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ORIGINAL PAPER

NIR TECHNOLOGY FOR NON-DESTRUCTIVE MONITORING OF APPLE QUALITY DURING STORAGE

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ABSTRACT. Background: Post-harvest losses are a major obstacle in achieving sustainable fresh produce chains. The causes of high waste are various and include inadequate logistics and quality control. Therefore, the research and development of rapid and accurate tools for fruit quality control is crucial for food quality assurance. Near-infrared (NIR) spectroscopy has become remarkably valuable in the agri-food sector. The aim of this study was to test NIR coupled with multivariate data analysis as a non-destructive tool to monitor apple quality during short-term storage.

Methods: NIR was used to test apples (n=171) from four varieties and with varying levels of freshness. Each sample was measured immediately after harvest (at time T_0) and after 14 days of storage at 10 ˚C (T_{14}) in a non-destructive manner. Pattern recognition techniques including principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA) were used to classify the apples. Variable importance in projection (VIP) was used to identify NIR spectra ranges that contributed significantly to the discrimination between fresh and stored apples.

Results: The classification model distinguishing apples according to variety was characterized by high classification performance reflected in a misclassification error below 1%. The model for apple freshness discrimination also showed good classification performance with errors at the level of 7.9% and 5.8% for validation and prediction, respectively. The global model of eight classes including both apple variety and freshness was characterized by misclassification errors in the range of 1.2–6.3% for validation and 2.0–3.9% for prediction. The VIP method revealed that the spectral ranges contributing significantly to the freshness classification mainly corresponded to the absorption of water.

Conclusions: NIR technology coupled with pattern recognition methods was found to be a promising tool for monitoring the overall loss of quality in fresh apples during short-term storage. The results may contribute to the development of a system supporting apple quality control and logistics during storage, e.g., while awaiting sale, transport or further processing. The findings are intended to guide various supply chain members and decision-makers so they can reduce post-harvest losses and improve the performance of the short fruit supply chain.

Keywords: short food supply chains, post-harvest losses, NIR technology, non-destructive testing, quality, sustainability

INTRODUCTION

An efficient post-harvest system is a chain of interlinked activities that ensures the harvested product reaches the customer in the shortest possible time without compromising its quality and safety [Gardas et al. 2018]. Post-harvest losses (PHL) in the fresh produce chain are a serious threat to food security and one of the major challenges for producers and retailers because of their negative impact on society, the economy and environment [Anand and Barua 2022]. After harvesting, fruits pass through a series of post-harvest operations, handling stages, and storage before reaching consumers. Between 40 and 50% of losses worldwide are of fruits and vegetables, with a total annual loss of US$750 billion [Santos 2020]. The reasons for these high losses are various and include inadequate logistics and quality control activities [Macheka et al. 2017]. Examples of improper logistic actions include poor seasonal demand forecasting, inefficient inventory control systems, and lack of supply chain coordination [Anand and Barua 2022, Gardas et al. 2018, Kaipia et al. 2013]. Examples of inadequate quality control activities contributing to PHL include unsatisfactory conditions in transportation and storage processes, improper

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packaging, and poor product quality control [Gardas et al. 2018, Negi and Trivedi 2021].

The management and performance of supply chains for fresh food products are significantly affected by the specific properties of the product. The quality of a food product is a complex variable based on numerous characteristics, including nutritional value, physical and chemical properties, microbiological safety, sensory attributes, and shelf-life stability. Standard physicochemical methods and sensory evaluations have been used over the years to determine the quality and authenticity of food products, but these methods are time consuming and expensive and often require the usage of a separate method to determine each quality parameter. Thus, fingerprinting methods such as spectroscopic and imaging techniques can be more suitable for analyzing complex materials, including food products. Such non-targeted methods enable the acquisition of information about several parameters simultaneously. Most non-targeted methods are consistent with the principle of non-destructive non-contact screening and are compatible with industry 4.0 technologies [Hassoun et al. 2023].

Industry 4.0 technologies show great potential for the agro-food industry. Such technologies are applied, e.g., in logistics, waste reduction, energy and water consumption, data collection and monitoring, and quality control [Jagtap et al. 2021]. Industry 4.0 may optimize the quality control processes by increasing automation and digitalization [Hassoun et al. 2023]. Near-infrared (NIR) spectroscopy has become remarkably valuable as a non-destructive analytical technique in several fields of application, including the agri-food sector [Cozzolino, 2022]. In recent years, numerous studies have demonstrated the successful application of NIR technology coupled with data analysis for the qualitative and quantitative evaluation of food properties and composition as well as to monitor food quality at various stages of the supply chain. NIR technology has therefore been widely adopted in high-throughput analysis in agriculture.

Currently, regional and local food systems and short food supply chains (SFSCs) are being promoted in line with the "farm to fork" strategy defined by the European Commission [Evola et al. 2022]. There are several types of SFSCs, including farmers' markets, roadside sales, home deliveries, cooperative shops and solidarity groups [Tiganis et al. 2023]. In accordance with the idea of a short supply chain, the number of market intermediaries is reduced and the distance between consumers and agricultural producers is shortened. Such food systems could support reduced dependence on long-haul transportation, which has environmental, economic and social benefits [Enthoven et al. 2023]. Therefore, fresh food production should be increased by utilizing advanced technologies and improving existing supply chains to reduce losses. SFSCs are considered more sustainable and reliable alternatives to global chains, supporting local economies and ensuring access to fresh and high-quality food [Tiganis et al. 2023].

Apple production is the second biggest form of fruit production in the world after banana production [Loiseau et al. 2020]. Poland is the largest apple producer in the European Union. In 2022, the apple harvest in Poland reached over 4.1 million tons [Euromonitor International 2023]. An extremely large proportion of the apples produced for consumption are stored. The need for storage in the fruit sector stems from the seasonality of the supply of raw materials. The long-term storage of apples requires the usage of technological knowledge and appropriate storage facilities (with low temperature, controlled humidity, and a controlled atmosphere) in order to fully maintain their physical, chemical, and sensory characteristics [Beghi et al. 2014].

Nowadays, an important challenge in postharvest technology is non-destructive characterization of fruit in order to maximize quality and reduce losses. Emerging non-destructive and easy-to-use tools are used more and more often both to predict the optimum harvest time and to rapidly monitor fruit quality during the postharvest period. The food sector has shown an interest in NIR instruments (both mobile and online devices) since the beginning of the 1990s [Beghi et al. 2014]. Successful applications of NIR technology in apple quality assessment are well documented and include the control of various physicochemical properties [Pissard et al. 2021, Włodarska et al. 2021], the monitoring of fruit maturity [Zhang et al. 2022], and the differentiation of apple varieties [Vincent et al. 2018]. NIR has also been used to monitor changes during long-term storage [Beghi et al. 2014, Cédric et al. 2007, Ignat et al. 2014, Zhang et al. 2021]. The authors of previous studies have indicated that NIR could be an efficient tool for monitoring stock in the apple production sector. It can therefore be used as a non-destructive method for classifying apples into homogeneous lots in order to better manage the distribution of lots during the months of storage to avoid fruit losses. These previous studies have examined storage conditions in conventional (longer) supply chains. In short supply chains, long-term cold storage is replaced by storage at farms [Loiseau et al. 2020]. Therefore, the aim of the present study was to test an NIR system coupled with multivariate data analysis as a rapid and accurate tool to monitor apple quality during short-term storage and to differentiate samples based on freshness and variety.

MATERIALS AND METHODS

Apple samples

The apples (*Malus* × *domestica Borkh.*) were obtained from the late autumn harvest in 2021, from orchards located in the Greater Poland region of Poland. A total of 171 fruit samples from four varieties were studied, including Gala Royal (65 samples), Ligol (34 samples), Empire (35 samples), and Lobo (37 samples). The apples were harvested at the commercial maturity stage and immediately subjected to measurements. All apple samples were washed under running water, dried and subjected to spectral measurement (at time T_0). After measurement, samples were placed in cold storage at 10 °C for 2 weeks. Shading conditions were maintained. The storage conditions corresponded to the storage conditions used by retailers in short food supply chains. After 14 days of storage (T_{14}), the apples were subjected to spectral measurement once again.

NIR spectra of apples

The spectra of intact fruit were measured using a FT-NIR spectrometer (MPA, Bruker Optics, Ettlingen, Germany) equipped with OPUS software (v. 5 Bruker Optics, Ettlingen, Germany) to control instrument parameters and spectral acquisition. The spectra were collected in the range of 12,500–4,000 cm^{-1} with a resolution of 8 cm^{-1}, and 64 scans were co-added to obtain the averaged spectrum. A total of 1,102 data points were obtained for each sample. The measurements were made directly on whole fruit using diffuse reflectance techniques for fresh apples after harvest (at time T_0) and for apples after 14 days of storage (T_{14}). For each of the fruit, spectra were measured in five positions by manually rotating the sample. The five replicates for each apple were averaged, and a total of 342 NIR spectra were subjected to further data processing and analysis. The instrument used to measure the spectra is presented in Fig. 1.

Fig. 1. FT-NIR spectrometer for recording the spectra of fruits.

Multivariate data analysis

Principal component analysis (PCA) was performed on the NIR spectra. A matrix with dimensions of 342 × 1102 (number of samples × number of absorption wavelength) was used for analysis.

Partial least squares discriminant analysis (PLS-DA) was applied to explore and classify apples according to their freshness and variety. In the PLS-DA analysis, the X matrix represented spectral data (NIR spectra) and the Y matrix consisted of columns containing information on the assignment of a sample to a specific class (fresh T_0 *vs* stored T_{14} class, apple cultivar classes, and combined). Mean-centered data were used to develop the models. The optimal number of latent variables (LV) was selected based on the venetian-blinds variant of cross-validation with 10 data splits, and corresponded to the minimum in the plot of the average misclassification error rate as a function of the LV. The predictive ability of the models was tested based on an external validation procedure with an independent test sample set. The Kennard-Stone algorithm was applied to divide the entire sample set into the training set of 240 apple samples (22 Empire T_0, 48 Gala T_0, 21 Ligol T_0, 26 Lobo T_0, 24 Empire T_{14}, 52 Gala T_{14}, 22 Ligol T_{14}, 25 Lobo T_{14}) and the test set of 102 apple samples (13 Empire T_0, 17 Gala T_0, 14 Ligol T_0, 11 Lobo T_0, 11 Empire T_{14}, 13 Gala T_{14}, 12 Ligol T_{14}, 11 Lobo T_{14}). The classification performance of models was assessed by misclassification error. The misclassification error defines the proportion of samples which were incorrectly classified. Note that the misclassification error for a class A represents both samples of class A which were incorrectly classified as not class A, and samples not of class A which were incorrectly classified as being class A.

Variable importance in projection (VIP) was used to identify variables (NIR spectra ranges) that contributed significantly to the PLS-DA model. All variables with a VIP score close to or greater than unity were considered significant in the classification model [Chong and Jun 2005]. The multivariate data analysis was performed using Solo v. 5.0.1 software (Eigenvector Research Inc., Wenatchee, WA, USA).

RESULTS AND DISCUSSION

NIR spectra of apples

The spectra of fruit were recorded for 171 apple samples originating from four apple cultivars. Firstly, the NIR spectra were recorded for each piece of fresh fruit (at time T_0) and for apples after 14 days of storage at 10 °C (T_{14}). The spectra of apples from various cultivars under study are shown in Fig. 2.

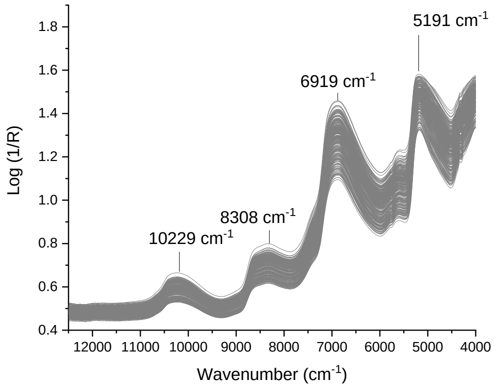

Fig. 2. The NIR spectra of apples from four cultivars. Source: own work.

The NIR spectra of the entire set of apple samples exhibit similar spectral characteristics, with absorption bands in a similar position and with a similar shape but with a wide range of intensities. Differences were observed in the spectra of apples from various varieties as well as in the spectra of fresh and stored fruits. The spectral bands are attributed to the overtones and combination tones of the structural groups containing hydrogen, mainly O–H and C–H. Different compounds contribute to this absorption, such as: water, sugars, other carbohydrates, organic acids, polyphenolic compounds, some vitamins, and some amino acids. The two most intense absorption peaks were observed at about 6,919 cm^{-1} and 5,191 cm^{-1}, corresponding to water absorption [Kapoor et al. 2022]. A band in the range of 10,310–10,000 cm^{-1} is associated with sugars. To extract relevant information from NIR spectra multivariate data analysis was applied.

Multivariate exploratory analysis of NIR spectra

To evaluate the main differences between the apple samples studied, an exploratory analysis was performed using principal component analysis. The results are shown in Fig. 3.

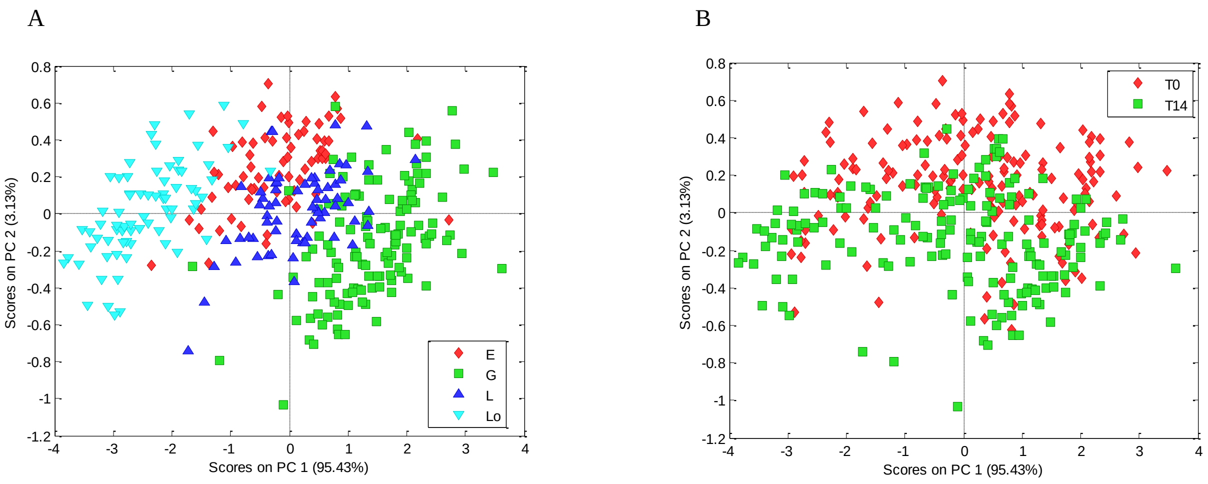

Fig. 3. Principal component analysis of NIR spectra: A) scores plot of PC1 *vs* PC2 with four apple cultivars marked, B) scores plot of PC1 *vs* PC2 with storage time marked. Source: own work.

Analysis of the PCA score plots revealed quite a clear separation between the NIR spectra of the apples of the four varieties (Fig. 3A) and a less pronounced separation between fresh (T_0) and stored (T_{14}) apples (Fig. 3B). The first (PC1) and second (PC2) principal components accounted, respectively, for 95.43 % and 3.13 % of the variance in the experimental data. PC1 distinctly differentiated apples based on variety whereas PC2 differentiated apples to some extent based on apple freshness. A large dispersion of apple samples was observed, reflecting the diverse quality of the studied samples. No outliers were revealed by PCA analysis, therefore all of the 342 spectra were used for further analysis.

Multivariate classification models

As the results of the PCA showed separation between apples from the four cultivars and between fresh and stored apples, in the next step of the study the possibility of using the NIR spectra to differentiate apples based on various criteria was checked. The training set (n = 240) was used for the development and optimization of the classification models, and the final models were validated using the test set (n = 102). Three models were developed: (1) a model distinguishing apples according to variety, (2) a model differentiating apples according to freshness, and (3) a model differentiating apples according to both variety and freshness. The performance of all the classification models is presented in Table 1.

Table 1. Characteristics of classification models developed based on NIR spectra of apples

Model	**LV**	**Class**	**Misclassification error (Cross Validation)**	**Misclassification error (Prediction)**
Apple variety	8	Empire	0.008	0
		Gala	0.004	0
		Ligol	0.004	0
		Lobo	0	0
Apple freshness	10	T_0	0.079	0.058
		T_{14}	0.079	0.058
Apple variety and freshness	7	Empire T_0	0.042	0.020
		Gala T_0	0.063	0.029
		Ligol T_0	0.017	0.020
		Lobo T_0	0.013	0.020
		Empire T_{14}	0.054	0.020
		Gala T_{14}	0.063	0.039
		Ligol T_{14}	0.021	0.029
		Lobo T_{14}	0.013	0.020

Source: own work.

All the classification models were characterized by high classification performance. The best model was obtained for apple variety discrimination. Both fresh and stored apple samples were included in the model. In the calibration set, only two samples were assigned incorrectly (Empire apple predicted as Gala and Ligol apple predicted as Empire), whereas in the prediction set all the samples were correctly attributed. The obtained results indicate that the NIR system can be successfully used to distinguish apple varieties regardless of storage time (with an error of less than 1%).

The model for apple freshness discrimination also showed good classification performance. Misclassification error was at the level of 0.079 and 0.058 for validation and prediction, respectively. In the calibration set, eight samples were incorrectly assigned as stored, and 11 samples were incorrectly assigned as fresh. In the prediction set, six apple samples were incorrectly assigned. These results indicate that the freshness of apples could be assessed using an NIR system with an error rate of approximately 6–8%.

The global model consisting of eight classes included both apple variety and freshness and was characterized by good classification performance with misclassification error in the range of 1.2–6.3% for validation and 2.0–3.9% for prediction. Nine samples of the prediction set were incorrectly attributed. For comparison, Vincent et al. [2018] used a portable NIR spectrometer to predict apple variety, and they achieved an accuracy of 94%. Cédric et al. [2007] demonstrated the ability of a Vis-NIR system to correctly classify fruits of three varieties in more than 95% of cases. Beghi et al. [2014] successfully used NIR for apple classification according to the storage time during long-term storage in a cold room. Ignat et al. [2014] demonstrated the potential of NIR to predict apple internal composition changes during storage based on the spectra of fruit at the time of harvest. Zhang et al. [2021] developed a model to predict the internal qualities of apples during cold storage, taking into account the time in cold storage and three levels of maturity at harvest.

To identify the spectral ranges that significantly contribute to the discrimination between fresh and stored apples, the variable importance in projection (VIP) method was used.

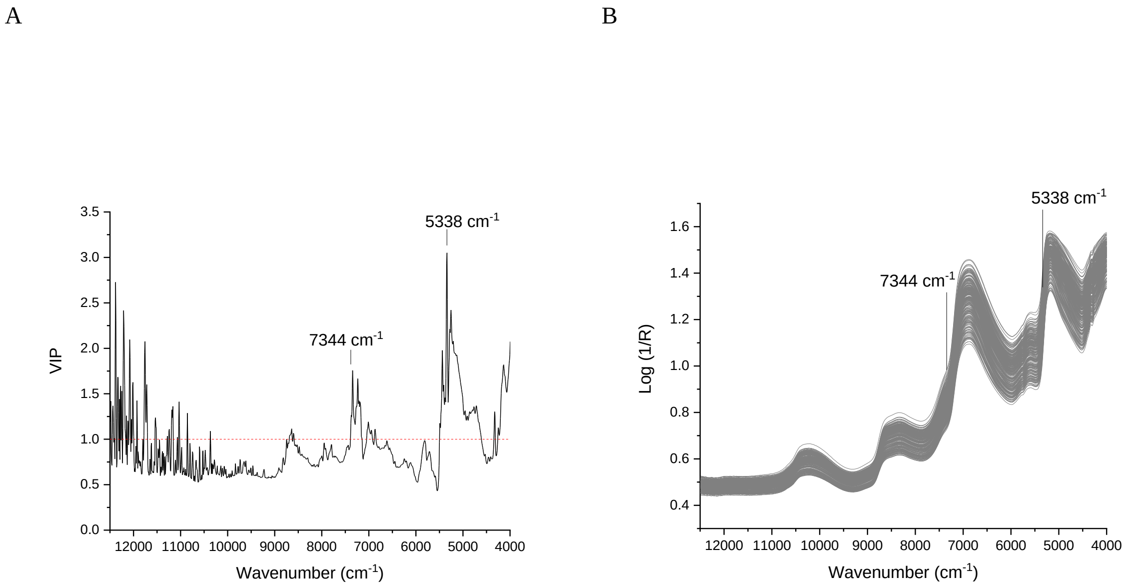

Fig. 4 Classification model for apple freshness obtained using the PLS-DA method: A) variable importance in projection (VIP) plot, B) NIR spectra of all tested apples with indicated variable with high VIP values. Source: own work.

The analysis of the VIP plot revealed the spectral ranges contributing significantly to the model (Fig 4A). As the spectra were measured in the whole NIR range with a resolution of 8 cm^{-1}, a total of 1,102 variables were analyzed for each sample (Fig. 4B). Significant ranges with VIP scores above unity mainly corresponded to those associated with the absorption of water. Water analysis is an important quality parameter, because the presence of water can have a significant impact on food properties. The allowable water loss varies depending on the fruit. Apples start to show signs of drying out after losing approximately 4–5% of their water post-harvest [Sottocornola et al. 2023]. That is why it is so important to monitor the freshness of apples throughout the entire supply chain. The results of the present study indicate the potential of NIR technology in monitoring the freshness of apples in terms of water loss. Systematic scanning of all apples could provide objective data to predict the characteristics of the final product and thus reduce losses. Further work is needed to study apples under different growing and various storage conditions to provide guidance that can ensure a stable final quality.

Perspectives on the use of NIR systems in the sustainable fresh food supply chain

Providing food in a sustainable way is a challenge. Due to the complexity of food production processes, which have to take into account food safety and food waste issues, managing sustainable production through supply transformation is crucial in the contemporary agri-food industry. Industry 4.0 makes use of business-applied solutions with the support of a scientific background [Cyplik and Zwolak 2022]. Incorporating some elements of Industry 4.0 into the agri-food industry can ensure effective long-term supply chain management [Lahane et al. 2023]. One of the suggested strategies for achieving sustainable development goals is shortening the supply chain [Michel-Villarreal et al. 2021]. Emerging technologies such as sensor technologies and NIRs are becoming more widely used, with important implications for supply chain sustainability. They help close the demand-supply gap, enhance the quality and security of food, and enable faster responses to changes [Cyplik and Zwolak 2022].

In recent years, NIR instruments have undergone radical changes to become more portable and accessible. They are therefore better adapted to provide direct on-site analysis in various workplaces (e.g., gardens, warehouses) without the need to transport the product to the laboratory for measurement [Ignat et al. 2014]. These portable and handheld instruments are a convenient and cost-effective alternative to traditional benchtop spectrometers. The rapidly expanding published literature on miniaturized and portable NIR spectrometers reflects the sharp edge in using this technology. Recently, miniaturized NIR instruments have been extensively applied in the analysis of apples to develop fast and non-destructive methods for monitoring various quality parameters [Yao et al. 2023, Zhu and Tian 2018]. The devices used are characterized by portability, easy handling, flexibility, and the ability to analyze apples directly on the tree without the need for sample preparation. Currently, data sharing via mobile phone is one of the latest developments in NIR technology. Data can be shared between NIR instruments and mobile phone via Bluetooth for further analysis [Vincent et al. 2018, Yao et al. 2023].

Further research and development of NIR technology for apple quality assessment is needed to improve the efficiency, quality and safety of the apple supply chain and to reduce waste. The reduction of food waste is essential for the achievement of sustainable development goals.

CONCLUSIONS

Traditional evaluation methods, such as sensory evaluation and chemical and physical measurements, have particular limitations such as destructiveness, reagent and time consumption, and cost. Recently, an increasing number of nondestructive evaluation technologies have been explored and employed in food quality control and logistics. NIR technology has gained remarkable popularity as a non-destructive analytical tool for rapid quality assessment. In this study, the use of NIR technology coupled with multivariate analysis to monitor apple quality during short-term storage was tested. Storage of several days may be required while apples are awaiting sale, transport or further processing, and the storage of fresh agricultural produce causes reductions in quality parameters such as color, texture, and mass that affect the nutritional and sensory properties of the product. Market pressures faced by farmers include, among other factors, the increasing consumer demand for high food quality. Adequate monitoring of food quality attributes during storage would help reduce food losses and ensure that high-quality fresh fruit is available to consumers. The obtained research results confirm that NIR technology coupled with multivariate analysis is an appropriate tool to assess the overall loss of quality in fresh apples during short-term storage.

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