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Mixing fruits in ready-to-eat packaging leads to physiological changes that modify quality attributes and antioxidant composition

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ABSTRACT

Fresh-cut fruits in ready-to-eat packaging are convenient healthy snacks that can be composed of one type of fruit or a mixture of different fruits to attract consumer's attention. However, to date, no studies have been performed to determine whether fruit mixing could impair fruit quality traits or their shelf-life. Here, we aimed at evaluating quality and hormonal changes in unmixed and mixed cut fruits in packaging of kiwis, mangoes, oranges and pineapples over a 6-day period in cold storage to (i) determine endogenous events compromising cut fruit quality and (ii) assess whether fruit mixing could have an impact in their storage. Results showed fruit cutting led to rapid losses in water content and firmness, while respiration rates increased. Fruit mixing altered several quality parameters, delaying firmness loss in mangoes, oranges and pineapples, and increasing ratios of sugars by acids (TSS/TA) over time. Fruit mixing increased vitamin C contents in mangoes and oranges but decreased total phenols accumulation in oranges and pineapples. Kiwis had an opposite pattern of vitamin C accumulation, with unmixed kiwis having the highest ascorbate contents, while no significant differences were found for total phenols. Increased abscisic acid contents were also found in mangoes, oranges and pineapples of unmixed packaging, and kiwis displaying a much lower accumulation compared to the other fruits. Other phytohormones were also affected by fruit composition, suggesting an active involvement in fruit quality regulation. In conclusion, fruit composition in ready-to-eat packaging is an important factor determining the final quality and shelf-life of cut fruits.

1. Introduction

Rushing lifestyles trying to keep a balanced and healthy diet have promoted the widespread presence of fresh-cut fruit and vegetables in ready-to-eat packaging at food markets. Although convenient, this form of fresh fruit distribution leaves a smaller window for their consumption due to the shorter shelf life resulting from processing methods, such as peeling, slicing, or dicing, among others (Ma et al., 2017). In fact, handling and processing of fresh fruit for ready-to-eat packaging induce a series of physiological changes associated with wounding stress, increasing fruit respiration rates and ethylene production, accelerating fruit ripening, promoting browning of the cut surface, increasing the production of secondary metabolites and off-flavours, while promoting cell wall degradation and accelerated softening (Baldwin & Bai, 2011).

Several approaches have been implemented to control wounding effects related to ethylene production and increased respiration rates, including precooling, modified atmosphere packaging (MAP) and other active packaging, such as 1-methylcyclopropene (1-MCP) or ethylene absorbents (Soliva-Fortuny & Martín-Belloso, 2003). Even though these techniques might be effective for some fruits, especially in climacteric fruits where ethylene is the main phytohormone driving postharvest overripening, they might not work so efficiently for fruits described as non-climacteric where ethylene plays a minor role. Besides, wound-stress responses of cut fruit have also been related to the activation of other hormonal groups, like the jasmonic acid (JA), salicylic acid (SA) or abscisic acid (ABA) pathways that activate wound responsive genes (Han et al., 2018; Li et al., 1992; Wasternack et al., 2006). However, there is still no information on how other group of hormones with potential delayed ripening effects (Xiang et al., 2020), like gibberellins (GAs), cytokinins (CKs) or auxins, such as indole-3-acetic acid

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(IAA), participate in the wound response after fruit is cut.

Antioxidant composition after fruit processing is also altered by increased production rates of reactive oxygen species (ROS) from cell wall disassembly and increased respiration rates after wounding (Cisneros-Zevallos, 2003; Li et al., 2018; Reyes et al., 2007). For instance, it is well documented that fruit cutting elicits phenol biosynthesis in apple (Murata et al. 1995), mango (Robles-Sánchez et al., 2013), pitaya fruit (Li et al., 2017) or kiwis (Wei, Guan, et al., 2021). Although these antioxidants have a high antioxidant activity to counteract ROS production, their accumulation is undesirable in cut fruits since they induce tissue browning (Baldwin & Bai, 2011). Other antioxidants like ascorbic acid can have beneficial properties both for the maintenance of cut fruit and for human consumption. However, its role in wounding is still not fully clear since different patterns have been found after fruit cutting and final composition is even affected by cutting intensity (Solomon et al., 2018).

A common practice in ready-to-eat packaging is to create compositions of mixed fruits, to increase hedonic appreciation and aesthetics of the packaging by the combination of fruits with different colors and sizes (Mielby et al., 2012). Even though this practice can be useful to increase complexity and attractiveness of cut fruit packaging, mixing different types of fruit with contrasting postharvest performance may influence quality attributes and shelf-life of these fruits. In the present study, kiwis, mangoes, oranges and pineapples, which have a differential postharvest regulation and require peeling and slicing for their consumption in ready-to-eat packaging, were selected to analyze undergoing physiological changes in single-fruit packaging (onwards from here named unmixed) or packaging with a mixed composition of all four fruits. Ultimately, we aimed at examining whether or not fruit mixing alters fruit quality attributes and fruit shelf-life.

2. Materials and methods

2.1. Fruit material, packaging, and samplings

Whole fruit pieces of kiwi (*Actinidia deliciosa* var. Hayward), mango (*Mangifera indica* var. Osteen), orange (*Actinidia deliciosa* var. Navel Lane Late) and pineapple (*Ananas comosus* var. Cayenne Lisse) were purchased at commercial ripe stage (BBCH 89 for oranges and kiwis, and BBCH 87 for mangoes and pineapples) and transferred to the lab for peeling, cutting, mixing and immediate distribution in the bowls of packaging. For each fruit, approximately 100g were weighed, separated and sealed in bowls of 400 mL with polyethylene plastic film, having a total of 20 bowls per fruit, 5 bowls for each sampling point. The fruit mix was performed by adding two pieces of each fruit to each packaging, so that there was 100g of fruit per bowl. An initial time point was performed with 100g of each fruit after cutting and mixing, taking five times this amount prior to fruit distribution into packaging. All bowls were kept at 4 °C and only five bowls per fruit were taken for each sampling performed at 1, 2, 4 and 6 days after fruit cutting. For each sampling, half of the fruit was used *in situ* for quality measurements and the other half immediately frozen in liquid nitrogen and stored at −80 °C until biochemical analyses were performed.

2.2. Respiration, water loss and quality measurements

To determine respiration rates during cold storage of fresh-cut fruits, CO_2 production was measured at each sampling day with a headspace gas analyzer OXYBABY® 6.0 (WITT Gas Techniques, Witten, Germany) by injecting the needle into the plastic film of each packaging and atmospheric CO_2 was used for calibration. Afterwards, water losses were assessed by weighing each bowl once excess water was removed and calculated by the difference from initial weights.

To describe organoleptic changes during the storage of fresh-cut fruit, quality measurements were performed, including total soluble solids (TSS), titratable acidity (TA), pH and fruit firmness. TSS were determined with a refractometer (Hanna Instruments, Salerno, Italy) evaluating 1 mL of fruit juice to obtain °Brix (Boulton et al. 1999). On the other hand, TA and pH were measured from 5g of grinded fruit and resuspended in 10 mL of distilled water. From this mixture, pH was assessed with a Crison pH-meter (Crison Instruments, Barcelona, Spain). Afterwards, 10 mL of the mixture were diluted with 100 mL of distilled water and TA estimated with an acid-base titration with NaOH 0,1M and phenolphthalein 1% as indicator and expressed as citric acid equivalents (Latimer, 2012). Along with these quality parameters, fruit firmness was measured with a PCE-PTR 200 penetrometer (PCE instruments, Southampton, UK) and expressed in kg.

2.3. Antioxidant analysis

To understand the physiological patterns on antioxidant accumulation in cut fruits of ready-to-eat packaging, total phenols, vitamin C and the redox state of ascorbate were estimated. Total phenols were determined by the Folin-Ciocalteu method and calculated as gallic acid equivalents (GAE) (Kähkönen et al. 1999). Briefly, 1g of grinded fruit were extracted with 2 mL of cold methanol in a 25 mL tube, homogenized with an ULTRA-TURRAX (IKA-Werke, Staufen im Breisgau, Germany) for 90s and then centrifuged at 12000 rpm for 5 min at 4 °C. Supernatant was recovered and pellet re-extracted with another 2 mL of cold methanol. Both supernatants were pooled and 20 μL of each sample were reacted with 80 μL of Folin-Ciocalteu and 80 μL of sodium carbonate 20% in a 96-multiwell plate for 1h in the dark. After the dark incubation, 80 μL MiliQ water were added, and absorbance read at 765 nm. For calculations, a standard curve of gallic acid was performed.

For measurements of vitamin C contents and the estimation of ascorbate redox state, ascorbic acid (AA) and dehydroascorbate (DHA) were determined as described in Miret and Munné-Bosch (2016) with some modifications. For this, 50 mg of grinded fruit were extracted with 175 μL of cold extraction buffer made up with 6% (w/v) meta-phosphoric acid and 0.2 mM diethylene triamine pentaacetic acid. After vortexing, cold ultrasonication for 20 min and centrifugation at 13000 rpm for 10 min at 4 °C, supernatant was recovered, and pellet re-extracted with 175 μL of the cold extraction buffer. Both supernatants were pooled and vitamin C determinations were performed in triplicate following Queval and Noctor (2007) using a 96-multiwell quartz plate (Hellma, Müllheim, Germany). Vitamin C redox state was calculated as AA/(AA + DHA) and expressed as a percentage.

2.4. Phytohormones determination

Phytohormones from cut fruits were extracted from 100 mg of each fruit grinded in liquid nitrogen as described by Müller and Munné-Bosch (2011). Sample tissue was spiked with the isotopically labelled internal standard and then extracted with 250 μl of cold methanol with 0.01% glacial acetic acid (v/v) using ultrasonication for 30 min, vortexed and centrifuged (13000 rpm for 15 min at 4 °C). Supernatant was then collected, and the pellet re-extracted with 250 μl of methanol with 0.01% (v/v) glacial acetic acid. All supernatants were combined, centrifuged (13000 rpm for 5 min at 4 °C) and filtered through a 0.22 μm PTFE filter (Phenomenex, Torrance, CA, USA) to be analyzed using a UHPLC/ESI–MS/MS system. The LC system consisted of an Aquity UHPLC TM System (Waters, Milford, MA USA) and phytohormones in samples (5 μl) were first separated on a C18 Kinetex column (50 × 2.1 mm, 1.7 μm; Phenomenex, Macclesfield, UK). MS/MS experiments and detection were performed on an API3000 triple quadruple mass spectrometer (PE Sciex, Concord, Ont., Canada) by using multiple reaction monitoring (MRM) in negative and positive ion mode. The optimized MS/MS conditions were determined in infusion experiments using a purified standard and its isotopically labelled internal standard. MRM transitions were used as described by Müller and Munné-Bosch (2011). Quantification was performed by a ten-point calibration curve including an isotopically labelled internal standard for each phytohormone using

Analyst™ software (PE Sciex, Concord, Ont., Canada).

2.5. Statistical analysis

Statistical tests were performed with SPSS 27.0 statistical package. To estimate the effect of packaging over time and composition mean values were tested by two-way ANOVA and Tukey post hoc test to determine statistical differences at different times after fruit cutting. Tukey post hoc tests were also used to determine statistical differences of packaging composition at specific time points. Pearson correlations were performed for each fruit to describe putative relationships between quality parameters, antioxidants and hormonal composition.

3. Results

3.1. Changes in fruit quality parameters related to packaging composition

Analysis of quality parameters in mixed and unmixed cut fruit packaging resulted in differences related to packaging composition (Fig. 1A). In general, kiwis and mangoes had a mild progressive loss of water over the days of analysis and a maximum of 1g of water loss, while oranges and pineapples exhibited severe water losses after fruit cutting that increased up until the end of the experiment, and led to severe dehydration (Fig. 1b). Likewise, when considering the packaging of fruit mixture, water loss values achieved similar levels to the ones registered for oranges and pineapples, showing a rapid loss of water from the first day of experiment and abrupt increases towards the end (Fig. 1b). In contrast, when considering CO_2 production in the packaging, kiwi was the only fruit with a high increase in CO_2 accumulation, starting from the day after cutting with about 3-times the initial values and only decreased after two days of cold storage (Fig. 1b). All other fruits, either did not show variations in CO_2 accumulation like mangoes or had a low production, as it was the case for oranges and pineapples (Fig. 1b). On the other hand, the mix of fruits presented an increase in the accumulation of CO_2 from the second day onwards, which contrasted with the pattern of CO_2 accumulation in the packaging of individual fruits (Fig. 1b).

Fruit mixing impaired fruit quality parameters with increases in TSS and TA, pointing out symptoms of accelerated overripening in mango, orange and pineapple, even though these fruits also retained better firmness values when mixed fruit (Fig. 2). From all fruits, kiwis had fewer variations in quality parameters during cold storage, mostly found towards the end of the evaluation (Fig. 2). For instance, the lowest values of TSS were found after four days of packaging and were 3% lower than at the beginning of the experiment. Nevertheless, fruit firmness was the parameter with higher variations, progressively decreasing from the second day until the end of their storage. After cutting, pH also had a slight increase in kiwis but remained stable for the following days. In fact, pH was the only parameter showing statistical differences between kiwis in unmixed and mixed packaging, but these changes were not greater than 5% (Fig. 2). Mango, orange and pineapple had higher differences in quality traits than kiwi both over storage time

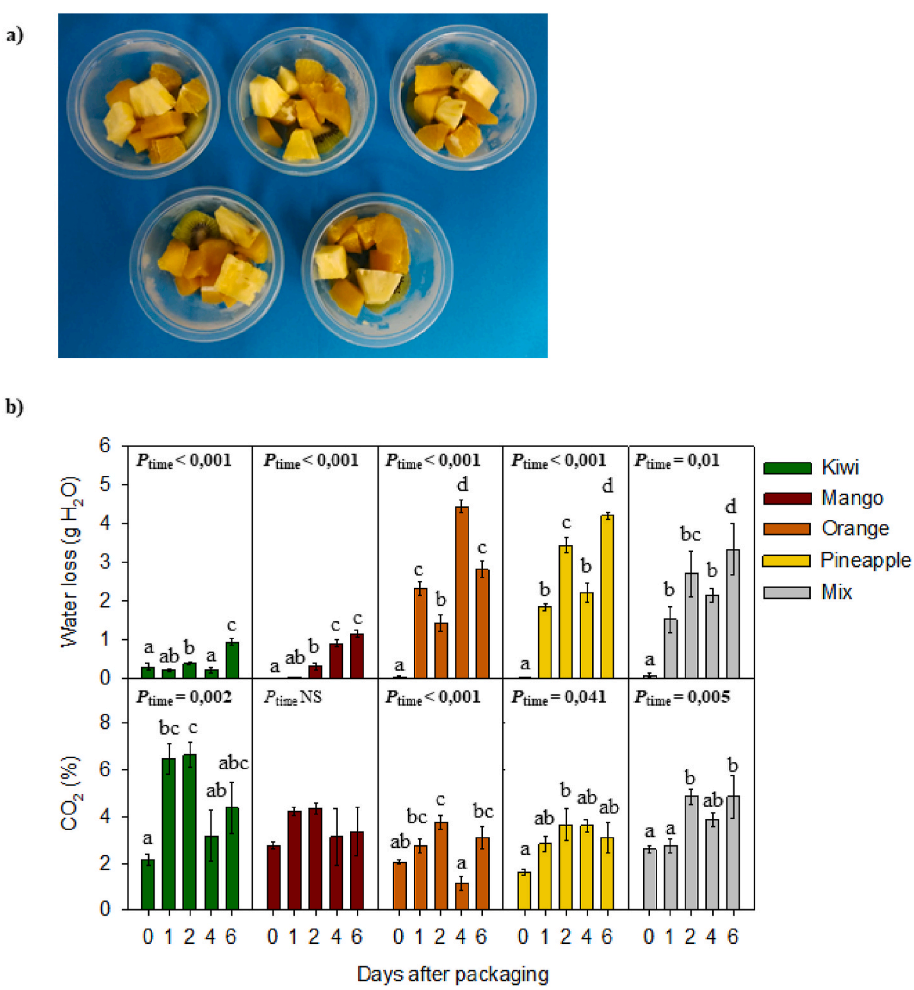

Fig. 1. A) Example of mixed fruit in bowls as ready-to-eat packaging and **b)** Water losses and CO_2 accumulation in individual and mixed bowls of kiwi, mango, orange and pineapple. Data show the mean ± SE of n = 5. Different letters indicate significant differences between days of storage ($P < 0.05$) using Tukey post hoc tests. NS, Not significant.

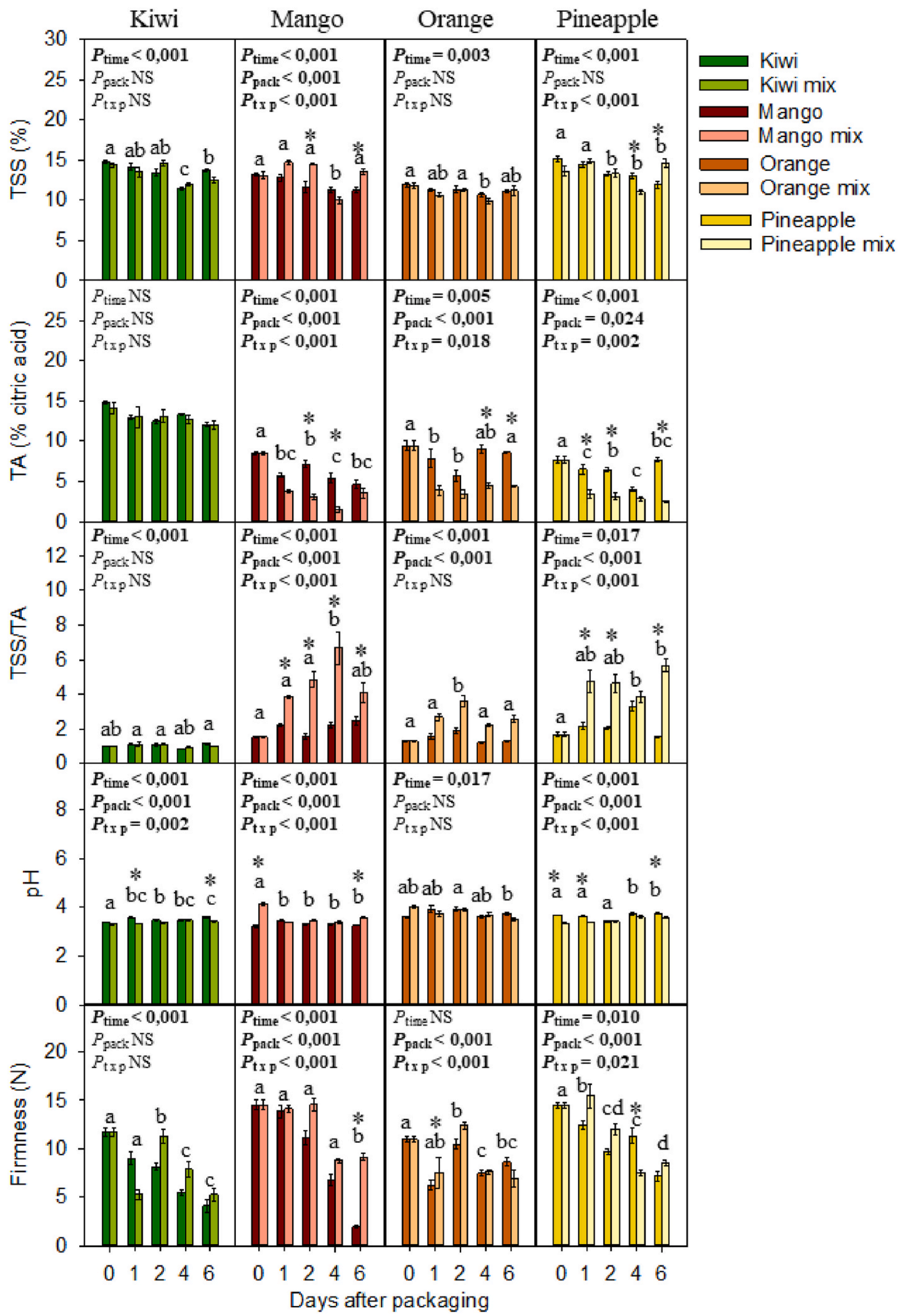

Fig. 2. Quality parameters of kiwi, mango, orange and pineapple slices in unmixed and mixed packaging. Total soluble solids (TSS); Titratable acidity (TA). Data show the mean ± SE of n = 5 in all cases, except for pH, in which n = 3. Different letters indicate significant differences between days after packaging ($P < 0.05$) using Tukey post hoc tests and asterisks indicate significant differences between packaging composition. NS, Not significant.

and comparing different packaging composition. TSS values in mango remained almost constant throughout storage. However, TA progressively declined from fruit cutting-onwards, and resulted in TSS/TA increases that were greater for mangoes of the mix than in unmixed packaging. In fact, mangoes from mixes showed increases in the TSS/TA ratio 2–3 times higher than those registered for mangoes in unmixed packaging. The maximum values of TSS/TA were acquired after 4-day storage in mangoes of mixes, but later decreased to after cutting values (Fig. 2). Values of pH only had slight variations in mangoes since pH values remained almost constant around 3.5 (Fig. 2). As in kiwis, firmness in mango slices also decreased progressively during storage but those in the mixed packaging retained fruit firmness for a longer period and had 4-times higher values on the last day of analysis (Fig. 2). In oranges, TSS values were more stable than in mangoes, with slight variations over time. Nevertheless, as in mangoes, TA values in oranges also declined the day after cutting and only stabilized afterwards, which lead to almost constant values of TSS/TA (Fig. 2). Even so, oranges in mixed packaging had a smaller reduction of TA and consequently, achieved higher levels of TSS/TA than oranges of unmixed packaging. At the same time, oranges did not show reductions in firmness values during storage and only slight variations were found for pH (Fig. 2). In fact, differences between mixed and unmixed oranges were only found for firmness values the day following fruit cutting, where oranges from mixed fruits had a delay in firmness reduction but afterwards followed the same pattern as oranges in unmixed packaging (Fig. 2). Quality traits of pineapples mimicked mango dynamics after cutting and also showed reductions in TSS and TA over the time of analysis in cold storage (Fig. 2). As in mangoes, slices of pineapple in mixed packaging also had increased values of TSS/TA from the first day after cutting and kept these higher values until the end, 6 days afterwards where differences in pineapple between mixed and unmixed packaging were greater than previous days (Fig. 2). In this case, pineapple of unmixed packaging showed slightly higher values of pH than those that were in mixes, but in general, pH remained constant and had mild increases towards the end of storage. Pineapples also had firmness reductions over time, attaining the lowest values the last day of analysis, 6-days after fruit cutting. Likewise, pineapples from mixed packaging had greater values of fruit firmness after cutting, except for at the 4th day of analysis, where pineapples from unmixed packaging showed a transient increase in fruit firmness. However, unlike mangoes, pineapples from both packaging compositions achieved the same firmness levels at the end of the experiment (Fig. 2).

3.2. Antioxidants of fresh-cut fruits are positively affected by packaging composition

Fruit mixing conditioned antioxidant composition in cut fruits with benefits for mangoes, oranges and pineapples but a detrimental effect for kiwis (Fig. 3). In total phenols, two distinct patterns were identified between all fruits. On one hand, kiwis and mangoes showed an initial reduction of total phenol contents the day after fruit cutting and packaging, and these were 15 and 67% lower than initial values for kiwi and mango, respectively. On the other hand, packaging composition resulted in a differential accumulation of total phenol contents in oranges and pineapples. While oranges did not show statistical differences in phenol contents over the time of storage after fruit cutting, higher contents of these antioxidants were found for oranges in non-mixed packaging (Fig. 3). Likewise, pineapples also had statistical differences regarding packaging composition where slices of pineapple from the mixed packaging showed an initial reduction in total phenols that was not experienced by pineapple from unmixed packaging. In pineapples, the initial reduction 1 day after fruit cutting in mixed made the greatest difference in phenol content between packaging and was 4-times lower than pineapples from unmixed packaging (Fig. 3).

Vitamin C contents were also affected by fruit type and packaging composition over storage, having an important detriment for kiwis but enhanced benefits for mangoes and pineapples when mixed (Fig. 3). Particularly, vitamin C contents in kiwis decreased the first day after cutting and cold storage but thereafter increased and remained stable until the end of the experiment. These changes were different regarding packaging composition, since kiwi slices from unmixed packaging had greater contents of vitamin C. In fact, after 6-day storage, kiwi fruit from the unmixed packaging had twice the contents estimated for kiwis from the mix packaging with other fruits (Fig. 3). That was not the case for mangoes and oranges, where the contents of vitamin C decreased in non-mixed packaging. In mangoes, vitamin C contents mango slices from unmixed packaging reduced their content up to 85% and led to almost undetectable values. In contrast, mangoes from the packaging with mixed fruits increased vitamin C contents achieved the maximum 6-days after fruit cutting and storage, around 10% higher than initial values (Fig. 3). For oranges, differences in vitamin C accumulation between different packaging started the day after cutting and storage. Slices from the non-mixed packaging had a major loss in vitamin C contents 2-days after fruit cutting. Vitamin C contents of oranges from the mixed packaging decreased after 6-days of storage and there were no significant differences with the unmixed packaging (Fig. 3). Unlike all other fruits, packaging composition was not a significant factor for vitamin C contents in pineapples.Thereafter, vitamin C contents decreased in

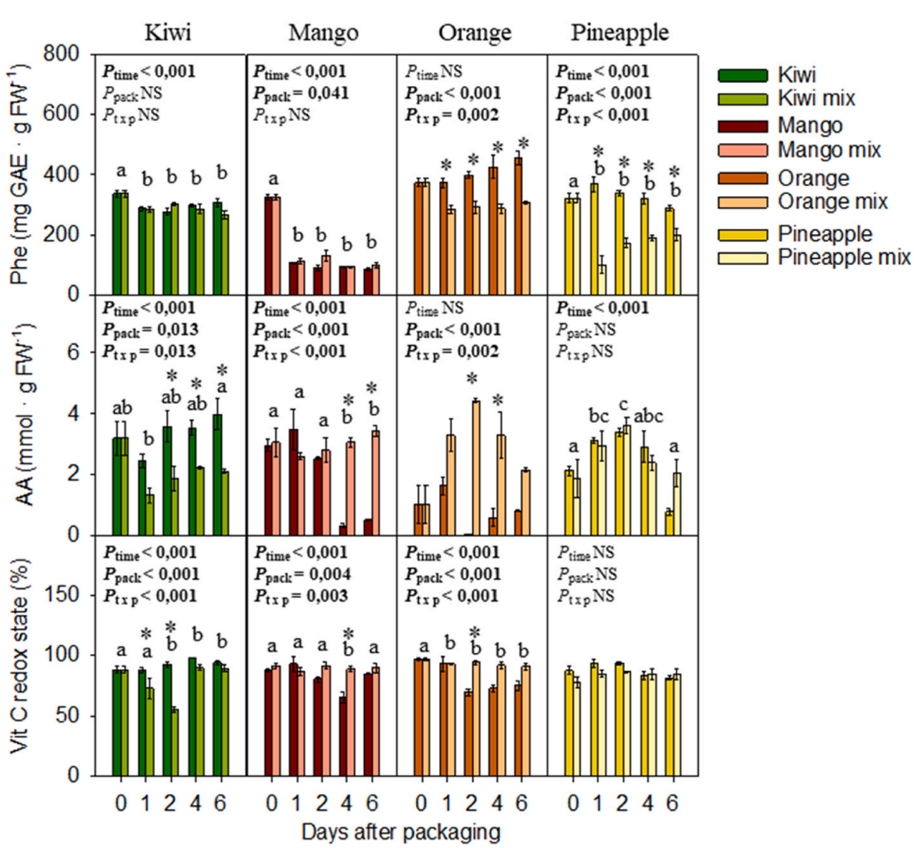

Fig. 3. Antioxidants in fresh-cut fruits with different packaging composition. Total phenols (Phe); vitamin C (vit C). See materials and methods for vitamin C redox state calculations. Data show the mean ± SE of n = 5 for total phenols and n = 3 for vitamin C. Different letters indicate significant differences between days after packaging ($P < 0.05$) using Tukey post hoc tests and asterisks indicate significant differences between packaging composition. NS, Not significant.

pineapples of both packaging compositions and reestablished to the values registered at the beginning of the experiment (Fig. 3). Likewise, the redox state of vitamin C followed a similar trend to the ones described for vitamin C contents and differences between packaging composition were also significant with contrasted patterns between kiwis and the dynamics of mangoes and oranges (Fig. 3). Thereafter, the vitamin C redox state of kiwi in mixed packaging restored to the same values as the non-mixed kiwi and remained constant until the end of the experiment, 6 days after fruit cutting and storage (Fig. 3). Contrary, mango and orange in mixed packaging were the ones with a more stable vitamin C redox state than the unmixed counterparts.

3.3. Phytohormone composition in cut and mixed fruits

ABA was one of the phytohormones with higher variations in fruits (Fig. 4). In kiwis, only small contents of ABA were found, but kiwis from the mixed packaging accumulated slightly higher contents of this phytohormone, although such increases were not higher than 25% (Fig. 4). Contrary, greater differences were found in mango, orange and pineapple for ABA contents with regards to packaging composition. Differences in ABA accumulation in mango from different packaging were even greater by the end of the experiment, 6 days after fruit cutting and storage, when mango from the unmixed packaging accumulated the highest contents of ABA (Fig. 4). A strong negative correlation was found between ABA accumulation and total vitamin C contents in mangoes, while there was a positive correlation between this phytohormone and mango fruit firmness (Suppl. Table 2). Likewise, orange also had significant differences in ABA accumulation considering packaging composition, starting earlier than in mango, the second day after fruit cutting. Besides, in oranges, ABA had strong positive correlations with TA and total phenols, but a very strong negative correlation with the TSS/TA parameter and ascorbate and its redox state (Suppl. Table 3). As for pineapple, this fruit had fewer variations in ABA contents and endogenous increases of this phytohormone were found 6-days after packaging but only on pineapple slices from the unmixed packaging and were 6 times higher than those registered for the mixed packaging. Nevertheless, a strong negative correlation was also found between ABA and the redox state of ascorbate in pineapple (Suppl. Table 4). So, in general except for kiwis, ABA contents were greater in fruits from the unmixed packaging than those in the mix.

At the same time, ACC contents also showed differences between fruits (Fig. 4). The day after fruit cutting and packaging, kiwis had a reduction in the ACC contents of 30% in both packaging composition but 2 days after packaging, kiwis from the unmixed packaging restored

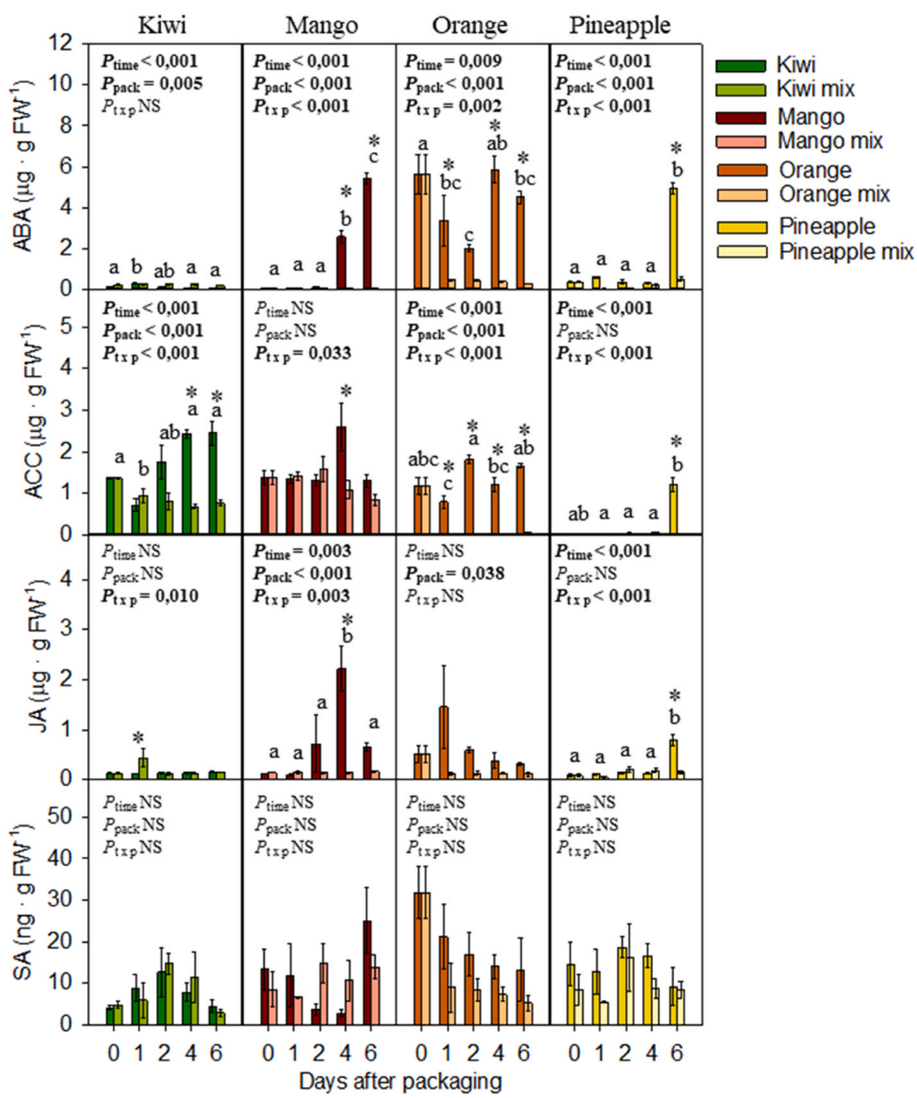

Fig. 4. Hormonal contents of abscisic acid (ABA), 1-aminocyclopropane-1-carboxylic acid (ACC), jasmonic acid (JA) and salicylic acid (SA) in fruits of different packaging composition. Data show the mean ± SE of n = 3. Different letters indicate significant differences between days after packaging (P < 0.05) using Tukey post hoc tests and asterisks indicate significant differences between packaging composition. NS, Not significant.

initial levels and even surpassed them between 4 and 6 days of storage. In opposition to this pattern, ACC contents of kiwi slices from the mixed packaging remained after the initial drop and the highest difference between the two-packaging composition was 4-days after cutting. ACC in kiwis had a strong positive correlation with total ascorbate values but showed a negative correlation with ABA in this fruit (Suppl. Table 1). In mango, ACC contents only had transient variations regarding packaging composition and no differences were found over time. In contrast, a severe reduction in ACC contents was found for oranges of the mixed packaging, whose levels decreased by 99% to almost undetectable contents the day after fruit cutting (Fig. 4). Unlike kiwis, in mango, orange and pineapple there was the opposite pattern of correlations with ACC, which had a strong negative correlation with total ascorbate, and a positive correlation with ABA for orange and pineapple (Suppl. Table 2–4). Therefore, for all fruits ACC contents were higher at the unmixed packaging transitorily or over time, relying upon fruit type, but there were contrasting patterns between this phytohormone and ascorbate or ABA, depending on whether kiwifruit or all other fruits were involved.

Lesser variations were found for JA between fruits and packaging composition (Fig. 4). While kiwis only showed a single time point where JA contents were higher in the mixed packaging than in the non-mixed packaging by 20% the day after cutting, mango had a peak of JA at 4-days after fruit cutting and packaging in the slices from the unmixed packaging, which was twice higher than the values obtained in fruits from the mixed packaging. Nevertheless, afterwards, these contents decreased, and no differences were found in mango from different packaging compositions by the end of storage (Fig. 4). Besides, pineapples also had an increase in JA contents in the slices from the unmixed packaging. In general, oranges from the unmixed packaging had higher contents than the ones in the mix, but without a specific production at a single time point (Fig. 4).

No differences in the hormonal contents of GAs were found during storage after fruit cutting except for pineapple slices, which showed a transitory increase in the contents of GA_4 at the second day of storage for both packaging composition (Fig. 5). Nevertheless, in general, higher contents of GA_1, GA_3 and GA_7 were found for cut mango from the unmixed packaging, while only GA_4 was higher in mango from the mix. Indeed, mango from the unmixed packaging had twice the contents of GA_1 and GA_3 than mango from the mix (Fig. 5). That was also the case of oranges, were GAs contents were also higher in the unmixed packaging than those in the mix, with the exception of GA_4 were oranges from the mix had higher contents, while no differences were found for GA_3 (Fig. 5). From all fruits, kiwi was the only one with no differences in GAs contents between different packaging composition. In contrast, endogenous accumulation of IAA was very low for all fruits and also showed variations between fruits and packaging but not over storage (Fig. 6a). While kiwi and mango did not show any differences neither over time, nor for packaging composition, orange presented statistical differences for packaging composition and those slices from the mixed packaging, had greater contents of IAA than the cut oranges from the unmixed packaging (Fig. 6a). Inversely, the first day after fruit cutting, pineapple of the unmixed packaging accumulated up to 80% higher contents of IAA than slices of pineapple from the mix packaging (Fig. 6a).

Kiwis had specific CKs accumulation due packaging composition with contrasting patterns regarding CKs groups. For instance, higher contents of *t*-Z and its precursor *t*-ZR were found in cut kiwis from the unmixed packaging (Fig. 6). In contrast, 2iP and IPA had the opposite pattern of accumulation and greater contents of these phytohormones were found in cut kiwi from the mixed packaging over the timing of storage. Indeed, the main differences between packaging's for 2iP contents was found 4-days after fruit cutting, when kiwi from mixed bowls had 92% higher contents than those from the unmixed (Fig. 6). Moreover, in kiwi slices, a strong correlation was found between CKs contents and ABA or ACC. While there was a significant negative correlation between *t*-Z or *t*-ZR contents and ABA, this phytohormone had a positive correlation with 2iP and IPA in kiwifruits. The opposite correlation pattern was found for ACC, which positively correlated with *t*-Z and *t*-ZR but had a negative correlation with 2iP and IPA (Suppl. Table 1). All other fruits had a more general increase/decrease in CKs contents with regards of packaging composition and while mango accumulated similar contents of CKs, these were much lower for orange and pineapple from both packaging. Besides, 2iP had a high variability in mango and no differences were found neither for packaging, nor over time, but cut mango from the mix packaging had greater contents of IPA over time and showed a peak at 4-days after packaging, where these fruits had twice the contents than mango slices from the non-mixed packaging (Fig. 6). Furthermore, *t*-Z and *t*-ZR contents were higher in mango slices from the mix than in the mixed packaging, specially towards the end (Fig. 6) and a positive correlation was found between this group of CKs and quality and antioxidant parameters (Suppl. Table 2). In contrast, a strong negative correlation was found for all CKs with ABA and JA in mangoes (Suppl. Table 2). Even orange fruits had lower contents than kiwis and mangos, packaging also influenced the endogenous accumulation of CKs. In this line, orange from the unmixed packaging had greater contents of all CKs studied in the analysis, being *t*-Z and *t*-ZR differentially accumulated between the 4th and 6th day after fruit cutting, where the contents of these phytohormones were around 95% higher in orange from the unmixed packaging than the slices from the mix (Fig. 6). Pineapples accumulated very low contents of CKs with values like those found for oranges.

Table 1
Mixing effects on fruit quality and antioxidant composition versus single-fruit packaging. NS, not significant.

	Kiwi	Mango	Orange	Pineapple
TSS	NS	Better	NS	NS
TA	NS	Better	Better	Better
TSS/TA	NS	Better	Better	Better
Firmness	NS	Better	Better	Better
pH	Worse	Better	NS	Worse
Total phenols	NS	Worse	Better	Better
Total vitamin C	Worse	Better	Better	NS
Vitamin C redox state	Worse	Better	Better	NS

4. Discussion

4.1. Fruit mixing in the packaging improves quality traits and promotes better preservation in minimally processed fruits

It is well stablished that fresh-cut fruits have shorter shelf-life than whole fruits during postharvest because of the wounding-like response after peeling and slicing operations required for packaging that unleash physiological changes in cut-fruits commodities (Baldwin & Bai, 2011; Ma et al., 2017). In this sense, our results on water loss and respiration rates are in accordance with previous studies performed on mangoes (Ali et al., 2004), pineapples (Pizato et al., 2019) or kiwis (Manzoor et al., 2021), which reported lower water contents and increased respiration rates after fruit cutting. In this case, the mixed fruit packaging also showed the same trend than oranges and pineapples of the unmixed packaging for water loss and CO_2 accumulation, probably due to the mixed effects detected for individual fruits. However, for any of the fruits or fruit composition, packaging atmosphere did not evolve to semi-anaerobic conditions ($\geq$20% CO_2) that usually lead to the production of fruit off-odors that could lead to consumers' rejection (Rux et al., 2021). Nevertheless, when looking at fruit quality parameters such as TSS or TA, a differential pattern was found between fruit packaging compositions in mangoes, oranges and pineapples but not in kiwis. It is known that, in general, during fruit postharvest there is an increase in the sugar-acid metabolism both related to the respiratory burst and in response to environmental stress factors (Brizzolara et al., 2020) that are linked to lower levels of TSS and TA over time. Kiwifruits

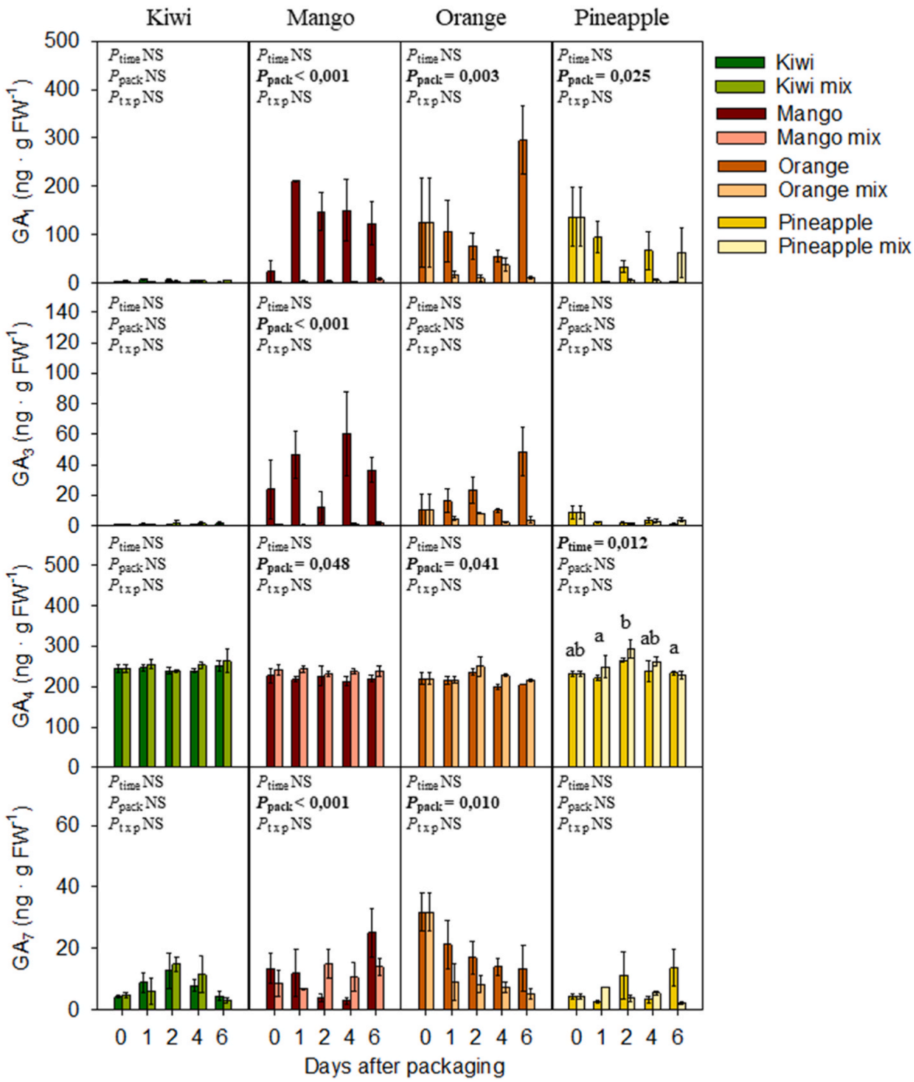

Fig. 5. Gibberellin (GAs) contents in cut-fruits stored in different packaging composition. Data show the mean ± SE of n = 3. Different letters indicate significant differences between days after packaging (P < 0.05) using Tukey post hoc tests and asterisks indicate significant differences between packaging composition. NS, Not significant.

followed this pattern of TSS and TA accumulation in both unmixed and mixed packaging and had lesser contents towards the end of the experiment, but in all other fruits, the mix composition had greater reductions in TA than fruits from the unmixed packaging. These results could indicate that fruit mixing was accelerating over ripening in the fruit slices, especially in terms of acid metabolism and, in consequence, also changed the profile of the TSS/TA of mango, orange and pineapple of the mix. Other experiments performed in mangoes (Salinas-Hernández et al., 2015), showed a decrease in TSS values over time, a quality attribute that negatively affected consumers' perception of the fruit shelf-life in the packaging mainly by its high correlation with flavor and sweetness. Moreover, in citrus fruits (Zhou et al., 2018) TSS/TA is used to evaluate sweetness and consumers' acceptance, having higher values of TSS/TA better acceptability. Other quality traits such as fruit firmness also had an improvement in mixed packaging. While a general loss of fruit firmness was found for all fruits over time, mango, orange and pineapple slices of the mix retained higher firmness values than those from the non-mixed packaging. Fruit firmness is a quality trait related to palatability and higher values are associated with better fruit preservation (Barrett et al., 2010; Salinas-Hernández et al., 2015). Moreover, fruit mixing also gave a 2-day window for firmness attributes in the mixed packaging that could have an important impact on storability and stock rotation in shops to reduce wastage of such perishable commodities.

Taken together, these results showed that fruit mixing in packaging positively affected fruit quality traits such as TSS/TA and firmness, even though there was an aggravation of acids metabolism for all fruits except kiwis (Table 1). Therefore, fruit mixing seems a convenient strategy to have a better preservation of fresh fruits in minimally processed packaging in terms of quality traits.

4.2. *Antioxidants are differentially affected by fruit and packaging composition*

Antioxidant composition is an important factor determining storage and shelf-life of cut fruits (Rico et al., 2007). Early wounding responses include increased phenol contents that evolve into fruit browning at cut-edges due to higher phenolic oxidation by polyphenol oxidases or peroxidases because of cellular decompartmentalization after cut (Reyes et al., 2007; Toivonen & Brummell, 2008). In the present study, there was a reduction in total phenols for all fruits the day after fruit cutting except for oranges and pineapples of the unmixed packaging. Since no symptoms of browning were found for these fruits over the period of analysis, total phenols may be acting as protective antioxidants in these

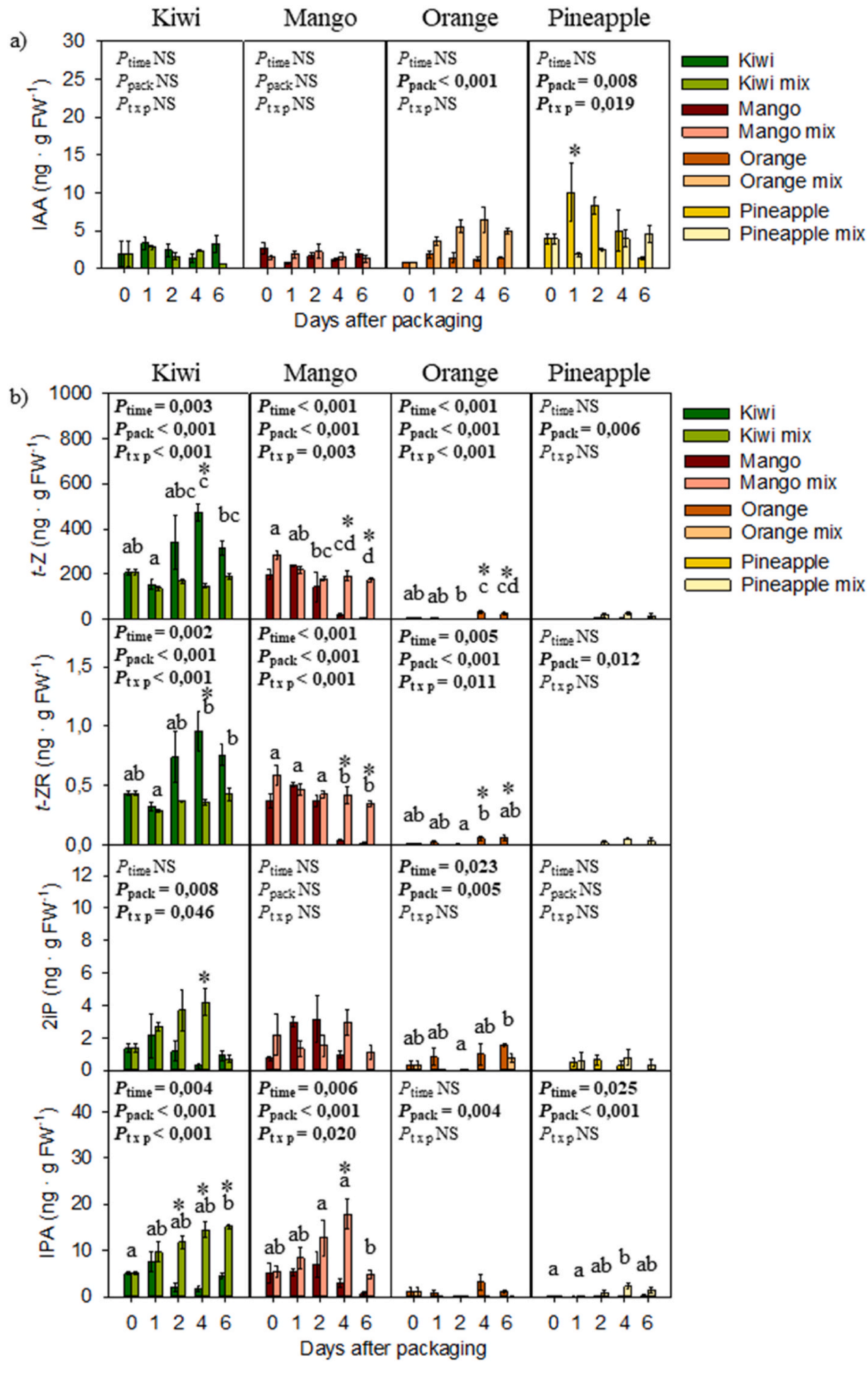

Fig. 6. Endogenous contents in cut fruit with different packaging composition of **a)** indole-3-acetic acid (IAA) and **b)** citokinins, including *trans*-zeatin (*t*-Z), *trans*-zeatin riboside (*t*-ZR), 2-isopentenyladenine (2iP), isopentenyladenosine (IPA). Data show the mean ± SE of n = 3. Different letters indicate significant differences between days after packaging ($P < 0.05$) using Tukey post hoc tests and asterisks indicate significant differences between packaging composition. NS, Not significant.

fruits, especially because oranges of the unmixed packaging had higher vitamin C oxidation as shown by lower values of vitamin C redox state. Ascorbic acid also acts as an oxygen scavenger, removing molecular oxygen in polyphenol oxidase reactions and reducing the formation of o-quinones whose accumulation in fruit tissues give browning colorations (Reyes et al., 2007). Therefore, higher accumulation of ascorbic acid could also prevent from browning. In the present study, vitamin C contents were only detrimentally affected in kiwis from the mix packaging. All selected fruits of this study are characterized by accumulating large amounts of ascorbic acid (Lee & Kader, 2000) and reductions on this antioxidant could imbalance the beneficial properties of their intake. In kiwis, the reductions in vitamin C contents because of the mixing were immediate and substantial (up to 50%), which could indicate that mixing of these fruits could have adverse effects in terms of health-promoting antioxidants. It should be considered that it is possible that the observed reductions might be influenced by the type of fruit composition in the mix and other mixes could have better results for kiwifruits. Nevertheless, mangoes and oranges substantially benefited from fruit mixing since these fruits preserved vitamin C contents in a greater extent than the unmixed cut fruits (Table 1). Considering that other studies in mangoes (Djioua et al., 2009) and oranges (Sicari et al., 2017) have also shown that postharvest time reduces the contents of ascorbic acid, mixing of these fruits states as a promising strategy to preserve their vitamin C composition in minimally processed packaging.

4.3. Fruit mixing elicits hormonal changes that determine final fruit quality in the packaging

Wounding and dehydration stresses are frequent in fresh-cut commodities. Catabolic and degradation processes occurring because of stress responses are tightly regulated by hormonal changes. In this sense, ABA has been described to regulate tissue suberization in wound stress responses in fruits that have been damaged during harvest, storage or transportation (Leide et al., 2012; Tao et al., 2016; Wei, Wei, et al., 2021). Nevertheless, there is still very little knowledge of the role of this and other phytohormones in minimally processes products. In the present experiment with the analysis of the hormonal content of different phytohormones in fresh cut products, it was visible that there is an active regulation of fruits by ABA, JA, GAs and CKs, but the dynamics and involvement of these phytohormones were defined by both fruit type and packaging composition. ABA and JA were the highest accumulating phytohormones, in particular in the fruit slices of mango, orange and pineapple of the unmixed packaging. It is relevant to mention that oranges and pineapples in non-mixed packages were also the fruits with higher phenol accumulation and a strong relationship has already been described between ABA and JA for the activation of phenylpropanoid metabolism (Złotek et al., 2014; Wei, Wei, et al., 2021). In this sense, in the present experiment oranges had a strong positive correlation between ABA and phenols, indicating that phenol accumulation in the orange mixed packaging could be partially promoted by enhanced ABA accumulation in their tissues. Likewise, mango, orange and pineapple slices that were not mixed in their storage, also had an accelerated firmness loss than those in the mixed packaging. In line with this, mangoes fruit firmness was also positively correlated with ABA and negatively correlated with *t*-Z and *t*-ZR, indicating the endogenous balance of these phytohormones as an important trait to keep mango firmness in the mix packaging. Several studies have highlighted the role of ABA in cell wall degradation and textural changes (Alférez et al., 2005; Sun et al., 2012; García-Pastor et al., 2021; Zhou et al., 2021) and for this reason, fruits of the unmixed packaging with higher contents of this phytohormone could have experienced a rapid loss in fruit firmness. At the same time, in fruits like mangoes where fruit mixing promoted *t*-Z and *t*-ZR accumulation, may have contributed to a delay on increasing ABA contents, because of the antagonistic role of CKs in ABA accumulation (Nishiyama et al., 2011; Fenn & Giovannoni, 2020). Through this phytohormonal equilibrium, fruit mixing might have promoted a better preservation of mango fruit firmness, which could be used as an innovative strategy to reduce fruit softening of fresh-cut mangoes. On the other hand, wounding after fresh-cut processing has been also described to activate ACC synthase and ethylene production (Toivonen & Brummell, 2008). ACC accumulation showed a uniform pattern for all fruits even if some of them are not considered climacteric fruits. In this respect, all fruits that were in the unmixed packaging during the postharvest period, accumulated higher contents of ACC, especially towards the end of the experiment. ACC contents strongly correlated with vitamin C and the redox state for all fruits, but it is important to mention that while kiwis had a positive correlation between these parameters, all other fruits had a negative correlation. Since vitamin C contents and the redox state were affected by packaging composition, only with detrimental effects for kiwis, ACC or its immediate product, ethylene, depict as an important target to maintain vitamin C contents in ready-to-eat fruit packaging. These results agree with previous studies in apple slices (Tardelli et al., 2013) and whole mango (Wang et al., 2009) and kiwi (Zhang et al., 2021) fruits, where the application of 1-methylciclopropane (1-MCP), a structural analogue of ethylene that hinders its signal transduction, slowed the reduction of ascorbate over storage. For this reason, since similar results have been obtained for ascorbate contents in the mixed packaging, mixtures of different fruits could be a good strategy to reduce the use of chemical compounds such as 1-MCP in ready-to-eat packaging.

Other less studied phytohormones in fresh-cut commodities such as GAs and CKs also showed particular patterns of accumulation considering packaging composition and fruit type. In general, gibberellins have been described with a protective role in over ripening of fruits in postharvest (Huang et al., 2014; Tijero et al., 2019), but no studies have been conducted for minimally processed fruits. Here, higher contents of gibberellins were found in oranges and mangos of the non-mixed packaging but all other fruits showed no variations for the accumulation of this group of phytohormones. GAs have also been associated with the modulation of JA signaling, since GAs regulate the accumulation of DELLA proteins, which in turn are responsible of the inhibition of the JA response (Hou et al., 2010). Considering that JA greatly accumulated in oranges and mangos of the unmixed packaging, giberellins could be acting to modulate this response. In contrast, as previously mentioned, CKs of mangoes showed the opposite pattern and those in the mixed packaging accumulated greater contents of *t*-Z, *t*-ZR and IPA. At the same time, kiwi slices of the mixed packaging also experienced transient increases of 2iP and a constant increase on IPA, while the contents of *t*-Z and *t*-ZR where higher at the unmixed packaging. Very little is known about the accumulation of specific CKs and quality traits during fruit postharvest, and only a study by Massolo et al. (2014) has investigated the role of CKs to delay cell wall degradation during postharvest because in general, CKs contents in fruits tend to decrease during this period (Tijero et al., 2019). In broccoli florets, CKs biosynthesis and in particular *t*-Z and *t*-ZR increased as a result of water stress treatments (Zaicovski et al., 2008). Here, CKs from mangos seem to be antagonizing the effects of ABA in the mixed packaging, especially *t*-Z and *t*-ZR, but since water stress is one of the main events taking place after fruit cutting, increases in CKs in mangoes and kiwifruits could also be related to water dynamics of fruit slices in minimally processed products.

5. Conclusions

To ensure greater postharvest shelf-life of ready to eat packaging of fruits it is essential to find innovative strategies for their preservation. The present experiment demonstrated that fruit mixing largely affects fruit quality and nutritional traits, with beneficial effects for mangoes, oranges and pineapples, but slight detrimental effects for kiwifruits in terms of antioxidant composition. Likewise, ABA, JA, GAs and CKs were identified as hormonal components that could be subjected to endogenous modifications to expand fruit shelf-life and improve quality traits to meet consumer's expectations. Altogether, the present study sets the physiological foundations for future innovative technologies aimed to preserve cut fruits.

Authors' contribution

P.M., M.P.A, C.A., G.I.H. and S.M.-B. designed the study. P.M., C.A. and G.I.H. performed the experiments. P.M. and C.A. performed the analysis. P.M., M.P.A and S.M.-B. analyzed the data. P.M. wrote the manuscript and all authors contributed to the final discussion.

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CRediT authorship contribution statement

Paula Muñoz: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, preparation, Writing – review & editing, Visualization, All authors have read and agreed to the published version of the manuscript. **María Pilar Almajano:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition, All authors have read and agreed to the published version of the manuscript. **Clara Álvarez:** Methodology, Formal analysis, Investigation, Writing – review & editing, All authors have read and agreed to the published version of the manuscript. **Gádor Indra Hidalgo:** Methodology, Formal analysis, Investigation, Writing – review & editing, All authors have read and agreed to the published version of the manuscript. **Sergi Munné-Bosch:** Conceptualization, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

All the authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

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References

Alférez, F., Sala, J. M., Sánchez-Ballesta, M. T., Mulas, M., Lafuente, M. T., & Zacarías, L. (2005). A comparative study of the postharvest performance of an ABA-deficient mutant of oranges: I. Physiological and quality aspects. *Postharvest Biology and Technology, 37*, 222–231.

Ali, Z. M., Chin, L. H., & Lazan, H. (2004). A comparative study on wall degrading enzymes, pectin modifications and softening during ripening of selected tropical fruits. *Plant Science, 167*, 317–327.

Baldwin, E. A., & Bai, J. (2011). Physiology of fresh-cut fruits and vegetables. In *Advances in fresh-cut fruits and vegetables processing*. Boca Raton, FL, USA: Taylor & Francis.

Barrett, D. M., Beaulieu, J. C., & Shewfel, R. (2010). Color, flavor, texture, and nutritional quality of fresh-cut fruits and vegetables: Desirable levels, instrumental and sensory measurement, and the effects of processing. *Critical Reviews in Food Science and Nutrition, 50*, 369–389.

Boulton, R. B., Singleton, V. L., Bisson, L. F., & Kunkee, R. E. (1999). *Principles and practices of winemaking* (1st ed.). New York, NY, USA: Springer.

Brizzolara, S., Manganaris, G. A., Fotopoulos, V., Watkins, C. B., & Tonutti, P. (2020). Primary metabolism in fresh fruits during storage. *Frontiers of Plant Science, 11*, 80.

Cisneros-Zevallos, L. (2003). The use of controlled postharvest abiotic stresses as a tool for enhancing the nutraceutical content and adding-value of fresh fruits and vegetables. *Journal of Food Science, 68*, 1560–1565.

Djioua, T., Charles, F., Lopez-Lauri, F., Filgueiras, H., Coudret, A., Freire, M., Jr., Ducamp-Collin, M.-N., & Sallanon, H. (2009). Improving the storage of minimally processed mangoes (*Mangifera indica* L.) by hot water treatments. *Postharvest Biology and Technology, 52*, 221–226.

Fenn, M. A., & Giovannoni, J. J. (2020). Phytohormones in fruit development and maturation. *The Plant Journal, 105*, 446–458.

García-Pastor, M. E., Falagán, N., Giné-Bordonaba, J., Wójcik, D. A., Terry, L. A., & Alamar, M. C. (2021). Cultivar and tissue-specific changes of abscisic acid, its catabolites and individual sugars during postharvest handling of flat peaches (*Prunus persica* cv. platycarpa). *Postharvest Biology and Technology, 181*, 111688.

Han, X.-Y., Mao, L.-C., Lu, W.-J., Tao, X.-Y., Wei, X.-P., & Luo, Z.-S. (2018). Abscisic acid induces differential expression of genes involved in wound-induced suberization in postharvest tomato fruit. *Journal of Integrative Agriculture, 17*, 2670–2682.

Hou, X., Lee, L. Y. C., Xia, K., Yan, Y., & Yu, H. (2010). DELLAS modulate jasmonate signaling via competitive binding to JAZs. *Developmental Cell, 19*, 0–894.

Huang, H., Jing, G., Wang, H., Duan, X., Qu, H., & Jiang, Y. (2014). The combined effects of phenylurea and gibberellins on quality maintenance and shelf-life extension of banana fruit during storage. *Scientia Horticulturae, 167*, 36–42.

Kähkönen, M. P., Hopia, A. I., Vuorela, H. J., Rauha, J. P., Pihlaja, K., Kujala, T. S., & Heinonen, M. (1999). Antioxidant activity of plant extracts containing phenolic compounds. *Journal of Agricultural and Food Chemistry, 47*, 3954–3962.

Latimer, D. W. (2012). *Official methods of analysis of AOAC International* (19th ed.). Rockville, MD, USA: AOAC International.

Lee, S. K., & Kader, A. A. (2000). Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biology and Technology, 20*, 207–220.

Leide, J., Hildebrandt, U., Hartung, W., Riederer, M., & Vogg, G. (2012). Abscisic acid mediates the formation of a suberized stem scar tissue in tomato fruits. *New Phytologist, 194*, 402–415.

Li, X. A., Li, M. L., Han, C., Jin, P., & Zheng, Y. H. (2017). Increased temperature elicits higher phenolic accumulation in fresh-cut pitaya fruit. *Postharvest Biology and Technology, 129*, 90–96.

Li, X., Li, M., Wang, L., Wang, J., Jin, P., & Zheng, Y. (2018). Methyl jasmonate primes defense responses against wounding stress and enhances phenolic accumulation in fresh-cut pitaya fruit. *Postharvest Biology and Technology, 145*, 101–107.

Li, N., Parsons, B. L., Liu, D., & Mattoo, A. K. (1992). Accumulation of wound-inducible ACC synthase transcript in tomato fruit is inhibited by salicylic acid and polyamines. *Plant Molecular Biology, 18*, 477–487.

Manzoor, S., Gull, A., Wani, S. M., Ganaie, T. A., Masoodi, F. A., Bashir, K., Malik, A. R., & Dar, B. N. (2021). Improving the shelf life of fresh cut kiwi using nanoemulsion coatings with antioxidant and antimicrobial agents. *Food Bioscience, 41*, 101015.

Ma, L., Zhang, M., Bhandari, B., & Gao, Z. (2017). Recent developments in novel shelf-life extension technologies of fresh-cut fruits and vegetables. *Trends in Food Science & Technology, 64*, 23–38.

Miret, J. A., & Munné-Bosch, S. (2016). Abscisic acid and pyrabactin improve Vitamin C contents in raspberries. *Food Chemistry, 203*, 216–223.

Müller, M., & Munné-Bosch, S. (2011). Rapid and sensitive hormonal profiling of complex plant samples by liquid chromatography coupled to electrospray ionization tandem mass spectrometry. *Plant Methods, 7*, 37.

Murata, M., Tsurutani, M., Tomita, M., Homma, S., & Kaneko, K. (1995). Relationship between apple ripening and browning: Changes in polyphenol content and polyphenol oxidase. *Journal of Agricultural and Food Chemistry, 43*, 1115–1121.

Nishiyama, R., Watanabe, Y., Fujita, Y., Tien, D., Kojima, M., Werner, T., Vankova, R., Yamaguchi-Shinozaki, K., Shinozaki, K., Kakimoto, T., Shakakibara, H., Schmülling, T., & Tran, L. P. (2011). Analysis of cytokinin mutants and regulation of cytokinin metabolic genes reveals important regulatory roles of cytokinins in drought, salt and abscisic acid responses, and abscisic acid biosynthesis. *The Plant Cell Online, 23*, 2169–2183.

Pizato, S., Chevalier, R. C., Dos Santos, M. F., Da Costa, T. M., Arévalo, R., & Cortez, W. R. (2019). Evaluation of the shelf-life extension of fresh-cut pineapple (Smooth cayenne) by application of different edible coatings. *British Food Journal, 121*, 1592–1604.

Queval, G., & Noctor, G. (2007). A plate reader method for the measurement of NAD, NADP, glutathione, and ascorbate in tissue extracts: Application to redox profiling during Arabidopsis rosette development. *Analytical Biochemistry, 363*, 58–69.

Reyes, L. F., Villarreal, J. E., & Cisneros-Zevallos, L. (2007). The increase in antioxidant capacity after wounding depends on the type of fruit or vegetable tissue. *Food Chemistry, 101*, 1254–1262.

Rico, D., Martín-Diana, A. B., Barat, J. M., & Barry-Ryan, C. (2007). Extending and measuring the quality of fresh-cut fruit and vegetables: A review. *Trends in Food Science & Technology, 18*, 373–386.

Robles-Sánchez, R. M., Rojas-Graü, M. A., Odriozola-Serrano, I., González-Aguilar, G., & Martin-Belloso, O. (2013). Influence of alginate-based edible coating as carrier of antibrowning agents on bioactive compounds and antioxidant activity in fresh-cut Kent mangoes. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 50*, 240–246.

Rux, G., Bohne, K., Huyskens-Keil, S., Ulrichs, C., Hassenberg, K., & Herppich, W. B. (2021). Effects of modified atmosphere and sugar immersion on physiology and quality of fresh-cut 'Braeburn' apples. *Food Packaging and Shelf Life, 29*, 100726.

Salinas-Hernández, R. M., González-Aguilar, G. A., & Tiznado-Hernández, M. E. (2015). Utilization of physicochemical variables developed from changes in sensory attributes and consumer acceptability to predict the shelf life of fresh-cut mango fruit. *Journal of Food Science & Technology, 52*, 63–77.

Sicari, V., Dorato, G., Giuffrè, A. M., Rizzo, P., & Albunia, A. R. (2017). The effect of different packaging on physical and chemical properties of oranges during storage. *Journal of Food Processing and Preservation, 41*, Article e13168.

Soliva-Fortuny, R. C., & Martín-Belloso, O. (2003). New advances in extending the shelf-life of fresh-cut fruits: A review. *Trends in Food Science & Technology, 14*, 341–353.

Sun, L., Sun, Y., Zhang, M., Wang, L., Ren, J., Cui, M., Wang, Y., Ji, K., Li, P., Li, Q., Chen, P., Dai, S., Duan, C., Wu, Y., & Leng, P. (2012). Suppression of 9-cis-epoxy-carotenoid dioxygenase, which encodes a key enzyme in abscisic acid biosynthesis, alters fruit texture in transgenic tomato. *Plant Physiology, 158*, 283–298.

Tao, X., Mao, L., Li, J., Chen, J., Lu, W., & Si, H. (2016). Abscisic acid mediates wound-healing in harvested tomato fruit. *Postharvest Biology and Technology, 118*, 128–133.

Tardelli, F., Guidi, L., Massai, R., & Toivonen, P. M. (2013). Effects of 1-methylcyclo-propene and post-controlled atmosphere air storage treatments on fresh-cut Ambrosia apple slices. *Journal of the Science of Food and Agriculture, 93*, 262–270.

Tijero, V., Teribia, N., & Munné-Bosch, S. (2019). Hormonal profiling reveals a hormonal cross-talk during fruit decay in sweet cherries. *Journal of Plant Growth Regulation, 38*, 431–437.

Toivonen, P. M. A., & Brummell, D. A. (2008). Biochemical bases of appearance and texture changes in fresh-cut fruit and vegetables. *Postharvest Biology and Technology, 48*, 1–14.

Wang, B., Wang, J., Feng, X., Lin, L., Zhao, Y., & Jiang, W. (2009). Effects of 1-MCP and exogenous ethylene on fruit ripening and antioxidants in stored mango. *Plant Growth Regulation, 57*, 18.

Wasternack, C., Stenzel, I., Hause, B., Hause, G., Kutter, C., Maucher, H., Neumerkel, J., Feussner, I., & Miersch, O. (2006). The wound response in tomato – role of jasmonic acid. *Journal of Plant Physiology, 163*, 297–306.

Wei, X., Guan, W., Yang, Y., Shao, Y., & Mao, L. (2021a). Methyl jasmonate promotes wound healing by activation of phenylpropanoid metabolism in harvested kiwifruit. *Postharvest Biology and Technology, 175*, 111472.

Wei, X., Wei, X., Guan, W., & Mao, L. (2021b). Abscisic acid stimulates wound suberisation in kiwifruit (*Actinidia chinensis*) by regulating the production of jasmonic acid, cytokinin and auxin. *Functional Plant Biology, 48*, 1100–1112.

Xiang, W., Wang, H.-W., & Sun, D.-W. (2020). Phytohormones in postharvest storage of fruit and vegetables: Mechanisms and applications. *Critical Reviews in Food Science and Nutrition, 61*, 2969–2983.

Zaicovski, C. B., Zimmerman, T., Nora, L., Nora, F. R., Silva, J. A., & Rombaldi, C. V. (2008). Water stress increases cytokinin biosynthesis and delays postharvest yellowing of broccoli florets. *Postharvest Biology and Technology, 49*, 436–439.

Zhang, Y., Wang, K., Xiao, X., Cao, S., Chen, W., Yang, Z., & Shi, L. (2021). Effect of 1-MCP on the regulation processes involved in ascorbate metabolism in kiwifruit. *Postharvest Biology and Technology, 179*, 111563.

Zhou, Y., He, W., Zheng, W., Tan, Q., Xie, Z., Zheng, C., & Hu, C. (2018). Fruit sugar and organic acid were significantly related to fruit Mg of six citrus cultivars. *Food Chemistry, 259*, 278–285.

Zhou, Q., Zhang, F., Ji, S., Dai, H., Zhou, X., Wei, B., Cheng, S., & Wang, A. (2021). Abscisic acid accelerates postharvest blueberry fruit softening by promoting cell wall metabolism. *Scientia Horticulturae, 288*, 110325.

Złotek, U., Świeca, M., & Jakubczyk, A. (2014). Effect of abiotic elicitation on main health-promoting compounds, antioxidant activity and commercial quality of butter lettuce (*Lactuca sativa* L.). *Food Chemistry, 148*, 253–260.