D., Santos, C. E., Dias, J. F., Henriques, J. A., Salvador, M. (2010) Macro and micro minerals: are frozen fruits a good source? *Annals of the Brazilian Academy of Sciences*, 82, (4), 861-867. DOI: <https://doi.org/10.1590/S0001-37652010000400008>
- Struk, O., Starchenko, G., Koshovyi, O., Stremoukhov, O., Klymenko, Y., Raal, A. (2024) Mineral composition of black currant (*Ribes nigrum* L.) fruits and leaves. *Open Agriculture Journal*, 18, (1). DOI: <http://dx.doi.org/10.2174/0118743315309357240507103606>
- Sun, Q., Li, K., Zhang, G., Li, D., Chai, X., Wu, T., Zhang, X., Xu, X., Han, Z., Wang, Y. (2020) Characterization of Fe deficiency induced Ring finger family members in apple species. *Plant Gene*, 21,100209. DOI: <https://doi.org/10.1016/j.plgene.2019.100209>
- Turra, C., Fernandes, E. A., Bacchi, M. A., Barbosa Júnior, F., Sarriés, G. A., Blumer, L. (2011) Chemical elements in organic and conventional sweet oranges. *Biological Trace Element Research*, 144, 1289-1294. DOI: <https://doi.org/10.1007/s12011-011-9127-5>
- Wang, Q., Liu, J., Cheng, S. (2015) Heavy metals in apple orchard soils and fruits and their health risks in Liaodong Peninsula, Northeast China. *Environmental monitoring and assessment*, 187, (1), 4178. DOI: <https://doi.org/10.1007/s10661-014-4178-7>
- Who, J. (2003) Consultation: nutrition and the prevention of chronic diseases. *World Health Organization Technical Report Series*, 916, 1-149.
- Wicklund, T., Guyot, S., Le Quéré, J. (2021) Chemical composition of apples cultivated in Norway. *Crops*, 1, (1), 8-19. DOI: <https://doi.org/10.3390/crops1010003>
- Wińska-Krysiak, M., Łata, B. (2010) Influence of lipoxygenase activity and calcium and potassium contents on bitter pit occurrence in commercial apple cultivars. *Folia Horticulturae*, 22, 13-17. DOI: <https://doi.org/10.2478/fhort-2013-0145>
- Wojcik, P. P. (2004) Nutrition and calcium fertilization of apple trees. Dordrecht, Netherland, Springer.
- Zavalloni, C., Marangoni, B., Tagliavini, M., Scudellari, D. (2001) Dynamics of uptake of calcium, potassium and magnesium into apple fruit in high density planting. *Acta Horticulturae*, 564, 113-122. DOI: <https://doi.org/10.17660/ActaHortic.2001.564.12>