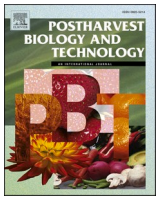
Postharvest Biology and Technology 245 (2027) 114879



Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio



# European orchard survey on 'CH201/FRED®' pears: Mineral nutrition, harvest quality, and their role in controlled-atmosphere-related storage disorders

Samuel Köchli [a,*], Pierre-Yves Cotter [a], Felix Büchele [b], María Emma García-Pastor [c], Daniel Alexandre Neuwald [b,d], Séverine Gabioud Rebeaud [a]

[a] Fruit Crops in the Alpine Region, Agroscope, Conthey 1964, Switzerland
[b] Lake of Constance Research Centre for Fruit Cultivation, Ravensburg 88213, Germany
[c] Department of Applied Biology, Institute for Agri-Food and Agro-Environmental Research and Innovation (CIAGRO), University Miguel Hernández, Alicante 03312, Spain
[d] Department of Production Systems of Horticultural Crops, University of Hohenheim, Stuttgart 70593, Germany

ARTICLE INFO

*Keywords:*
*Pyrus communis*
Cavities
Internal browning
Mineral composition
Quality parameters
Orchard

ABSTRACT

'CH201/FRED®' is a recently launched bicolored pear cultivar with long-term storage potential. However, its susceptibility to disorders associated with controlled atmosphere (CA) storage, primarily cavities and internal browning (IB), can result in substantial losses during storage. This study investigated whether mineral composition, together with quality parameters, density, seed number, and orchard-related characteristics at harvest, could be used to predict the susceptibility of 'CH201/FRED®' pears to CA-related disorders. Pears from 20 orchards in Belgium, France, Germany, Italy, and Switzerland, harvested at commercial maturity according to the recommendations established for each production region, were stored in the same CA room. The incidence of cavities and IB varied widely among orchards and could not be attributed to a single parameter across all orchards. The potassium (K) to calcium (Ca) ratio (K/Ca) showed a positive correlation with cavity development, particularly when only Swiss and Italian orchards were considered. Fruit density, dry matter, total soluble solids, and color were also associated with susceptibility to cavity development. A preliminary predictive model identified dry matter, tree age, and the K/Ca ratio as potentially useful indicators of cavity risk, although further validation across independent datasets, growing seasons, and storage conditions is required.

## 1. Introduction

Pear (*Pyrus communis* L.) is one of the most important fruit crops cultivated commercially worldwide (FAO, 2023). Declining pear consumption in Europe has resulted in an increased demand for new, attractive cultivars that deliver consistently high yields with long-term storability. The 'CH201' pear cultivar, marketed under the tradename 'FRED®', was developed through Agroscope's breeding program and launched in 2018 in Switzerland, with production now expanding across several European countries, primarily Belgium, France, and Italy. Characterized by high yields and rapid entry into production, CH201/FRED®' boasts a red blush, a crunchy, juicy texture, and long-term storage potential (Gabioud Rebeaud et al., 2024). This cultivar also shows early, regular, and high yields in both quince and pear rootstocks (Monney et al., 2024). Due to its firm texture, the cultivar has high resistance to mechanical damage during handling along the supply chain, particularly after cold storage. 'CH201/FRED®' typically develops a buttery texture after 7–10 days of shelf life at 20°C. Initial studies indicated that this cultivar stores well under controlled atmosphere (CA) conditions (Büchele et al., 2024; Gabioud Rebeaud et al., 2024). However, it is prone to browning disorders, particularly cavity formation, during CA storage.

Browning disorders in pears manifest in various forms, such as flesh browning, core browning, and cavity formation (Franck et al., 2007). These disorders have been reported in various cultivars, including 'Conference' (Franck et al., 2007; Larrigaudière et al., 2024), 'Williams/Bartlett' (Antoniolli et al., 2016; Wang and Sugar, 2013), 'Rocha' (Deuchande et al., 2016; Saquet et al., 2019), and 'Comice' (Ma and

* Corresponding author.
*E-mail address:* samuel.koechli@agroscope.admin.ch (S. Köchli).

https://doi.org/10.1016/j.postharvbio.2026.114879
Received 29 January 2026; Received in revised form 9 October 2026; Accepted 15 November 2026
Available online 21 November 2026
0925-5214/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Chen, 2003). The symptoms often appear asymmetrically, vary in size, and differ in browning intensity. Since these symptoms are internal and not visible without cutting the fruit, they are particularly difficult to detect after storage. Although flesh and core browning frequently occur together with cavities in pears, they are not necessarily manifestations of the same physiological disorder, and evidence suggests that they may arise from distinct metabolic processes (Franck et al., 2007). Previous studies on 'CH201/FRED®' have shown that cavities may occur either independently or in combination with flesh and core browning (Büchele et al., 2024; Gabioud Rebeaud et al., 2024; Monney et al., 2024). Accordingly, cavity formation and internal browning (IB), comprising both flesh and core browning, are considered two distinct physiological disorders and examined in the present study.

Browning in pear is caused by the enzymatic oxidation of phenolic compounds by polyphenol oxidase, leading to the formation of highly reactive *o*-quinones that polymerize into brown pigments (Mathew and Parpia, 1971; Nicolas et al., 1994), commonly accompanied by dried lesions or cavities (Lammertyn et al., 2003; Verlinden et al., 2002). Cavity formation in fruit tissues has often been directly linked to injuries caused by elevated carbon dioxide ($CO_2$) and low oxygen ($O_2$) levels during CA storage (Lammertyn et al., 2001; Saquet et al., 2000; Streif et al., 2003). High $CO_2$ disrupts membrane integrity and metabolic processes, leading to localized tissue collapse and cavity development (Deuchande et al., 2016; Franck et al., 2003). In 'CH201/FRED®' pears, $CO_2$ is the primary postharvest factor that drives cavity formation (Büchele et al., 2024; Gabioud Rebeaud et al., 2024). Complete $CO_2$ removal during storage effectively prevents the disorder, while low $O_2$ levels contribute to a lesser extent (Büchele et al., 2024). As is typical for $CO_2$-injuries, a delay between harvest and CA storage reduces incidence, whereas 1-methylcyclopropene treatment exacerbates symptoms (Büchele et al., 2024; Gabioud Rebeaud et al., 2024).

Although browning disorders manifest during storage, preharvest conditions significantly influence fruit susceptibility. Seasonal climate, soil characteristics, irrigation, fertilization, and fruit position on the tree affect the susceptibility of pears to postharvest disorders, which then develop under unfavorable storage conditions (Ferguson et al., 1999; Franck et al., 2007). The causative effects of these preharvest factors have yet to be fully unraveled. Excessive irrigation programs have been found to reduce phenolic content and antioxidant activity, thus increasing IB in 'Rocha' pears (Bonora et al., 2021b). In 'CH201/FRED®' pears, the use of vigorous rootstocks is associated with a greater risk of cavity formation during storage (Monney et al., 2024). According to Gabioud Rebeaud et al. (2025), inducing the growth of one-year-old shoots by removing floral bouquets or shortening branches at the bud stage increased cavity incidence during CA storage of 'CH201/FRED®' pears, with the resulting higher leaf area-to-crop load ratio also associated with reduced fruit calcium (Ca) levels. The authors further suggested that this treatment may increase flesh density and reduce gas diffusivity, thereby increasing susceptibility to cavity formation, although these relationships require further investigation.

Numerous studies have demonstrated a link between the mineral composition of pears and storage disorders. Cork spots in 'Anjou' (Raese and Drake, 1995), IB disorders in 'Rocha' (Saquet et al., 2019), and black ends in 'Packam's Triumph', 'B. Bosc', 'Anjou', and 'Bartlett' (Gil et al., 1994) have been associated with low Ca levels and, in some cases, with elevated nitrogen (N) content. Additionally, a high boron (B) concentration has been shown to enhance the storability of 'Conference' pears (Xuan et al., 2001).

Mineral composition has been proposed as a tool for predicting the predisposition of apples and pears to browning disorders during storage at harvest. However, the results linking mineral levels and browning disorder incidence are inconsistent across cultivars. In apples, significant correlations have been reported between 'Braeburn' browning disorder and levels of K, phosphorus (P), and, in some cases, the K/Ca ratio (Neuwald et al., 2014). In Asian pears, higher contents of Ca and K were observed in fruit more severely affected by IB (Seo et al., 2015), while in 'Rocha' pears, increased copper (Cu) levels were associated with greater disorder incidence (Deuchande et al., 2017).

Fruit Ca concentration has been positively associated with the number of fully developed seeds, suggesting that successful pollination contributes to Ca accumulation during fruit development (Bramlage et al., 1990; Buccheri and Di Vaio, 2005). Accordingly, fruit with more seeds generally exhibit a lower susceptibility to Ca-related physiological disorders (Brookfield et al., 1996). However, the relationship between seed numbers and the development of CA-related disorders in pears has not yet been investigated. Assessing whether this parameter is associated with the incidence of these disorders may improve our understanding of their physiological determinants and contribute to the identification of reliable predictors of storage disorders.

Early detection of orchard-specific susceptibility of 'CH201/FRED®' pears to CA-related disorders would help reduce postharvest losses and optimize storage strategies. If batches susceptible to CA-related disorders can be identified at harvest, their postharvest itinerary could be adjusted and economic losses limited (e.g., susceptible fruit stored in normal air and commercialized quickly rather than stored in CA conditions for a long period). The aim of this study was to examine how fruit mineral composition, quality attributes measured at harvest, and orchard-related factors relate to susceptibility to CA-induced disorders and to identify the most relevant parameters for predicting their development under CA storage. Enhanced knowledge of orchard-dependent influences on disorder expression will contribute to improved postharvest management strategies for this new pear cultivar.

## 2. Materials and methods

### 2.1. Fruit, orchard-related data, and storage conditions

This multi-orchard, international study involved 'CH201/FRED®' pears from Belgium (2 orchards), France (5 orchards), Germany (1 orchard), Italy (4 orchards), and Switzerland (8 orchards). Pears were grown during the 2023 season, harvested at commercial maturity according to the recommendations established for each production region, and transported to Agroscope (Conthey, Switzerland) for storage (Table 1). Agronomic characteristics (tree age, rootstock type, crop load, and tree vigor) were recorded for each orchard (Table 1). Crop load and tree vigor were classified as low (1), medium (2), and high (3). The crop load-to-vigor ratio was calculated as the crop load divided by tree vigor. Climatic variables, including cumulative degree-days (DD F-H; sum of degree between base [5°C] and ceiling temperature [35°C]), the number of days with a maximum temperature exceeding 30°C (ND $T° > 30$), and cumulative rainfall, were calculated from full bloom to harvest for each orchard location using Open-Meteo (OpenMeteo, 2025) for European orchards and Agrometeo (Agrometeo, 2025) for Swiss orchards (Table 1). Pears were stored at 0.5°C and 90–95% relative humidity for 4 weeks (CA-delay), then transferred to CA storage at the same temperature and relative humidity, under 3 kPa $O_2$ and 1 kPa $CO_2$, for 5 months.

#### 2.1.1. CA-related disorders

After 5 months of CA storage followed by 7 days of shelf life at 20°C, 3 batches of 50 pears per orchard were cut into 1.5 cm thick slices and visually evaluated for cavities and IB disorders. Cavities were defined as internal voids in the fruit flesh resulting from localized tissue breakdown, with or without browning of the tissue surrounding the voids (Fig. S1, and S3, A). IB was defined as diffuse brown discoloration of the fruit flesh without the formation of a void (Fig. S2, and S3, B). The two disorders were assessed independently, and fruit exhibiting both symptoms were recorded as affected by both cavities and IB. Both disorders were assessed using a severity score ranging from 0 to 3 (Fig. S1 and S2), based on the extent of the surface of the visible symptoms (0: no symptoms, 1: slight damage ($< 5\%$), 2: moderate damage (5–20%), and 3: severe damage ($> 20\%$) and expressed in terms of severity index calculated as follows:

**Table 1**
Harvest date, tree age, rootstock, crop load, tree vigor, crop load-to-vigor ratio, DD F-H, ND T° > 30 and cumulative rainfall in the 'CH201/FRED ®' orchards. Decimal values (e.g., 1.5 and 2.5) indicate intermediate levels between adjacent classes.

| Orchard | Harvest date | Tree age [years] | Rootstock | Crop load [1−3] | Tree vigor [1−3] | Crop load / vigor ratio | DD F-H | ND T° > 30 | Rainfall [mm] |
|---|---|---|---|---|---|---|---|---|---|
| Belgium 1 | 9/12/2023 | 3 | Quince Kwee C (intermediate stem: Beurré Hardy) | 2.0 | 1.0 | 2.0 | 1753.9 | 3 | 398.8 |
| Belgium 2 | 9/12/2023 | 5 | Quince Kwee C (intermediate stem: Beurré Hardy) | 2.0 | 2.0 | 1.0 | 1760.3 | 3 | 415 |
| France 1 | 9/4/2023 | 11 | Quince Sydo | 2.0 | 2.0 | 1.0 | 1957.9 | 17 | 266.7 |
| France 2 | 9/4/2023 | 4 | Quince Adams | 1.5 | 2.5 | 0.6 | 1957.9 | 17 | 266.7 |
| France 3 | 9/4/2023 | 3 | Quince Adams | 2.0 | 2.5 | 0.8 | 1895.3 | 12 | 317.7 |
| France 4 | 9/4/2023 | 3 | Quince Adams | 3.0 | 1.5 | 2.0 | 1977.5 | 17 | 265.3 |
| France 5 | 9/4/2023 | 3 | Quince Sydo | 2.0 | 2.5 | 0.8 | 1956.9 | 17 | 284.9 |
| Germany 1 | 9/20/2023 | 2 | Quince Adams | 1.0 | 2.0 | 0.5 | 1842.7 | 11 | 550.1 |
| Italy 1 | 9/11/2023 | 3 | Quince BA29 | 1.0 | 2.0 | 0.5 | 2590.1 | 57 | 421.9 |
| Italy 2 | 9/20/2023 | 1 | Quince BA29 | 1.0 | 2.0 | 0.5 | 2766.3 | 55 | 588.8 |
| Italy 3 | 9/14/2023 | 3 | Quince BA29 | 1.0 | 2.0 | 0.5 | 2675.0 | 55 | 543.2 |
| Italy 4 | 9/13/2023 | 2 | Quince BA29 | 1.0 | 2.0 | 0.5 | 2542.7 | 47 | 539.2 |
| Switzerland 1 | 9/7/2023 | 5 | Quince BA29 | 2.0 | 2.5 | 0.8 | 2024.3 | 43 | 198.6 |
| Switzerland 2 | 9/13/2023 | 6 | Pyrus Pyriam | 3.0 | 3.0 | 1.0 | 2113.5 | 27 | 316.6 |
| Switzerland 3 | 9/13/2023 | 12 | Quince BA29 | 3.0 | 2.0 | 1.5 | 2113.5 | 27 | 316.6 |
| Switzerland 4 | 9/12/2023 | 4 | Quince Adams | 3.0 | 2.0 | 1.5 | 2113.5 | 27 | 316.6 |
| Switzerland 5 | 9/12/2023 | 9 | Quince BA29 | 1.0 | 3.0 | 0.3 | 2111.6 | 17 | 228.3 |
| Switzerland 6 | 9/15/2023 | 4 | Quince BA29 | 1.5 | 3.0 | 0.5 | 2190.1 | 23 | 313.6 |
| Switzerland 7 | 9/19/2023 | 7 | Quince Eline | 1.5 | 1.5 | 1.0 | 2190.1 | 23 | 313.6 |
| Switzerland 8 | 9/19/2023 | 9 | Quince Adams | 2.0 | 3.0 | 0.7 | 1986.1 | 15 | 535.4 |

$$\text{Severity index} = \sum \frac{\text{number of affected fruit } x \text{ severity level}}{\text{total number of fruit } x \text{ maximal severity level}} \text{x100}$$

### 2.2. Classical quality parameters

The fruit quality of 30 pears per orchard was determined on their arrival at the laboratory (referred to as 'at harvest' in this study). Skin color was assessed using a CM-600d spectrophotometer (Konica Minolta, Tokyo, Japan) operating in the CIE L*a*b* color space under D65 standard illumination. Color measurements were expressed as hue angles (hue, $\tan^{-1}(b^*/a^*)$), where 0° corresponded to red, 90° to yellow, and 180° to green. An automated Pimprenelle instrument (Setop Giraud-Technologie, Cavaillon, France) was used to determine mass (g), firmness (N), total soluble solids (TSS, %), and titratable acidity (TA, g/L). Firmness and TSS measurements were performed on individual fruit, while TA was measured on the juice obtained from 3 batches of 10 fruit per orchard. Firmness measurements were performed on unpeeled pears with a 0.5 $cm^2$ probe.

### 2.3. Fruit density

Density was measured at harvest on 20 fruit per orchard using Archimedes' principle, according to the method described by Joas et al. (2009).

### 2.4. Seed number

The number of seeds was determined by counting the ripe seeds in 150 fruit per orchard after 5 months of CA storage and 7 days of shelf life. Only round, dark seeds, which are considered mature and viable, were included in the analysis.

### 2.5. Mineral analyses and dry matter

The dry matter and content of the minerals K, Ca, magnesium (Mg), and P were assessed on 3 batches of 30 fruit per orchard according to methodology described by Neuwald et al. (2014). Slices of each fruit were cut, crushed, homogenized, weighed (~100 g), freeze-dried, and the dry substance was calculated. Aliquots weighing 1.40–1.45 g were then ashed at 480°C for 6 h. Subsequently, the ash was liquefied with bi-distillated water, 2 mL hydrochloric acid (20%), and 1 mL lanthanum (0.1%) to a volume of 100 mL. The K, Ca, and Mg content were measured by atomic absorption spectrometry (flame absorption spectroscopy – GBC 908AA, GBC, Victoria, Australia). Standards were prepared in correspondence to average concentrations in the tissue (0, 2, 4, 6, and 8 ppm of Ca; 0, 20, 40, 50, 70, and 100 ppm of K; 3, 6, 8, 10, and 12 ppm of Mg) and measured together with fruit samples. P was analyzed using a molybdenum blue colorimetric procedure (spectral photometer at 580 nm, UV-1900i UV–VIS Spectrophotometer, Shimadzu, Oregon, USA) using standards with concentrations of 0, 1, 2, 3, 4, 5, 7, and 10 ppm. The content of each mineral was expressed as mg per 100 g of fresh mass (FW).

### 2.6. Statistical analyses

Statistical analyses were performed using R-Studio (4.4.2).

#### 2.6.1. Analyses of fruit parameters and disorders

Differences among orchards were assessed separately for each measured variable. Continuous variables were analyzed using generalized linear models, with orchard included as the explanatory factor. The error distribution was selected according to the response variable using *Gaussian* distributions for normally distributed data and *Gamma* distributions for positively skewed data. Model assumptions and goodness of fit were evaluated by visual inspection of residuals and quantile-quantile

plots, with additional residual diagnostics performed using the *DHARMa* package. When model diagnostics indicated an adequate fit, the overall effect of orchard was tested using analyses of variance (ANOVA), and multiple means were then compared with the Tukey HSD test. Differences were considered significant at $p \leq 0.05$.

Physiological disorders (cavities and IB) and seed number (ordinal variables) were analyzed using the non-parametric Kruskal–Wallis test. When a significant orchard effect was obtained, pairwise comparisons were performed using Dunn's post hoc test. Differences were considered significant at $p \leq 0.05$.

#### 2.6.2. Multivariables analyses

Multivariate analyses were performed to investigate variations in the measured parameters among orchards and their relationships with CA-related disorders. Principal component analysis (PCA) was conducted using the *FactoMineR* package, and correlation matrices were calculated and visualized using the *corrplot* package. For these analyses, each orchard was considered an independent experimental unit (n = 20 orchards), and orchard-level values were used. Individual fruit sampled within each orchard were considered subsamples and were not treated as independent experimental units.

Hierarchical clustering of principal components was subsequently performed on the PCA results to identify groups of orchards with similar characteristics. The optimal number of clusters was evaluated using silhouette, elbow, and gap statistical methods. The final number of clusters was selected by considering both these statistical criteria and the biological interpretability of the resulting groups.

#### 2.6.3. Predicted model

A predictive model was developed to assess the relationships between cavity incidence and fruit quality attributes, mineral composition, orchard characteristics, and climatic variables. As for the multivariate analyses, each orchard represented one independent experimental unit (n = 20), and the model was therefore developed using orchard-level data rather than individual fruit observations. IB was not modeled because its occurrence was largely restricted to Italian orchards, resulting in an unbalanced distribution. Candidate predictors were selected based on PCA and Pearson correlation analyses while avoiding highly correlated variables. Multicollinearity was assessed using variance inflation factors (*car* package). Candidate models were compared on root mean squared error (RMSE), mean absolute error (MAE), coefficient of determination ($R^2$), and the correlation between the observed and predicted values. The final model included dry matter, tree age, and the K/Ca ratio and was fitted by the ordinary least square (*rms* package). Because of the limited number of independent experimental units, the dataset was not divided into separate training and validation subsets. Instead, the model was fitted using all 20 orchards and internally validated by bootstrap resampling (*rms* package) to estimate optimism-corrected model performance, including $R^2$ and the calibration slope. No independent dataset was available for external validation.

## 3. Results

### 3.1. CA-related disorders

Marked differences in the prevalence of cavities and IB were observed between orchards, with a severity index ranging from 1 to 87 for cavities, and 0–96 for IB (Fig. 1). Italy 4 and France 3 showed the highest percentages of cavities among all orchards, whereas Belgium 1 and Switzerland 2, 3, 4, and 7 had the lowest percentages (Fig. 1, A). All Italian orchards were severely affected by IB, whereas pears from the other origins were slightly or not affected at all (Fig. 1, B).

Different cavity types were observed among countries and orchards (Fig. S4 and Table S1). In pears from France 1, 4, and 5, Switzerland 5 and 7, and Belgium, cavities were generally located in the center of the fruit, adjacent to the seed chamber, and were associated with core browning. By contrast, cavities in pears from Switzerland 1, 2, 3, 4, and 8 and Italy 2 and 3 were predominantly or exclusively located in the flesh. Pears from Italy 1 and 4, Germany, France 2 and 3, and Switzerland 6 exhibited flesh and core cavities in the same batch.

### 3.2. Classical quality parameters

The quality parameters varied significantly among the orchards at harvest (Table 2). Fruit mass exceeded 200 g in Belgium 2, France 3, Switzerland 6 and 8, Germany, and all Italian orchards, while pears < 170 g were harvested in Belgium 1, France 1, 2, and 4, and Switzerland 2 and 5 orchards. Depending on the orchard, TSS values varied between 10.9% and 16.8%, TA between 2.7 and 5.5 g/L, and color (hue) between 94.3 and 100.1. Firmness was relatively uniform, ranging from 61.1 N (Italy 1) to 74.3 N (Switzerland 1), with most orchards averaging around 65 N. Italian pears displayed the highest TSS, large fruit mass, and high TA but exhibited some of the lowest hue values, reflecting a more yellow skin color. By contrast, Switzerland 1 combined the highest firmness with elevated TA and color values. High TSS values were also recorded in France 1, 2, and 3, Belgium 2, and Switzerland 4 and 5, while pears from Swiss orchards showed the highest color values overall. Compared with Belgium 2, Belgium 1 produced fruit with lower firmness, TSS, TA, and color values. The quality parameters in Germany 1 were within the overall average range.

### 3.3. Fruit density

The average orchard fruit density ranged from 1.009 to 1.031 kg/cm$^3$ (Fig. 2). Italian pears exhibited the highest fruit density, whereas the lowest values were measured for Belgium 1 and Germany 1. Among

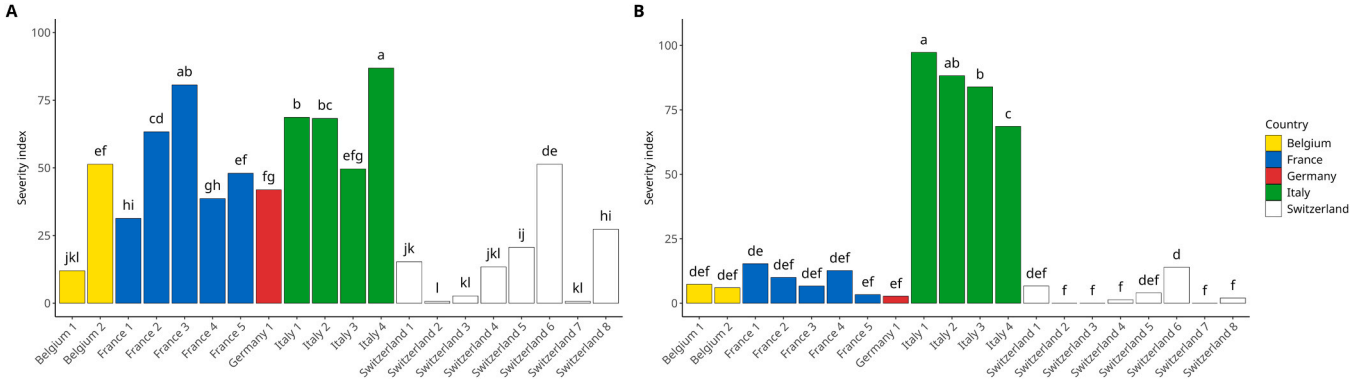



**Fig. 1.** Influence of the orchard on the proportion of 'CH201/FRED®' pears affected by cavities (A) and IB (B) disorders after 5 months of CA storage and 7 days of shelf life. Values are the means of 3 replicates of 50 fruit. Means with the same letters do not differ significantly at $p \leq 0.05$ in Dunn's test.

**Table 2**
Influence of the orchard on mass, firmness, TSS, TA, and color of 'CH201/FRED®' pears at harvest. The mass, firmness, TSS, and color values are the means of 30 fruit, while the TA values are the means of 3 replicates of 10 fruit. Means with the same letters do not differ significantly at $p \leq 0.05$ in the Tukey's HSD test. n.c.: not calculated (only one replicate available).

| Orchard | Mass [g] | Firmness [N] | TSS [%] | TA [g/L] | Color [hue] |
|---|---|---|---|---|---|
| Belgium 1 | $160.4^{ef} \pm 51.3$ | $62.5\ f^{g} \pm 7.2$ | $11.1^{k} \pm 1.7$ | $3.2^{i} \pm 0.2$ | $94.4^{j} \pm 3.5$ |
| Belgium 2 | $217.5^{a} \pm 29.1$ | $63.6^{defg} \pm 7.5$ | $14.8^{c} \pm 0.6$ | $4.4^{e} \pm 0.2$ | $98.7^{cde} \pm 2.1$ |
| France 1 | $163.8^{ef} \pm 22.6$ | $63.7^{defg} \pm 6.3$ | $14.3^{c} \pm 1$ | $3.8^{fgh} \pm 0.1$ | $96.7^{gh} \pm 2.2$ |
| France 2 | $161.9^{ef} \pm 26.3$ | $66.5^{bcd} \pm 6.4$ | $13.7^{d} \pm 0.6$ | $4.6^{de} \pm 0.1$ | $97.8^{efg} \pm 1.8$ |
| France 3 | $213.2^{a} \pm 45.2$ | $63.0^{efg} \pm 5.6$ | $13.7^{d} \pm 0.7$ | $5.0^{bcd} \pm 0.1$ | $98.2^{def} \pm 2.2$ |
| France 4 | $156.9\ ^{f} \pm 27.8$ | $63.4^{defg} \pm 6.4$ | $12.4^{fgh} \pm 0.7$ | $3.9^{fg} \pm 0$ | $97.4^{fg} \pm 1.7$ |
| France 5 | $188.0^{bcd} \pm 45.7$ | $63.2^{efg} \pm 5.1$ | $12.2^{ghi} \pm 0.9$ | $3.6\ ^{h} \pm 0.1$ | $98.4^{def} \pm 2.6$ |
| Germany 1 | $219.5^{a} \pm 24.9$ | $65.0^{cdef} \pm 5$ | $13.3^{de} \pm 0.7$ | $4.5^{e} \pm 0.2$ | $97.0\ ^{g} \pm 2.7$ |
| Italy 1 | $223.6^{a} \pm 31.8$ | $61.1\ ^{g} \pm 5.6$ | $16.6^{a} \pm 1$ | $5.3^{ab} \pm 0.4$ | $94.3^{j} \pm 2.4$ |
| Italy 2 | $221.1^{a} \pm 39.6$ | $64.0^{defg} \pm 7.3$ | $15.4^{b} \pm 1.2$ | $5.0^{bc} \pm 0.2$ | $94.6^{j} \pm 2.1$ |
| Italy 3 | $222.6^{a} \pm 41.3$ | $66.6^{bcd} \pm 6$ | $16.8^{a} \pm 0.9$ | $4.8^{cde} \pm 0.1$ | $95.0^{ij} \pm 2.2$ |
| Italy 4 | $204.5^{abc} \pm 32.8$ | $66.1^{bcde} \pm 3.7$ | $15.8^{b} \pm 1.2$ | $5.1^{abc} \pm 0.4$ | $95.8^{hi} \pm 2$ |
| Switzerland 1 | $186.3\ ^{cd} \pm 27$ | $74.3^{a} \pm 5$ | $11.8^{ij} \pm 0.8$ | $5.5^{a} \pm 0.1$ | $100.1^{a} \pm 1.6$ |
| Switzerland 2 | $157.7\ ^{f} \pm 35.8$ | $68.1^{bc} \pm 7.8$ | $11.4^{jk} \pm 0.9$ | $2.7\ ^{n.c.} \pm$ nd | $99.6^{abc} \pm 1.7$ |
| Switzerland 3 | $189.2^{bcd} \pm 52.9$ | $63.9^{defg} \pm 4.6$ | $10.9^{k} \pm 1.1$ | $3.6\ ^{n.c.} \pm$ nd | $99.0^{bcd} \pm 1.9$ |
| Switzerland 4 | $177.8^{de} \pm 37.6$ | $63.2^{efg} \pm 9.8$ | $13.4^{d} \pm 1.5$ | $4.7\ ^{n.c.} \pm$ nd | $96.7^{gh} \pm 2.1$ |
| Switzerland 5 | $167.5^{ef} \pm 31.5$ | $68.6^{b} \pm 7.9$ | $14.8^{c} \pm 1.2$ | $3.7^{gh} \pm 0.3$ | $99.0^{abcd} \pm 1.7$ |
| Switzerland 6 | $221.5^{a} \pm 59.1$ | $65.0^{cdef} \pm 6.1$ | $12.9^{ef} \pm 1$ | $4.1\ ^{f} \pm 0.3$ | $99.8^{ab} \pm 1.8$ |
| Switzerland 7 | $173.8^{def} \pm 28$ | $62.2^{fg} \pm 6$ | $11.9^{hi} \pm 0.6$ | $2.9^{j} \pm 0.2$ | $98.4^{def} \pm 2.1$ |
| Switzerland 8 | $207.1^{ab} \pm 58$ | $68.5^{b} \pm 5.5$ | $12.7^{fg} \pm 0.9$ | $3.9^{fgh} \pm 0.1$ | $98.9^{bcd} \pm 2.1$ |

the Swiss orchards, fruit density varied from 1.009 to 1.025 kg/cm$^3$ and was particularly high in Switzerland 4 and 5. Regarding French pears, the highest densities were recorded in French 1 and 2 orchards.

### 3.4. Seed number

The number of seeds per fruit varied between orchards, averaging 2.4 (Fig. 3). Switzerland 2 and Germany 1 showed the highest values, with 4.2 and 4.5 seeds per fruit, respectively. By contrast, Belgium 2 and Switzerland 8 had poor seed development, averaging only 0.6 and 0.7 seeds per fruit, respectively.

### 3.5. Mineral composition and dry matter

Pear origin influenced Ca, Mg, K, and P levels (Table 3). Pears from Italy 1, 2, and 4, Belgium 2, and Switzerland 6 and 8 orchards exhibited the highest K/Ca ratios, which were associated with low Ca. Although Belgium 1 and Italy 4 had relatively low Ca levels, their K/Ca ratios remained within the range of the average values measured across all orchards. Mg content ranged from 6.1 to 8.9, with the highest values measured in the Italian orchards and some of the Swiss (1, 3, and 4) and French orchards (1, 2, and 3). Most Italian pears (except Italy 3), along with Switzerland 1, had the highest K concentrations. By contrast, K levels in Belgium 1, France 4 and 5, and Switzerland 7 were lower. The highest dry matter values were recorded in the Italian orchards, whereas Belgium 1 had the lowest values (Table 3).

### 3.6. Correlations between the different parameters

Two PCA were first performed to explore the effects of the origin of the pears on the different parameters and their relationships with cavities (Fig. 4 A) and IB (Fig. 4 B). Principal component (PC) 1 accounted for 44.5% and 45%, respectively, of the total variation and discriminated Italian orchards from all others. PC1 was mainly correlated with the incidence of cavities or IB, TSS, and fruit density but also DD F-H and K/Ca. PC2 accounted for 14.15% and 14.2% of the total variation and showed a poor correlation with the measured parameters. Switzerland 1 tended to be positively correlated with this PC, while Switzerland 6 and

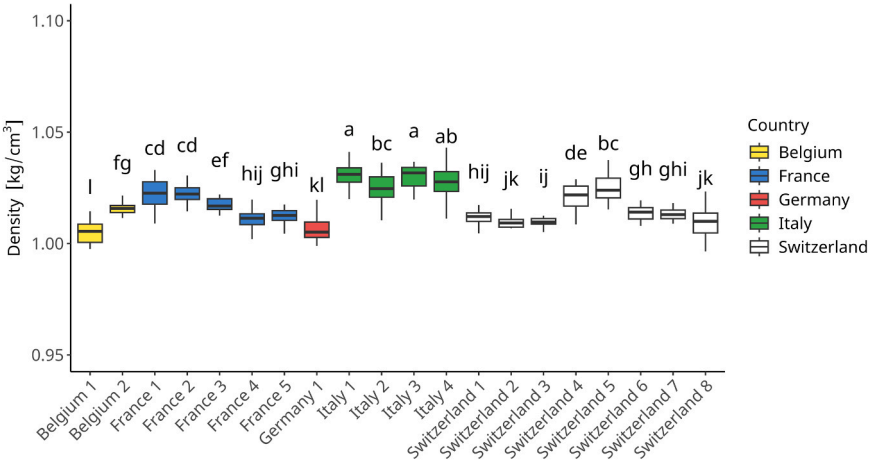



**Fig. 2.** Influence of the orchard on fruit density of 'CH201/FRED®' pears at harvest. Values are the means of 20 fruit per orchard. Means with the same letters do not differ significantly at $p \leq 0.05$ in the Tukey's HSD test.

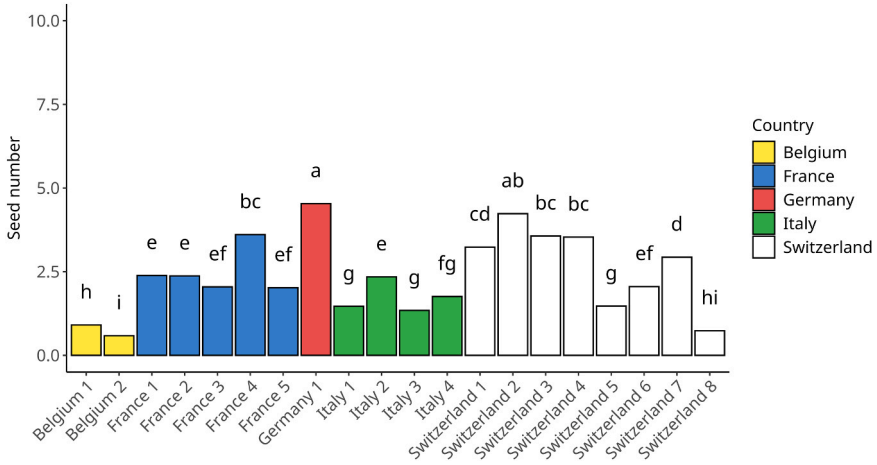



**Fig. 3.** Influence of the orchard on seed number of 'CH201/FRED®' pears. Values are the means of 150 fruit per orchard. Means with the same letters do not differ significantly at $p \leq 0.05$ in the Dunn's test.

**Table 3**
Influence of the orchard on mineral composition (Ca, Mg, K, P, and K/Ca ratio) and dry matter of 'CH201/FRED®' pears. Values are the means of 3 replicates of 30 fruit. Means with the same letters do not differ significantly at $p \leq 0.05$ in the Tukey's HSD test.

| Orchard | Ca [mg/100 g] | Mg [mg/100 g] | K [mg/100 g] | P [mg/100 g] | K/Ca ratio | Dry matter [%] |
|---|---|---|---|---|---|---|
| Belgium 1 | $9.0^{gh} \pm 0.2$ | $6.1^{h} \pm 0.2$ | $117.2^{ij} \pm 2.8$ | $10.5^{fghi} \pm 1.2$ | $13.0^{de} \pm 0.6$ | $14.7^{i} \pm 0.5$ |
| Belgium 2 | $9.6^{gh} \pm 0.7$ | $6.4^{gh} \pm 0.2$ | $136.4^{efg} \pm 5.7$ | $9.7^{ij} \pm 2$ | $14.3^{cd} \pm 1.6$ | $16.5^{fgh} \pm 0.2$ |
| France 1 | $17.4^{a} \pm 0.7$ | $8.2^{bc} \pm 0.2$ | $150.8^{cd} \pm 2.5$ | $14.4^{b} \pm 0.4$ | $8.7^{hi} \pm 0.3$ | $19.3^{cd} \pm 0.2$ |
| France 2 | $13.2^{de} \pm 1$ | $8.9^{a} \pm 0.3$ | $171.5^{ab} \pm 9$ | $13.7^{bc} \pm 1.4$ | $13.1^{de} \pm 1.6$ | $18.8^{de} \pm 0.1$ |
| France 3 | $11.9^{ef} \pm 0.8$ | $8.3^{bc} \pm 0.1$ | $147.1^{de} \pm 2.2$ | $11.5^{defg} \pm 0.3$ | $12.4^{e} \pm 1.1$ | $18.2^{e} \pm 0.1$ |
| France 4 | $14.3^{cd} \pm 1.4$ | $7.8^{cd} \pm 0.2$ | $114.6^{j} \pm 4.8$ | $9.0^{j} \pm 0.8$ | $8.1^{i} \pm 0.9$ | $16.5^{fgh} \pm 0.2$ |
| France 5 | $15.6^{bc} \pm 0.7$ | $7.9^{cd} \pm 0.1$ | $110.9^{j} \pm 5$ | $10.6^{fghi} \pm 0.6$ | $7.1^{j} \pm 0.1$ | $17.0^{f} \pm 0.4$ |
| Germany 1 | $13.2^{de} \pm 1$ | $6.6^{fg} \pm 0.1$ | $126.5^{ghi} \pm 2.3$ | $10.6^{fghi} \pm 0.3$ | $9.6^{gh} \pm 0.6$ | $17.0^{f} \pm 0.2$ |
| Italy 1 | $9.3^{gh} \pm 0.6$ | $8.2^{bc} \pm 0.2$ | $171.4^{ab} \pm 10.8$ | $18.2^{a} \pm 0.2$ | $18.5^{a} \pm 1.4$ | $20.2^{ab} \pm 0.4$ |
| Italy 2 | $9.2^{gh} \pm 0.3$ | $8.1^{bc} \pm 0.3$ | $169.5^{ab} \pm 4.9$ | $10.8^{fghi} \pm 0.7$ | $18.5^{a} \pm 0.5$ | $19.9^{bc} \pm 0.2$ |
| Italy 3 | $11.3^{f} \pm 0.7$ | $8.1^{bc} \pm 0.3$ | $131.2^{fgh} \pm 3.5$ | $12.5^{cd} \pm 0.3$ | $11.6^{ef} \pm 0.4$ | $20.7^{a} \pm 0.3$ |
| Italy 4 | $9.8^{h} \pm 0.7$ | $8.5^{ab} \pm 0.3$ | $161.6^{bc} \pm 12.5$ | $17.3^{a} \pm 0.8$ | $16.5^{ab} \pm 0.1$ | $20.4^{ab} \pm 0.3$ |
| Switzerland 1 | $14.0^{d} \pm 1.1$ | $8.8^{a} \pm 0.1$ | $182.6^{a} \pm 3.1$ | $12.2^{cde} \pm 1.4$ | $13.1^{de} \pm 1$ | $16.7^{fgh} \pm 0.1$ |
| Switzerland 2 | $14.5^{cd} \pm 1.1$ | $7.0^{e} \pm 0.2$ | $126.4^{ghi} \pm 7.2$ | $10.0^{ghij} \pm 0.9$ | $8.7^{hi} \pm 0.4$ | $16.0^{gh} \pm 0.3$ |
| Switzerland 3 | $17.3^{ab} \pm 0.2$ | $8.1^{bc} \pm 0.3$ | $138.8^{ef} \pm 2.7$ | $9.5^{ij} \pm 1.1$ | $8.0^{ij} \pm 0.1$ | $16.1^{gh} \pm 0$ |
| Switzerland 4 | $17.3^{ab} \pm 0.9$ | $8.1^{bc} \pm 0.2$ | $134.5^{fg} \pm 9.4$ | $12.0^{def} \pm 0.6$ | $7.8^{ij} \pm 1$ | $17.1^{f} \pm 0.4$ |
| Switzerland 5 | $11.7^{f} \pm 0.8$ | $7.6^{d} \pm 0.3$ | $124.0^{hi} \pm 3.5$ | $10.6^{fghi} \pm 0.7$ | $10.6^{fg} \pm 0.4$ | $19.0^{cd} \pm 0.1$ |
| Switzerland 6 | $9.3^{gh} \pm 0.2$ | $6.8^{ef} \pm 0.4$ | $132.8^{fgh} \pm 4.6$ | $11.3^{defgh} \pm 0.1$ | $14.4^{cd} \pm 0.9$ | $16.8^{fg} \pm 0.3$ |
| Switzerland 7 | $11.6^{f} \pm 0.2$ | $6.3^{gh} \pm 0.3$ | $111.1^{j} \pm 11.6$ | $10.0^{hij} \pm 0.9$ | $9.6^{gh} \pm 1.2$ | $15.9^{h} \pm 0.2$ |
| Switzerland 8 | $8.8^{g} \pm 0.9$ | $6.8^{ef} \pm 0.2$ | $129.7^{fgh} \pm 5.7$ | $10.9^{efgh} \pm 0.7$ | $14.8^{bc} \pm 1.3$ | $16.1^{gh} \pm 0$ |

Belgium 2 were negatively correlated.

Across all orchards, the correlations between cavities and IB and the various parameters yielded *r*-values ranging from −0.59–0.69 and from −0.73–0.89, respectively (Table 4). Cavities were positively correlated with K, P, the K/Ca ratio, mass, TSS, TA, density, and dry matter and negatively correlated with Ca, tree age, vigor, and the crop load-to-vigor ratio. IB showed correlations with the same parameters as cavities, except for the crop load-to-vigor ratio. Some correlations were stronger, particularly with TSS, density, and dry matter, while the strongest negative correlation was observed with skin color ($r$ = -0.73). In addition, IB was significantly associated with all climatic variables. When considering only Italian and Swiss pears, all correlations markedly increased, reaching *r*-values from −0.73–0.87 for cavities and −0.90–0.96 for IB (Table 4). In orchards predominantly affected by core cavities, a strong correlation was obtained between cavities and TA ($r = 0.91$; Fig. S5, C), whereas in orchards where flesh cavities predominated, cavity incidence was strongly negatively correlated with crop load ($r$ = - 0.91; Fig. S5, D).

Besides being correlated with both cavities ($r = 0.64$) and IB ($r = 0.67$), the K/Ca ratio also showed a positive correlation with mass, TSS, TA, and density and a negative correlation with seed number and crop load (Fig. S5, A). TSS was strongly related to both density and dry matter ($r > 0.9$), whereas firmness showed no correlation at all. Fruit mass and density were only poorly related ($r = 0.46$). Interestingly, seed number was correlated with Ca ($r = 0.66$), and this correlation increased to 0.80 when only Swiss and Italian orchards were considered (Fig. S5, B).

### 3.7. Predictive model for cavities

The Gaussian generalized linear model revealed that cavity incidence was significantly associated with dry matter content and tree age. Cavity incidence increased with increasing dry matter content ($\beta = 6.56 \pm 2.10$, $p = 0.006$) and decreased with tree age ($\beta = -2.98 \pm 1.16$, $p = 0.021$). The effect of the K/Ca ratio was positive but only marginally significant ($\beta = 2.21 \pm 1.10$, $p = 0.063$). The final fitted model is:

$$\text{Cavities} = -94.13 + 6.56 \times \text{Dry matter} - 2.98 \times \text{Tree age} + 2.21 \times \text{K/Ca}.$$

After bootstrap correction, the model based on dry matter, tree age, and the K/Ca ratio showed moderate predictive performance, with an optimism-corrected $R^2$ of 63.3% (calibration slope = 0.95; optimism =

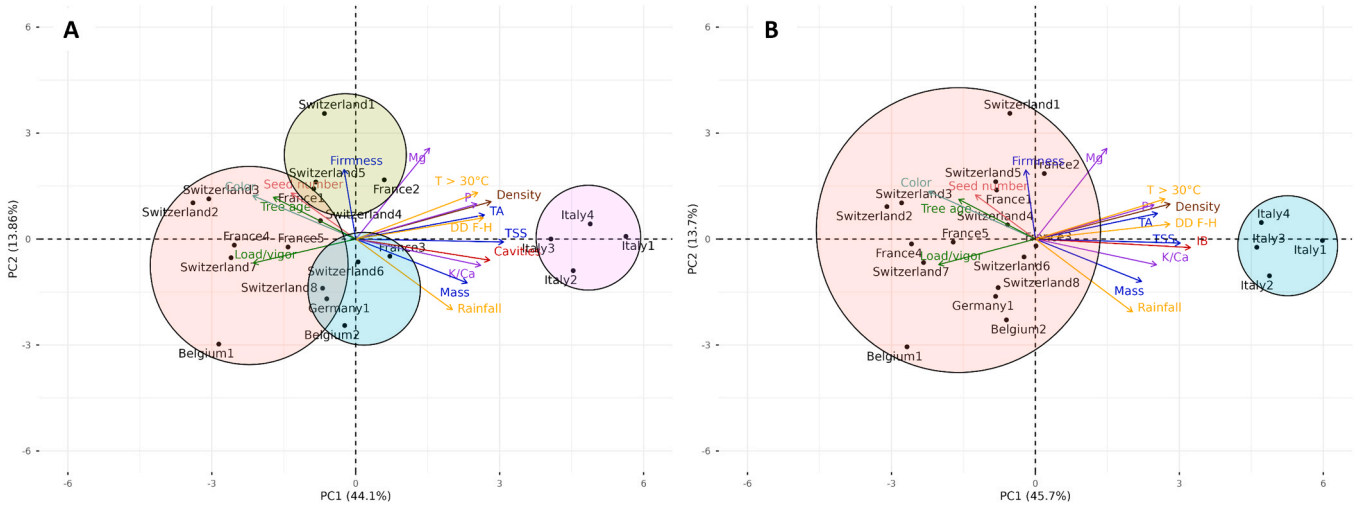



**Fig. 4.** Principal component analysis (PCA) based on the orchard means (n = 20) for cavities (**A**) and IB (**B**) together with Ca, Mg, K, P, the K/Ca ratio, mass, firmness, TSS, TA, color, density, seed number, tree age, the crop load-to-vigor ratio, DD F-H, ND T° > 30, and rainfall. Colors indicate the clusters identified by hierarchical clustering of principal components.

**Table 4**
Pearson's correlation coefficients (*r*) between cavities and IB and Ca, Mg, K, P, the K/Ca ratio, mass, firmness, TSS, TA, color, density, seed number, dry matter, tree age, crop load, vigor, the crop load-to-vigor ratio, DD F-H, ND T° > 30, and rainfall. The *r* values are presented only for statistically significant correlations ($p \leq 0.05$); ns: not significant.

| | All origins | | Italy and Switzerland | |
|---|---|---|---|---|
| | Cavities | IB | Cavities | IB |
| Ca | -0.48 | -0.45 | -0.73 | ns |
| Mg | ns | ns | ns | ns |
| K | 0.46 | 0.48 | ns | ns |
| P | 0.56 | 0.62 | 0.74 | 0.67 |
| K/Ca | 0.64 | 0.67 | 0.87 | 0.74 |
| Mass | 0.61 | 0.55 | 0.78 | 0.75 |
| Firmness | ns | ns | ns | ns |
| TSS | 0.69 | 0.78 | 0.79 | 0.87 |
| TA | 0.65 | 0.57 | 0.63 | 0.64 |
| Color | ns | -0.73 | -0.69 | -0.9 |
| Density | 0.57 | 0.74 | 0.71 | 0.82 |
| Seed number | ns | ns | -0.60 | ns |
| Dry matter | 0.68 | 0.78 | 0.80 | 0.88 |
| Tree age | -0.59 | -0.44 | -0.70 | -0.72 |
| Crop load | -0.57 | -0.59 | -0.73 | -0.68 |
| Vigor | ns | ns | ns | ns |
| Load/Vigor | -0.52 | ns | -0.68 | ns |
| DD F-H | ns | 0.89 | 0.78 | 0.96 |
| T > 30 °C | ns | 0.85 | 0.65 | 0.85 |
| Rainfall | ns | 0.60 | 0.67 | 0.71 |

0.089), an RMSE of 12.8, and an MAE of 11.1 (Fig. 5). The variance inflation factors for all predictors were below 1.4, indicating the absence of problematic multicollinearity. The correlation between the observed and predicted cavity incidences was 85%.

## 4. Discussion

This study investigated the relationship between mineral composition, quality parameters, orchard-related parameters, and the occurrence of CA-related disorders in 'CH201/FRED®' pears harvested from 20 orchards in Belgium, France, Germany, Italy, and Switzerland during storage. The results showed a relatively high incidence of cavities, with marked differences among orchards, whereas IB was observed in a more restricted number of orchards.

### 4.1. The influence of agronomic characteristics on CA-related disorders

Half of the assessed orchards (Belgium 1, Germany, Italy, and France 3, 4, and 5) were very young (less than 4 years old), and young tree age has previously been associated with an increased risk of cavity formation in 'CH201/FRED®' pears during CA storage (Gabioud Rebeaud et al., 2024). Consistent with these findings, tree age emerged as an important predictor in the model for identifying orchards at a higher risk of cavity formation before storage. However, the relationship between tree age and cavity development is likely to be indirect rather than causal. In young pear orchards, vegetative growth, fruiting, and crop

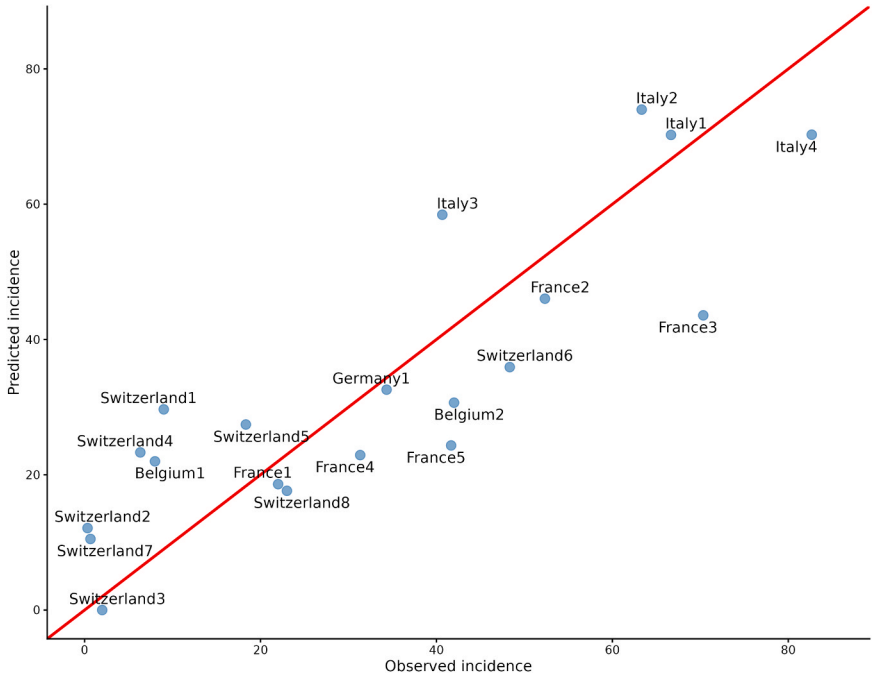



**Fig. 5.** Relationship between observed and predicted cavity incidence for the final generalized linear model. Each point represents one orchard. The red line is the linear regression fitted between the observed and predicted values, illustrating the predictive performance of the model.

load are closely interrelated, and an imbalance between vegetative growth and fruiting can influence assimilate and nutrient partitioning (Bound, 2021). Moreover, recent work on 'CH201/FRED®' showed that increased vegetative growth and a high leaf area-to-crop load ratio were associated with reduced fruit Ca concentration and increased cavity incidence, demonstrating that the balance between vegetative growth and crop load influences susceptibility to CA-related disorders (Gabioud Rebeaud et al., 2025). Crop load has also been shown to strongly influence cavity and internal browning development in 'Braeburn' apples (McCormick et al., 2021). Tree age may therefore integrate several orchard characteristics related to cavity susceptibility, including vegetative vigor, crop load, and fruit mineral balance, which could explain its importance in the predictive model.

Nevertheless, tree age is not the only factor associated with the disorder, as some older orchards also exhibited significant symptoms; for instance, 11-year-old orchard France 1 had 25% of its fruit affected. Additional orchard-related factors, such as soil and climatic conditions, rootstock, and cultural practices, may have contributed to an increased susceptibility of these pears to CA-related disorders, as reported in previous studies on 'CH201/FRED®' (Gabioud Rebeaud et al., 2025; Monney et al., 2024) and other pear cultivars (Bonora et al., 2021a; Franck et al., 2007). In particular, the effect of a low crop load is likely to be exacerbated on more vigorous rootstocks, such as Quince BA29 (Musacchi et al., 2021), resulting in a lower crop load-to-vigor ratio and potentially increasing the risk of CA-related disorders. Orchard management practices, including fertilization and pruning, may further influence tree vigor and, consequently, fruit susceptibility. Nevertheless, a low incidence of CA-related disorders was observed in Swiss orchards grafted on vigorous rootstocks (Pyrus Pyriam and Quince BA29) when a balanced crop load-to-vigor ratio was maintained, confirming the results obtained by Monney et al. (2024) and suggesting that appropriate orchard management can mitigate the effect of rootstock vigor on disorder development.

### 4.2. The influence of climatic factors on CA-related disorders

The orchards included in this study were distributed across several European pear-producing regions, providing a broad gradient of climatic conditions. Climatic factors, including DD F-H, T > 30°C, and cumulative rainfall, were evaluated because they have been associated with fruit maturity, quality at harvest, and, to some extent, susceptibility to postharvest disorders (Argenta et al., 2022; Bonora et al., 2021a; Łysiak, 2022). Although cumulative rainfall varied considerably among orchards, it showed no apparent relationship with the incidence of CA-related disorders. Likewise, marked regional differences in heat accumulation were observed: French and Swiss orchards reached harvest maturity after approximately 1900–2200 °-days, German and Belgian orchards after only 1750–1842 °-days, whereas Italian orchards accumulated more than 2500 °-days. These differences likely reflect the contrasting climatic conditions across regions and may have contributed to regional variation in fruit characteristics, and susceptibility to physiological disorders. However, despite these climatic contrasts, their influence on cavity incidence appeared less pronounced than that of orchard-related factors, particularly rootstock, tree age, and crop load. This observation is consistent with findings in 'Abate Fetel', where a multiyear multivariate analysis showed that the incidence of superficial scald was more strongly associated with orchard factors, including yield, orchard age, canopy volume, irrigation regime, soil texture, and rootstock, than with weather conditions alone (Bonora et al., 2021a).

### 4.3. IB in Italian pears

Besides cavities, IB was also observed in fruit across all the orchards, being more pronounced in Italian pears. In some cases, IB was associated with watercore symptoms (Fig. S6), suggesting a possible association between the two disorders. However, watercore incidence and severity were not specifically assessed in the present study; therefore, a direct relationship with IB could not be established. Watercore is characterized by the accumulation of fluid in the intercellular spaces of the fruit flesh and has been associated with the subsequent development of internal browning and tissue breakdown during storage (Fukuda, 1984; Argenta et al., 2002; Itai, 2015). More recently, Li et al. (2025) showed that watercore-affected apple tissues were particularly susceptible to browning during storage and associated this susceptibility with altered antioxidant and energy metabolism, accumulation of reactive oxygen species, and loss of membrane integrity. Although these findings were

primarily reported in apples, they provide a physiological basis for the possible association between the watercore symptoms and IB observed in the present study. Therefore, watercore may have contributed to the browning symptoms observed in Italian pears, although this hypothesis requires confirmation through a specific assessment of watercore in future studies.

Several preharvest factors have been reported to increase the risk of this disorder, including high temperatures during the preharvest period, large fruit size, low Ca concentration, high N and B nutrition, a low fruit-to-leaf ratio, and excessive fruit thinning (Itai, 2015). Interestingly, all Italian pears originated from orchards younger than 4 years old and exhibited some of the highest values of TSS, TA, mass, density, dry matter, K/Ca ratio, cavities, and IB, and the lowest hue values and crop load-to-vigor ratios. In addition, these pears developed under relatively high temperatures during the growing season. Collectively, these observations suggest that Italian pears accumulated high levels of carbohydrates before harvest, likely due to hot, sunny days in the region of production and low crop load-to-vigor ratios, which may have contributed to the high incidence of IB. A similar association between heat accumulation during fruit development and internal browning has been reported in 'Pink Lady®' apples (Jobling et al., 2005).

### 4.4. The influence of minerals on CA-related disorders

The high fruit mass and density of Italian pears, combined with low Ca levels and high K/Ca ratios, respectively, likely increased their susceptibility to the disorders. Ca plays a key role in maintaining fruit cell walls by stabilizing pectin, which strengthens tissues and leads to firmer fruit (Hocking et al., 2016). Low Ca levels were also measured in pears from Switzerland 6 and Switzerland 8, which had the highest cavity incidence of all tested Swiss origins. A correlation restricted to Swiss and Italian pears clearly presented the K/Ca ratio as a determinant factor among all other measured factors to explain the incidence of cavities ($r = 0.87$). This observation supports previous findings from studies on 'Rocha' pear (Saquet et al., 2019) and 'Braeburn' apples (Neuwald et al., 2014). However, the correlation dropped to $r = 0.64$ when all origins were included.

Although Italian orchards with the highest cavity incidence also exhibited the highest fruit K/Ca ratios, this relationship was not consistent across all production regions. For example, France 1, 4, and 5 displayed low K/Ca ratios despite severe cavity incidence, and similar K/Ca ratios in French and Swiss orchards were associated with markedly different incidences of CA-related disorders. This inconsistency appeared to be related to the predominant cavity type. Orchards predominantly affected by core cavities generally showed a weak association between cavity incidence and the K/Ca ratio, whereas orchards mainly affected by flesh cavities exhibited a stronger association. By contrast, TA was mostly correlated with cavity incidence in orchards predominantly affected by core cavities. However, TA was not retained in the final prediction model, as its predictive value across all orchards was lower than that of dry matter, and it showed moderate correlations with the three selected predictors ($r$ = -0.49 with tree age, 0.58 with K/Ca and 0.62 with dry matter).

The relationship between CA-related disorders and K and P levels is less clear and is consistent with previous reports in the literature indicating that the association of these macronutrients with browning disorders is often contradictory (Sidhu et al., 2023). Given that previous research has highlighted the importance of micronutrients such as iron and B in the incidence of CA-related disorders in pears (Saquet et al., 2019; Xuan et al., 2003), it would be interesting to investigate this relationship in 'CH201/FRED®' pears, particularly in origins where cavity incidence was observed in the absence of an association with Ca or the K/Ca ratio.

### 4.5. The influence of fruit quality parameters on CA-related disorders and their relationships

Besides minerals, cavities and IB also showed positive correlations with other parameters, such as fruit mass, density, dry matter, TSS, and TA. IB was also strongly correlated with color. Interestingly, mass and density were not significantly correlated, indicating that larger fruit were not necessarily denser. Dry matter, by contrast, showed a strong correlation with density, and confirmed results previously reported for other fruits, such as kiwifruit (Jordan et al., 2000), nectarines (Aubert et al., 2019), and mangoes (Hor et al., 2020). Additionally, dry matter was found to be strongly related to TSS ($r = 0.91$), and both correlated with CA-associated disorders ($r = 0.68$, 0.78).

The relationship between density and CA-related disorders in the 'CH201/FRED®' pears may be attributed to the reduced intercellular air spaces in denser fruit tissues, which restrict $O_2$ diffusion and hinder $CO_2$ removal (Ho et al., 2006). The low porosity of 'CH201/FRED®' pears was confirmed in a study conducted that used X-ray radiography and deep learning to determine porosity in various pear cultivars (Tempelaere et al., 2024). This restricted gas exchange capacity may promote the development of localized hypoxic conditions, leading to enhanced fermentative metabolism and the accumulation of toxic byproducts. The resulting ATP depletion further exacerbates cell damage, ultimately resulting in cell death and tissue browning (Franck et al., 2007). Moreover, higher tissue density is often associated with elevated soluble solid concentrations (Aubert et al., 2019), a trend also observed in the present study. Such conditions may exacerbate osmotic stress and predispose the fruit to structural collapse. The occurrence of watercore in some Italian pears, which also exhibited higher TSS levels, further supports this observation. In combination with a low Ca level, these factors probably increased the likelihood of internal browning and cavity development in 'CH201/FRED®' pears.

No association was found between fruit firmness measured at harvest and CA-related disorders. Values were relatively uniform across the various orchards, and softening varied depending on fruit origin, with no relationship with mineral content.

### 4.6. The association between seed number and Ca

This study also revealed an association between seed number and Ca content in 'CH201/FRED®' pears, particularly considering data from Italian and Swiss orchards ($r = 0.8$). These results are in line with studies performed on apples (Bramlage et al., 1990; Brookfield et al., 1996; Buccheri and Di Vaio, 2005). Parthenocarpic apples generally exhibit lower Ca concentrations (Bangerth, 1993), with seeds playing a crucial role in hormone production, particularly auxin and gibberellin, which can enhance fruit growth and facilitate the uptake of minerals (Luckwill et al., 1969). High pollination success supported by favorable weather conditions, a close presence of compatible pollen sources, and effective pollinator activity may therefore improve the storability of the 'CH201/FRED®' pears. However, despite the association between seed number and Ca concentration, seed number was not associated with cavity incidence. This suggests that although successful pollination may contribute to Ca uptake, Ca concentration alone is insufficient to explain the development of CA-related disorders in this cultivar. Rather, the occurrence of cavities appears to depend on multiple interacting preharvest factors, including tree age, crop load-to-vigor ratio, and fruit characteristics, such as dry matter and the K/Ca ratio, which are more closely associated with disorder incidence. Further research is nevertheless needed to determine how pollination, mineral nutrition, and fruit physiology interact to influence storage disorder susceptibility in 'CH201/FRED®' pears.

### 4.7. The predictive model for cavities

Finally, the predictive model calculated for cavity incidence showed

moderate internal predictive performance, suggesting that dry matter, tree age, and K/Ca ratio may be useful predictors of cavity risk. As these variables are readily measurable at harvest, they could potentially contribute to orchard-specific risk assessments. However, the model was developed using data from 20 orchards collected during a single growing season and was internally validated using the same dataset through bootstrap resampling. Its predictive performance for independent orchards and across different growing seasons therefore remains unknown. The model should thus be considered preliminary, and external validation using independent datasets from additional orchards, growing seasons, and production regions is required before it can be considered for practical application as a decision-support tool.

An additional limitation concerns the storage conditions used in this study. Postharvest storage conditions, particularly temperature and CA gas composition, have previously been shown to influence the development of CA-related disorders in 'CH201/FRED®' pears (Büchele et al., 2024; Gabioud Rebeaud et al., 2024). In the present study, all fruit were stored under the same CA condition to specifically investigate differences among orchards and their relationships with preharvest and fruit-related factors. Consequently, the relationships identified here should be interpreted within the specific storage conditions applied, and potential interactions between preharvest factors and storage conditions cannot be determined from the present study.

## 5. Conclusion

In this international, multi-orchard study, the susceptibility of the 'CH201/FRED®' pear cultivar to develop CA-related disorders was found to vary across European orchards. Most of the observed symptoms were cavities, while Italian pears were also strongly affected by IB. A correlation was observed between the K/Ca ratio and the incidence of cavities, and this correlation increased when the analysis was limited to Swiss and Italian orchards. This indicates that measuring mineral composition can be a useful tool for identifying susceptible pear batches at harvest, but the findings also suggest that additional orchard-related factors influence the strength of this correlation. High dry matter was shown to be correlated with a high incidence of disorders, density, and TSS. To some extent, a lower hue value at harvest, meaning a yellower ground color, and a high cumulative temperature between full bloom and harvest were associated with IB. Finally, the predictive model identified dry matter, tree age, and the K/Ca ratio as potentially useful indicators of cavity risk.

Overall, these findings highlight the multifactorial nature of CA-related disorders in 'CH201/FRED®' pears and the potential value of combining mineral, fruit quality, agronomic, and environmental factors for orchard-specific risk assessment. However, as the study was conducted over a single growing season and under one CA storage regime, the identified risk indicators should be considered preliminary. Validation across independent orchards, growing seasons, production regions, and storage conditions is required before their practical application.

## CRediT authorship contribution statement

**Samuel Köchli:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Pierre-Yves Cotter:** Investigation. **Felix Büchele:** Writing – review & editing, Investigation, Data curation. **María Emma García-Pastor:** Visualization. **Daniel Alexandre Neuwald:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Séverine Gabioud Rebeaud:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used BioRender (Toronto, Canada) and ChatGPT (OpenAI, San Francisco, USA) for the preparation of the Graphical Abstract.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

The authors thank Timothée Gaspoz, Marie Cachat-Terrettaz, Thibault Costaz, Sabine Scheer, Kiran Hivare, Adriana Lugaresi, Berenice Vollmar, and Daiane Neuwald for their contributions to this study. We thank Fabien Rebeaud for his support in writing this paper, and Claude Coureau, Richard Priscillia, Jean-Philippe Dupin, Ceredi Gianni, Thoelen Mieke, and Michael Weber for providing the fruit for this study.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.postharvbio.2026.114879.

## Data availability

Data will be made available on request.

## References

Agroscope, 2025. Agrometeo: Forecasting and Risk Analysis for Agriculture. https://www.agrometeo.ch. (Accessed 25 July 2025). Available at: accessed.

Antoniolli, L.R., Czermainski, A.B.C., Zucoloto, M., Siqueira, D.L., 2016. Postharvest treatments to mitigate the internal browning in 'Bartlett' pears. Curr. Agric. Sci. Technol. 22, 1–13. https://doi.org/10.18539/cast.v22i1.5638.

Argenta, L.C., Amarante, C.V.T., de Freitas, S.T., Brancher, T.L., Nesi, C.N., Mattheis, J. P., 2022. Fruit quality of 'Gala' and 'Fuji' apples cultivated under different environmental conditions. Sci. Hortic. 303, 1–11. https://doi.org/10.1016/j.scienta.2022.111195.

Argenta, L.C., Fan, X., Mattheis, J.P., 2002. Impact of watercore on gas permeance and incidence of internal disorders in 'Fuji' apples. Postharvest Biol. Technol. 24, 113–122. https://doi.org/10.1016/S0925-5214(01)00137-5.

Aubert, C., Chalot, G., Lurol, S., Ronjon, A., Cottet, V., 2019. Relationship between fruit density and quality parameters, levels of sugars, organic acids, bioactive compounds and volatiles of two nectarine cultivars, at harvest and after ripening. Food Chem. 297, 1–11. https://doi.org/10.1016/j.foodchem.2019.124954.

Bangerth, F., 1993. Polar auxin transport as a signal in the regulation of tree and fruit development. Acta Hortic. (329), 70–76. https://doi.org/10.17660/ActaHortic.1993.329.10.

Bonora, A., Muzzi, E., Franceschini, C., Boini, A., Bortolotti, G., Bresilla, K., Perulli, G.D., Venturi, M., Manfrini, L., Grappadelli, L.C., 2021a. Preharvest factors affecting quality on "Abate Fetel" pears: study of superficial scald with multivariate statistical approach. J. Food Qual. 1, 1–11. https://doi.org/10.1155/2021/99218.

Bonora, A., Noronha, H., Corelli Grappadelli, L., Sánchez, C., 2021b. Preharvest factors affecting quality during 'Rocha' pear long-term storage. Acta Hortic. (1303), 451–460. https://doi.org/10.17660/ActaHortic.2021.1303.62.

Bound, S.A., 2021. Managing crop load in European pear (*Pyrus communis* L.)—A review. Agriculture 11, 1–26. https://doi.org/10.3390/agriculture11070637.

Bramlage, W.J., Weis, S.A., Greene, D.W., 1990. Observations on the relationships among seed number, fruit calcium, and senescent breakdown in apples. Hort. Sci. 25, 351–353. https://doi.org/10.21273/HORTSCI.25.3.351.

Brookfield, P.L., Ferguson, I.B., Watkins, C.B., Bowen, J.H., 1996. Seed number and calcium concentrations of 'Braeburn' apple fruit. J. Hortic. Sci. 71, 265–271. https://doi.org/10.1080/14620316.1996.11515405.

Buccheri, M., Di Vaio, C., 2005. Relationship among seed number, quality, and calcium content in apple fruits. J. Plant. Nutr. 27, 1735–1746. https://doi.org/10.1081/PLN-200026409.

Büchele, F., Gabioud, S.R., Saquet, A.A., Neuwald, D.A., 2024. Influence of storage conditions on the quality and physiological disorders of the pear cultivar 'CH201. Acta Hortic. (1403), 141–148. https://doi.org/10.17660/ActaHortic.2024.1403.17.

Deuchande, T., Carvalho, S.M., Larrigaudière, C., Vasconcelos, M.W., 2017. Mineral concentrations at harvest as novel markers to predict internal browning disorders in

'Rocha' pear during storage under high $CO_2$. Sci. Hortic. 220, 102–106. https://doi.org/10.1016/j.scienta.2017.03.037.
Deuchande, T., Larrigaudière, C., Gine-Bordonaba, J., Carvalho, S.M., Vasconcelos, M. W., 2016. Biochemical basis of $CO_2$-related internal browning disorders in pears (*Pyrus communis* L. cv. Rocha) during long-term storage. J. Agric. Food Chem. 64, 4336–4345. https://doi.org/10.1021/acs.jafc.6b00740.
FAO, 2023. Faostat: Agriculture Data. Available online: http://www.fao.org/faostat/en/#data/QC (accessed on 18 November 2025).
Ferguson, I., Volz, R., Woolf, A., 1999. Preharvest factors affecting physiological disorders of fruit. Postharvest Biol. Technol. 15, 255–262. https://doi.org/10.1016/S0925-5214(98)00089-1.
Franck, C., Baetens, M., Lammertyn, J., Verboven, P., Davey, M.W., Nicolaï, B.M., 2003. Ascorbic acid concentration in cv. Conference pears during fruit development and postharvest storage. J. Agric. Food Chem. 51, 4757–4763. https://doi.org/10.1021/jf026229a.
Franck, C., Lammertyn, J., Ho, Q.T., Verboven, P., Verlinden, B., Nicolaï, B.M., 2007. Browning disorders in pear fruit. Postharvest Biol. Technol. 43, 1–13. https://doi.org/10.1016/j.postharvbio.2006.08.008.
Fukuda, H., 1984. Relationship of watercore and calcium to the incidence of internal storage disorders of 'Fuji' apple fruit. J. Jpn. Soc. Hortic. Sci. 53, 298–302. https://doi.org/10.2503/jjshs.53.298.
Gabioud Rebeaud, S., Cotter, P.-Y., Raemy, M., Dubois, S., Büchele, F., Neuwald, D., Monney, P., 2025. Pruning and flower thinning influence the storability of CH201/FRED® pears. Agronomy 15, 493. https://doi.org/10.3390/agronomy15020493.
Gabioud Rebeaud, S., Cotter, P.Y., Christen, D., 2024. Pre- and postharvest factors influence CA-related disorders on the new pear cultivar 'CH201. Acta Hortic. (1386), 55–64. https://doi.org/10.17660/ActaHortic.2024.1386.8.
Gil, G.F., Henríquez, J.A., Vera, C.A., Zoffoli, J.P., 1994. Physiological disorders of pears in relation with nutrition. Acta Hortic. (367), 296–303. https://doi.org/10.17660/ActaHortic.1994.367.42.
Ho, Q.T., Verlinden, B.E., Verboven, P., Nicolaï, B.M., 2006. Gas diffusion properties at different positions in the pear. Postharvest Biol. Technol. 41, 113–120. https://doi.org/10.1016/j.postharvbio.2006.04.002.
Hocking, B., Tyerman, S.D., Burton, R.A., Gilliham, M., 2016. Fruit calcium: transport and physiology. Front. Plant. Sci. 7, 1–17. https://doi.org/10.3389/fpls.2016.00569.
Hor, S., Léchaudel, M., Mith, H., Bugaud, C., 2020. Fruit density: a reliable indicator of sensory quality for mango. Sci. Hortic. 272, 1–9. https://doi.org/10.1016/j.scienta.2020.109548.
Itai, A., 2015. Watercore in fruits. In: Kanayama, Y., Kochetov, A. (Eds.), Abiotic Stress Biology in Horticultural Plants. Springer, Tokyo, Japan, pp. 127–145. https://doi.org/10.1007/978-4-431-55251-2_10.
Joas, J., Caro, Y., Lechaudel, M., 2009. Comparison of postharvest changes in mango (cv Cogshall) using a ripening class index (Rci) for different carbon supplies and harvest dates. Postharvest Biol. Technol. 54, 25–31. https://doi.org/10.1016/j.postharvbio.2009.04.008.
Jobling, J., Brown, G., Mitcham, E., Tanner, D., Tustin, S., Wilkinson, I., Zanella, A., 2005. Flesh browning of 'Pink Lady'™ apples: why do symptoms occur? Results from an international collaborative study. Acta Hortic. (682), 851–858. https://doi.org/10.17660/ActaHortic.2005.682.110.
Jordan, R.B., Walton, E.F., Klages, K.U., Seelye, R.J., 2000. Postharvest fruit density as an indicator of dry matter and ripened soluble solids of kiwifruit. Postharvest Biol. Technol. 20, 163–173. https://doi.org/10.1016/S0925-5214(00)00125-3.
Lammertyn, J., Dresselaers, T., Van Hecke, P., Jancsók, P., Wevers, M., Nicolai, B., 2003. MRI and X-ray CT study of spatial distribution of core breakdown in 'Conference' pears. Magn. Reson. Imaging 21, 805–815. https://doi.org/10.1016/S0730-725X(03)00105-X.
Lammertyn, J., Jancsok, P., Dresselaers, T., Van Hecke, P., Wevers, M., De Baerdemaeker, J., Nicolaï, B., 2001. X-ray CT and magnetic resonance imaging to study the development of core breakdown in 'Conference' pears. Paper number 016037, 2001 ASAE Annual Meeting A. https://doi.org/10.13031/2013.4430.
Larrigaudière, C., Barrera-Gavira, J.M., Echeverria, G., 2024. New insights into early biochemical prediction of internal browning disorder in 'Conference' pears. Postharvest Biol. Technol. 207, 1–8. https://doi.org/10.1016/j.postharvbio.2023.112595.
Li, Y., Mao, X., Ma, Q., Yue, X., Song, N., Si, Z., Wang, S., Zhang, X., Ren, X., Ding, Y., Ren, Y., 2025. Preharvest ABA treatment reduces browning of watercore apple fruit by regulating antioxidant and energy metabolism. Food Chem. 484, 144414. https://doi.org/10.1016/j.foodchem.2025.144414.
Luckwill, L.C., Weaver, P., Macmillan, J., 1969. Gibberellins and other growth hormones in apple seeds. J. Hortic. Sci. 44, 413–424. https://doi.org/10.1080/00221589.1969.11514325.
Łysiak, G.P., 2022. Degree days as a method to estimate the optimal harvest date of 'Conference' pears. Agriculture 12 (11), 1. https://doi.org/10.3390/agriculture12111803.
Ma, S.S., Chen, P.M., 2003. Storage disorder and ripening behavior of 'Doyenne du Comice' pears in relation to storage conditions. Postharvest Biol. Technol. 28, 281–294. https://doi.org/10.1016/S0925-5214(02)00179-5.
Mathew, A., Parpia, H., 1971. Food browning as a polyphenol reaction. Adv. Food Res. 75–145. https://doi.org/10.1016/S0065-2628(08)60031-2.
McCormick, R.J., Biegert, K., Streif, J., 2021. Occurrence of physiological browning disorders in stored 'Braeburn' apples as influenced by orchard and weather conditions. Postharvest Biol. Technol. 177, 111534. https://doi.org/10.1016/j.postharvbio.2021.111534.
Monney, P., Gabioud Rebeaud, S., Cotter, P.Y., Christen, D., 2024. Influence of rootstocks on yield, fruit quality and storage potential of 'CH 201' pear (*Pyrus communis*). Acta Hortic. (1403), 291–298. https://doi.org/10.17660/ActaHortic.2024.1403.39.
Musacchi, S., Iglesias, I., Neri, D., 2021. Training systems and sustainable orchard management for European pear (*Pyrus communis* L.) in the Mediterranean area: A review. Agronomy 11, 1765. https://doi.org/10.3390/agronomy11091765.
Neuwald, D.A., Sestari, I., Kittemann, D., Streif, J., Weber, A., Brackmann, A., 2014. Can mineral analysis be used as a tool to predict 'Braeburn' browning disorders (BBD) in apple in commercial controlled atmosphere (CA) storage in Central Europe? Erwerbs-Obstbau 56, 35–41. https://doi.org/10.1007/S10341-014-0202-X.
Nicolas, J.J., Richard-Forget, F.C., Goupy, P.M., Amiot, M.J., Aubert, S.Y., 1994. Enzymatic browning reactions in apple and apple products. Crit. Rev. Food Sci. Nutr. 34, 109–157. https://doi.org/10.1080/10408399409527653.
Open-Meteo, 2025. Open-Meteo Weather API. https://open-meteo.com/. (Accessed 25 July 2025). Available at: accessed.
Raese, J., Drake, S., 1995. Calcium sprays and timing affect fruit calcium concentrations, yield, fruit mass, and cork spot of 'Anjou' pears. Hort. Sci, 30, 1037–1039. https://doi.org/10.21273/HORTSCI.30.5.1037.
Saquet, A., Streif, J., Bangerth, F., 2000. Changes in ATP, ADP and pyridine nucleotide levels related to the incidence of physiological disorders in 'Conference' pears and 'Jonagold' apples during controlled atmosphere storage. J. Hortic. Sci. Biotechnol. 75, 243–249. https://doi.org/10.1080/14620316.2000.11511231.
Saquet, A.A., Streif, J., Almeida, D.P.F., 2019. Mineral composition and distribution within 'Rocha' pear in relation to internal storage disorders. Postharvest Biol. Technol. 158, 1–7. https://doi.org/10.1016/j.postharvbio.2019.111002.
Seo, H.-J., Chen, P.-A., Lin, S.-Y., Choi, J.-H., Kim, W.-S., Haung, T.-B., Roan, S.-F., Chen, I.-Z., 2015. The potassium to magnesium ratio enables the prediction of internal browning disorder during cold storage of Asian pears. Hortic. Sci. Technol. 33, 535–541. https://doi.org/10.7235/hort.2015.15150.
Sidhu, R.S., Bound, S.A., Swarts, N.D., 2023. Internal flesh browning in apple and its predisposing factors—A review. Physiologia 3, 145–172. https://doi.org/10.3390/physiologia3020012.
Streif, J., Saquet, A.A., Xuan, H., 2003. CA-related disorders of apples and pears. Acta Hortic. (600), 223–230. https://doi.org/10.17660/ActaHortic.2003.600.29.
Tempelaere, A., Minh Phan, H., Van De Looverbosch, T., Verboven, P., Nicolaï, B., 2024. X-ray radiography and deep learning for internal quality inspection of pear fruit. Acta Hortic. (1403), 133–140. https://doi.org/10.17660/ActaHortic.2024.1403.16.
Verlinden, B.E., de Jager, A., Lammertyn, J., Schotsmans, W., Nicolai, B.M., 2002. Effect of harvest and delaying controlled atmosphere storage conditions on core breakdown incidence in 'Conference' pears. Biosyst. Eng. 83, 339–348. https://doi.org/10.1006/bioe.2002.0127.
Wang, Y., Sugar, D., 2013. Internal browning disorder and fruit quality in modified atmosphere packaged 'Bartlett' pears during storage and transit. Postharvest Biol. Technol. 83, 72–82. https://doi.org/10.1016/j.postharvbio.2013.03.015.
Xuan, H., Streif, J., Pfeffer, H., Dannel, F., Römheld, H., Bangerth, F., 2001. Effect of preharvest boron application on the incidence of CA-storage related disorders in 'Conference' pears. J. Hortic. Sci. Biotechnol. 76, 133–137. https://doi.org/10.1080/14620316.2001.11511339.
Xuan, H., Streif, J., Saquet, A.A., Bangerth, F., 2003. Boron application affects respiration and energy status of 'conference' pears during CA-storage. Acta Hortic. (628), 167–174. https://doi.org/10.17660/ActaHortic.2003.628.20.