Non-destructive Internal Quality Evaluation of Apple Fruit Using X-ray CT

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Abstract

In this study, X-ray computed tomography (CT) as a non-destructive method for internal quality evaluation of apple fruit was investigated. For this purpose, three local apple fruit cultivars including: Red Delicious, Golden Delicious, and Golab were used. The CT number of the images, which indicates the amount of X-ray absorption, was extracted using K-PACS software. Quality parameters such as the amount of soluble solids content, titratable acidity, flavor index, and pH of studied cultivars were measured. The relationship between quality parameters and CT number obtained from tomography images of fruits in the form of linear regression models was investigated. According to the results, the correlation between CT number and quality parameters in all models was more than 0.900. For different cultivars, CT number had a positive correlation with the amount of titratable acidity, flavor index, pH, and soluble solids. The evaluation of quality parameters for the Red Delicious cultivar had the highest accuracy, achieving coefficients of determination (R^2) of 0.952 for flavor index, 0.964 for soluble solids, 0.941 for acidity, and 0.969 for pH. For all cultivars, the highest correlation was observed between the pH and the number of CT (with coefficients of explanation 0.969, 0.972, and 0.966 for Red Delicious, Golden Delicious, and Golab cultivars, respectively). This indicates that X-ray CT can reliably assess internal quality attributes without damaging the fruits. The established linear regression models provide a validated and reproducible method for non-destructive quality evaluation of apple fruits.

Keywords: Apple fruit, CT number, Non-destructive, Quality assessment. X-ray computed tomography

Introduction

Over the past decade, there has been a worldwide surge in interest regarding the production and study of apple (*Malus domestica Borkh*) fruit. Consequently, the global commercial cultivation of apple fruit has significantly increased (Argenta *et al.*, 2022; Doğan, Rashid, Lizalo, Soysal, & Demirsoy, 2024; FAO, 2021; Kumar *et al.*, 2022). The rising popularity of the fruit can be attributed to the increasing awareness among consumers regarding its nutritional value and the associated health benefits of its consumption (Guo *et al.*, 2023; Zhang *et al.*, 2022). These benefits are attributed to its high antimicrobial effects and antioxidant contents, which are contributed by various groups of phytochemicals and polyphenols present in the fruit (Angeli *et al.*, 2024; Rodríguez Madrera, Pando Bedriñana, & Suárez Valles, 2017; Pires *et al.*, 2018; Rana, Gupta, Rana, & Bhushan, 2015; Wang *et al.*, 2023). Additionally, the fruit is rich in organic acids, soluble solids, anthocyanins, vitamins, fatty acids, and mineral elements (Bajramova & Spégel, 2022; Han, Su, & Du, 2023; Kokalj, Zlatić, Cigić, Kobav, & Vidrih, 2019; Uzhel, Zatirakha, Smolenkov, & Shpigun, 2018).

The surge in interest in apple fruit aligns with consumers' increasing demand for consistent access to safe, nutritious, and traceable food items. This necessity for fruit of assured quality has prompted the development of innovative non-destructive techniques for both field and laboratory measurement, as well as in-line sorting and grading, relying on external and internal quality attributes (Akter *et al.*, 2024; Cakmak, 2019; Khodabakhshian, Bayati, & Emadi, 2022, Khodabakhshian & Emadi, 2016; Khodabakhshian, Seyedalibeyk Lavasani, & Weller, 2023; Luna *et al.*, 2024; Van Dael *et al.*, 2016). These non-destructive methods facilitate the assessment of fruit morphological structures and internal quality to ensure that all fruits meet the minimum acceptance standards in the market.

A broad array of objective nondestructive techniques for evaluating the external and internal quality of agricultural products has been extensively reviewed and discussed in the literature (Abasi, Minaei, Jamshidi, & Fathi 2018; Akter *et al.*, 2024; Arendse, Fawole, Magwaza, & Opara, 2018; Chen, Zhang, Zhao, & Ouyang, 2013; Khodabakhshian & Baghbani, 2025; Lei & Sun, 2019; Lu & Cen, 2013; Modupalli, Naik, Sunil, & Natarajan, 2021; Mohd Ali & Hashim, 2022). These techniques encompass various methods such as visible to near-infrared (NIR) spectroscopy (Jiang, Zhang, Mujumdar, & Wang, 2023; Li *et al.*, 2020; Nicolaï *et al.*, 2007; Zhang *et al.*, 2022), magnetic resonance imaging (MRI) (Barreiro *et al.*, 2008; Groß, Zick, & Guthausen, 2017; Horvat, Guthausen, Tepper, Falco, & Schuchmann, 2014; Mazhar *et al.*, 2015), electronic nose and electronic tongue (Ghasemi-Varnamkhasti, Apetrei, Lozano, & Anyogu, 2018; Kiani, Minaei, & Ghasemi-Varnamkhasti, 2016; Lu, Hu, Hu, Li, & Tian 2022), hyperspectral imaging (Caporaso, Whitworth, Fowler, & Fisk, 2018; Tang *et al.*, 2023), as well as X-ray radiographs and X-ray computed tomography (Haff, Slaughter, Sarig, & Kader, 2006; Schoeman, Williams, du Plessis, & Manley, 2016; Tempelaere, Minh Phan, Van De Looverbosch, Verboven, & Nicolai, 2023; Zhang, Lin, Tian, Tian, & Xu, 2023).

X-ray computed tomography (CT) has proven to be a reliable tool for non-destructive analysis of internal structures and defects in fruits (Van De Looverbosch *et al.*, 2020; Magwaza & Opara, 2014; Schoeman *et al.*, 2016; Tempelaere *et al.*, 2023; Zhang *et al.*, 2023). Recent advancements highlight its role in quality assessment, including the development of deep learning models like BraeNet by Tempelaere, Van Doorselaer, He, Verboven, and Nicolai (2024), which identifies internal disorders in apples with up to 96% accuracy. Similarly, Atamian, Davila, and Prakash (2023) explored the transcriptomic responses of 'Granny Smith' apples to X-ray irradiation, revealing significant gene expression changes associated with oxidative stress and quality preservation. Additionally, Van Dael, Verboven, Zanella, Sijbers, and Nicolai (2019) integrated X-ray CT with multisensory inspection, addressing density gradients to improve defect detection, particularly in apples with internal browning. Chigwaya *et al.* (2021) also used X-ray CT to map porosity in 'Fuji' apples, revealing how morphological and microstructural properties influence susceptibility to CO_2-induced internal browning. These studies underscore the potential of X-ray imaging, combined with advanced models and techniques, in enhancing postharvest quality management and reducing food waste.

The novelty of this research lies in its development and validation of a new method to correlate X-ray absorption with specific quality attributes of apple fruit, enabling the accurate and reproducible evaluation of fruit quality. Unlike previous studies that focused primarily on detecting external and internal defects, this research introduces a more comprehensive approach by correlating X-ray absorption data with nutritional and health-related quality attributes, such as antioxidant content and antimicrobial properties. This enables the non-destructive evaluation of multiple quality parameters simultaneously, offering a more holistic method for assessing apple fruit quality in a commercial context. This study also pioneers the application of X-ray CT for such an integrated assessment, marking a significant advancement in the practical use of non-destructive technologies for quality control in the apple industry.

Materials and Methods

Samples

For this study, three local apple fruit varieties, including: Red Delicious, Golden Delicious, and Golab, belonging to a commercial orchard in Mashhad, Khorasan Razavi province, Iran, were randomly selected during the ripening stage in 2021. These cultivars are the most famous and widespread commercial varieties cultivated in Iran. Subsequently, all samples were individually washed, numbered, and placed in plastic containers. Following selection, the apples were transported to the physical properties laboratory at the Department of Biosystems Engineering, Ferdowsi University of Mashhad, and stored. Before conducting the tests, the samples were removed from refrigeration and allowed to equilibrate to room temperature for approximately 2 hours (Khodabakhshian *et al.*, 2022). X-ray CT experiments were conducted on all samples.

X-ray CT scanning

To obtain CT scan images of apple samples, a sample from each of the three varieties was initially placed on a rotating platform inside the CT scan device (GE VCT 64, Milwaukee, USA). The specifications of the CT scan device used are presented in Table 1. Each scan was performed with a tube voltage of 120 kV and a tube current of 350 mA. The rotation speed was set to 1 second per revolution, ensuring high-resolution image acquisition. The nominal slice thickness was fixed at 2 mm for optimal balance between scanning time and image detail. The duration for capturing CT images of each apple sample was approximately 30 seconds. During this process, X-ray beams were passed through the fruit, and detectors recorded the transmitted intensity.

As the sample gradually rotated on the platform, a series of two-dimensional projection images were captured from multiple angles (360° rotation). These projections were reconstructed into a high-resolution three-dimensional volume using advanced reconstruction software integrated into the device. This process allowed detailed visualization of the internal structure and quality attributes of the apple samples. This method was repeated for 20 samples of each apple variety, ensuring consistent and reproducible imaging results.

Table 1- Specifications of the CT scan device

Parameters	Description
Model Name	GE VCT 64, Milwaukee, USA
Interface	1-Screen, Mouse Driven, Icon Based
Fastest rotation	1 second
Maximum tube current	350 mA at 120 kV
kV settings	80, 100, 120 kV
Nominal slice thicknesses (mm)	1, 2, 3, 4, 5, 6, 8, 10
Gantry Opening	60 cm

CT number

After performing the scan and collecting the data, linear attenuation coefficients are obtained for each voxel. These coefficients are a series of closely spaced numbers that differ from each other by fractions of decimals. Since these numbers are not directly usable, they need to be converted into simpler numbers to create a grayscale image. A standardized scale is used to convert these decimal numbers into simple numbers. The standard unit for measuring X-ray absorption intensity in CT scan systems is the Hounsfield unit (HU) or CT number. On the other hand, the CT number is a dimensionless unit that provides a relative measure of how much a structure attenuates the X-ray beam. The CT number is defined by Equation 1:

$$\text{CT Number} = 1000 \times \frac{(\mu - \mu_{water})}{\mu_{water}} \quad (1)$$

where, μ is the linear attenuation coefficient of the tissue, and μ_{water} is the linear attenuation coefficient of water.

The computer takes the numbers obtained from the detectors and converts them into CT numbers based on Equation 1. Then, using these numbers, an image is formed in grayscale, where higher CT numbers correspond to lighter shades (closer to white) and lower CT numbers correspond to darker shades (closer to black). In this study, various scans of different parts of apple fruits, including the core, flesh, and skin, were obtained, and then the respective CT numbers of the fruits were extracted using K-PACS software (the accompanying software with the device).

Measurement of apple fruit quality indices

Soluble solids content (SSC)

To measure the dissolved solids, the dissolved solids in a small sample of fruit extract were measured by an optical refractometer (ATAGO model, made in Japan) according to the ISO 2173:1978 standard. First, the refractometer was calibrated with distilled water, and a few drops of filtered fruit juice solution were poured onto the glass plate of the refractometer. Then, by placing the device in front of the light, the number placed in the shadow and the light area was read. This number shows the amount of dissolved solids (Brix degree).

Titratable acidity measurement

To measure titratable acid (TA), five milliliters of the obtained extract are taken from the sample and 45 milliliters of distilled water is added to it for dilution. The diluted extract was titrated with 0.1 normal sodium hydroxide (NaOH), and the titratable acid was calculated as a percentage using Equation 2.

$$TA = \frac{NaOH \times normality\ of\ soda \times acid}{juice} \times 100 \quad (2)$$

where *NaOH* represents sodium hydroxide (ml), *normality of soda* (NaOH) indicates the normality of the sodium hydroxide solution (N), *juice* refers to the volume of juice extract (ml), and *acid* denotes the dominant organic acid present in the fruit (Chen, Fu, Wan, Liu, & Chen, 2019).

Fruit flavor index

An important index that is usually used to determine the taste and describe the taste characteristics of fruit is the ratio of soluble solids to titratable acid (Zoran, Nikolaos, & Ljubomir, 2014).

pH measurement

A digital pH meter (model 827, made in Switzerland) was used to measure pH. First, this device was calibrated with pH = 7 and pH = 4 buffers. Then, its electrode was cleaned with distilled water and placed directly into some filtered fruit juice solution, after which the device's reading was recorded.

Statistical analysis

All data were analyzed in a completely randomized design using SPSS version 19 software. Mean comparisons were conducted using Tukey's test at a significance level of 5%. To determine the relationship between the CT number and the specified quality indices, a linear regression model was employed. Models were determined using Unscrambler X version 20 software. The relationships obtained from regression were evaluated using the null hypothesis and the t-test.

Results and Discussion

Apple fruit quality indicators

According to Table 2, Red Delicious and Golab do not differ significantly (both 'a'), but they differ significantly from Golden Delicious ('b') for soluble solids, titratable acidity, flavor index, and CT number. For pH, all varieties have 'a', indicating no significant differences at the 5% level between means. The highest and lowest levels of flavor index were related to Golden Delicious, and Golab cultivars (8.1 and 7.2). The CT number, expressed in Hounsfield Units (HU), ranged from 28 HU (Golab) to 35 HU (Golden Delicious), reflecting variations in the internal density and structure of the fruit. Golden Delicious, with the highest CT number, likely has a denser cellular structure and lower air space, correlating with its higher soluble solids content and flavor index. This demonstrates the utility of CT numbers as non-destructive indicators of internal quality. The highest and lowest amounts of titratable acidity were related to Golab and Golden Delicious (0.8 and 0.6 g per 100 ml fruit juice). In research by Hasanzadeh *et al.* (2022), Vis/NIR spectroscopy technology was used in the spectral range of 350-1150 nm for non-destructive detection of some quality parameters including pH, TA, and SSC of two varieties of Red Delicious and Golden Delicious apples. The pH grade indicates the concentration of H+ ions in apple juice and determines the acidic taste of the fruit juice. Also, on the basis of the results of other studies, the acceptable range of fruit acidity for apples is pH 3.1-3.8 and TA 0.3-1 percent (Asma, Morozova, Ferrentino, & Scampicchio, 2023; Hasanzadeh *et al.*, 2022; Sethi *et al.*, 2020). Generally, fruits with pH lower than 3.1 and TA higher than 1 percent are considered too sour, while those with pH higher than 3.9 and TA lower than 0.3 percent will taste flat or flavorless, i.e., too low in acidity. The highest and the lowest amounts of soluble solids were related to Golden Delicious and Golab cultivars (13.2 and 11.9). The amount of soluble solids in fruit juice is one of the most important quality characteristics that affect the taste and marketability of fruit. In fact, this property indicates the amount of soluble sugars in the fruit. The results of Martinez, Melgarejo, Hernández, Salazar, and Martinez (2006) and Cam, Hisil, and Durmaz (2009) show a similar trend to this research. The taste index, or ratio of total sugar to acid that is used as a key factor in determining the quality of export cultivars, was calculated for three cultivars of apple fruit. The maximum and minimum values of taste index for Red Delicious and Golab cultivars were 64.8 and 17.6, respectively. Al-Maiman and Ahmad (2002) stated that with increasing ripeness of apple fruit, its taste index increases.

Table 2- Quality attributes of three apple varieties

Variety	Soluble solids (Brix)	(g L^{-1})	pH	Flavor index	CT (Hounsfield Units)
Red Delicious	12.5 ± 0.5[a]	0.7 ± 0.1[a]	3.8 ± 0.1[a]	7.4 ± 0.4[a]	30 ± 2[a]
Golden Delicious	13.2 ± 0.4[b]	0.6 ± 0.1[b]	3.5 ± 0.2[a]	8.1 ± 0.3[b]	35 ± 3[b]
Golab	11.9 ± 0.3[a]	0.8 ± 0.1[a]	3.6 ± 0.2[a]	7.2 ± 0.3[a]	28 ± 2[a]

Different letters indicate significant difference ($p < 0.05$)

Investigation of the relationship between quality characteristics and CT number of apple Fruit

Linear regression equations for determining the relationship between quality characteristics and CT number for different apple fruit cultivars are presented in Table 3. According to this Table, the coefficients for explaining the relationships between CT number and the amount of quality characteristics were high for each three studied varieties. So the CT number, as a quantitative measure of X-ray attenuation, shows a strong correlation with various quality indices of fruits, including SSC, TA, pH, and Flavor Index. These relationships are valuable for the non-destructive evaluation of fruit quality, allowing for the prediction of sweetness, sourness, acidity, and overall taste before the fruits reach consumers. In the next sections, the relationship between each characteristic and the CT number is explained in detail.

Table 3- Regression analysis of quality attributes in different apple varieties

Variety	Index	Soluble solids	Titratable acidity	pH	Flavor index
Red Delicious					
	Equation	y = 0.42x + 0.1	y = 0.02x + 0.1	y = 0.01x + 3.5	y = 0.1x + 4.4
	Y-Intercept	45.7**	12.8**	49.2**	28.3**
	Slope coefficient	17.5**	18.9**	15.6**	19.7**
	R^2	0.964	0.941	0.969	0.952
	Intercept estimate	0.0-0.2	0.0-0.2	3.4-3.6	4.0-4.8
	Slope estimate	0.40-0.44	0.01-0.03	0.00-0.02	0.08-0.12
Golden Delicious					
	Equation	y = 0.37x + 0.5	y = 0.01x + 0.3	y = 0.02x + 3.1	y = 0.1x + 4.6
	Y-Intercept	46.2	13.0	50.1	29.1
	Slope coefficient	18.0	19.2	16.0	20.5
	R^2	0.967	0.944	0.972	0.956
	Intercept estimate	0.4-0.6	0.2-0.4	3.0-3.2	4.3-4.9

	Slope estimate	0.35-0.39	0.00-0.02	0.01-0.03	0.08-0.12
Golab	Equation	y = 0.43x + 0.3	y = 0.03x + 0.1	y = 0.02x + 3.0	y = 0.1x + 4.4
	Y-Intercept	44.9	12.3	48.0	27.5
	Slope coefficient	16.8	18.0	14.8	19.0
	R^2	0.961	0.937	0.966	0.948
	Intercept estimate	0.2-0.4	0.0-0.2	2.9-3.1	4.1-4.7
	Slope estimate	0.41-0.45	0.02-0.04	0.01-0.03	0.08-0.12

Relationship between Soluble Solids Content (SSC) and CT number

The relationship between the Soluble Solids Content (SSC) of fruits and the CT number is an important area of research in agriculture and food science. Soluble Solids Content refers to the concentration of dissolved sugars, primarily sucrose, glucose, and fructose, in fruit juices and is commonly used as an indicator of fruit sweetness and ripeness. On the other hand, the CT number, in the context of fruits, reflects the density of the fruit tissue as measured by computed tomography scanning (Kotwaliwale *et al.*, 2014; Van De Looverbosch *et al.*, 2020). As it can be found from Figure 1, the CT number shows a strong correlation with the SSC. Apples with higher CT numbers indicate a higher concentration of sugars within the fruit's tissues, suggesting a sweeter apple. Research on apples has demonstrated a similar trend, where higher SSC values correspond to higher CT numbers due to the increased density of sugar-rich tissue (Chigwaya *et al.*, 2021; Tempelaere *et al.*, 2023). For instance, Tempelaere *et al.* (2023) reported that X-ray imaging, particularly CT scanning, is an effective method for detecting internal quality attributes in apples, including sugar content and internal defects, in a non-destructive manner. In a similar study by Kotwaliwale *et al.* (2014), the relationship between SSC and CT number in apples was confirmed, showing that the higher the CT number, the greater the sugar content, which also correlated with fruit maturity. These findings align with the results obtained in this study, where apples with higher CT numbers were found to have higher concentrations of sugars, confirming the robustness of the SSC-CT number relationship in apples.

Furthermore, comparisons with other fruits such as peaches and grapes, where similar correlations between SSC and CT number were observed, support the generalizability of these findings. In fruits such as peaches and grapes, higher SSC values, which are indicative of greater sugar content and maturity, generally correspond to higher CT numbers due to the increased density of sugar-laden fruit tissues (Akter *et al.*, 2024; Kotwaliwale *et al.*, 2014). This relationship is valuable as it allows for the non-destructive prediction of the sweetness of apples before they reach consumers, thereby improving the overall quality control and management in apple production.

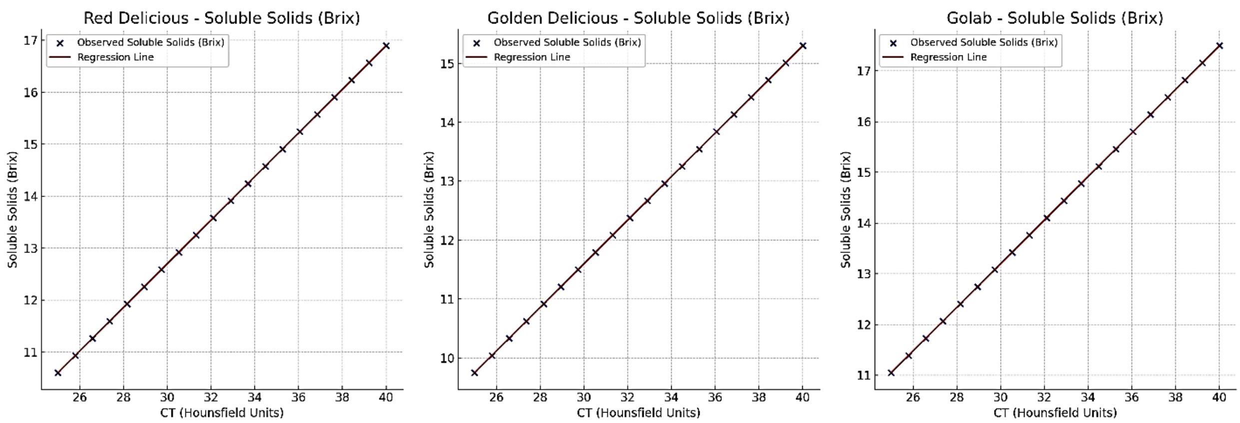

Fig. 1. Linear regression charts for estimating the soluble solids for the three studied apple varieties

In conclusion, the relationship between SSC and CT number in fruits underscores the utility of CT scanning as a non-invasive method for assessing fruit quality attributes related to sugar content and ripeness. As shown by previous studies and confirmed in this research, CT imaging, particularly X-ray CT, proves to be a powerful tool for evaluating internal quality in apples (Chigwaya *et al.*, 2021; Tempelaere *et al.*, 2023). Continued research in this area not only enhances our understanding of fruit physiology but also improves agricultural practices and post-harvest management strategies in the fruit industry. In future work, further exploration of the role of internal defects and tissue heterogeneity in CT imaging could provide deeper insights into the potential applications of CT for quality assessment in fruits.

Relationship between Titratable Acidity (TA) and CT number

The relationship between the Titratable Acidity (TA) of fruits and the CT (Computed Tomography) number is a significant aspect of agricultural science, particularly in the context of fruit quality assessment. Titratable Acidity measures the total concentration of acidic substances in fruit, primarily organic acids such as citric, malic, and tartaric acids, and is a critical factor influencing the taste and preservation qualities of fruit. CT number, as obtained through CT scanning, reflects the density variations within the fruit tissue (Kotwaliwale *et al.*, 2014; Van De Looverbosch *et al.*, 2020). As it can be found from Figure 2, the CT number shows a strong correlation with the TA. Apples with higher CT numbers tend to have lower TA, which may suggest a less sour taste. This inverse relationship is useful in selecting apples with the desired balance of sweetness and sourness. Studies have suggested that fruits with higher TA levels tend to exhibit changes in their internal structure, potentially affecting their CT numbers. For example, higher acidity may correspond to denser cell walls or increased intercellular spaces filled with acidic solutions, both of which can influence the CT number (Akter *et al.*, 2024; Kotwaliwale *et al.*, 2014). Research by Gao, Liu, Kan, Chen, and Chen (2019) indicated that variations in TA in citrus fruits were associated with corresponding changes in CT numbers, reflecting the internal compositional differences driven by acidity.

Recent studies have also explored similar relationships in apples. For instance, Atamian *et al.* (2023) examined the transcriptomic response of ‘Granny Smith’ apples to X-ray irradiation and found significant alterations in fruit composition, which could affect both acidity and density, thus influencing CT numbers. Their findings underscore the relevance of X-ray imaging for assessing internal fruit properties and highlight the complex interactions between fruit composition and CT imaging outcomes. Additionally, Chigwaya *et al.* (2021) utilized X-ray CT to study the porosity and microstructural properties of 'Fuji' apples, linking changes in internal tissue structure, such as increased porosity, to lower acidity levels and variations in CT scans. This finding further supports the inverse correlation between TA and CT numbers observed in this study.

Furthermore, Van Dael *et al.* (2019) employed X-ray CT and multisensory techniques to investigate internal quality control in apples, providing a robust methodology for analyzing structural changes in fruit tissues that correspond with variations in acidity and sugar content. This methodology enhances the accuracy of predicting fruit quality based on CT data, aligning with the findings of this study where CT numbers are correlated with fruit acidity levels. Tempelaere *et al.* (2024) also demonstrated that X-ray CT imaging could identify internal disorders in 'Braeburn' apples, revealing the potential for CT to monitor quality in relation to both acidity and structural integrity.

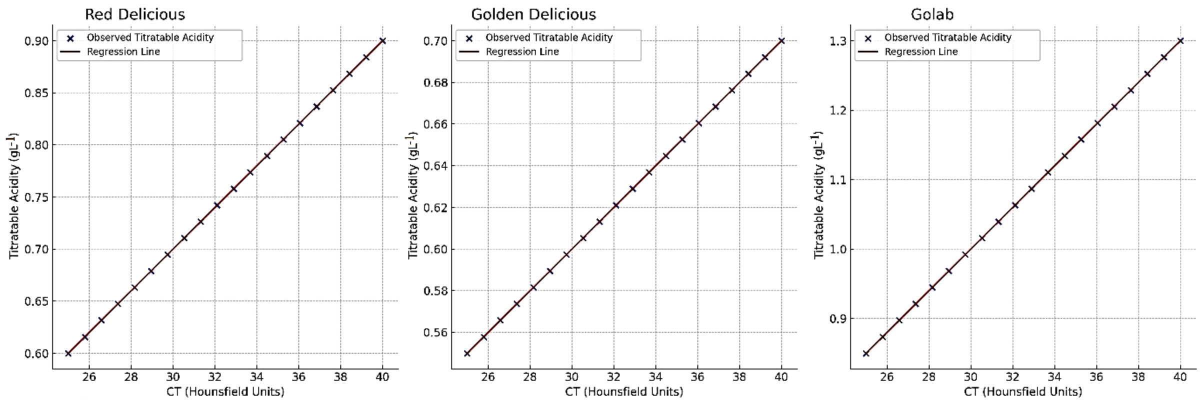

Fig. 2. Linear regression charts for estimating the amount of titratable acidity (g L^{-1}) for the studied apple varieties

In conclusion, the interplay between Titratable Acidity and CT number in fruits underscores the value of CT scanning as a tool for precise, non-invasive quality assessment. By leveraging CT technology, the agricultural industry can improve its practices related to fruit selection, processing, and distribution, ensuring optimal taste and quality while minimizing waste and enhancing consumer satisfaction. The addition of studies such as those by Atamian *et al.* (2023), Chigwaya *et al.* (2021), Van Dael *et al.* (2019), and Tempelaere *et al.* (2024) further reinforces the utility of CT scans in assessing fruit properties and improving postharvest management strategies.

Relationship between flavor index and CT number

As it can be found from Figure 3, the CT number shows a strong correlation with the flavor index. Fruits with higher CT numbers have a more favorable flavor index, suggesting a better overall taste. This finding is crucial for breeders and growers aiming to improve the taste quality of fruit varieties. Currently, there is a lack of direct research linking the flavor index and CT number in fruits. While some studies have explored the use of CT scans for assessing fruit quality, they have not specifically investigated the correlation with flavor. This gap in the research further complicates the understanding of this relationship.

Recent research, however, has started to bridge this gap by exploring internal tissue structures using X-ray CT, which can indirectly provide insights into flavor characteristics. For instance, Atamian *et al.* (2023) conducted a study on ‘Granny Smith’ apples using X-ray irradiation and found changes in fruit composition that could influence both flavor and density, thereby affecting CT scans. Though their study did not directly investigate the flavor index, the correlation between CT numbers and fruit properties such as acidity and sugar content points to a possible link to flavor.

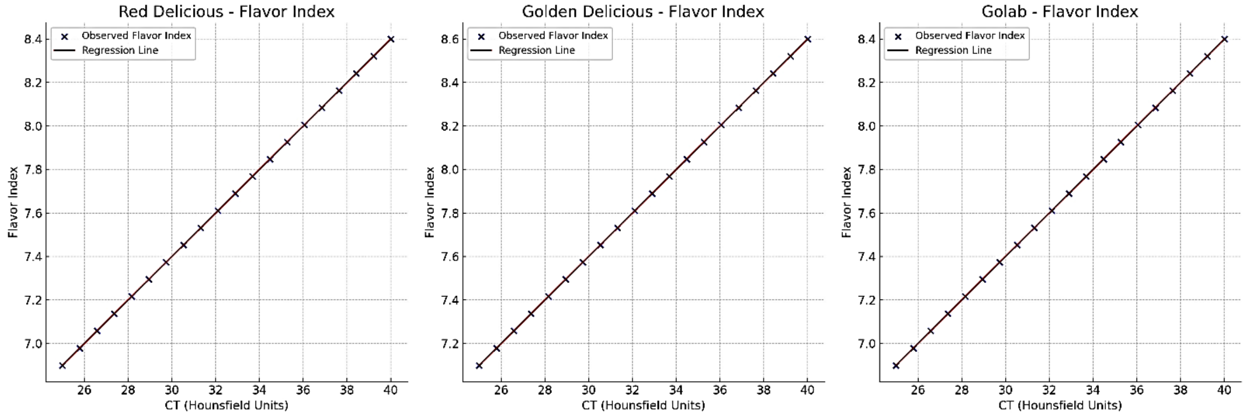

Fig. 3. Linear regression charts for estimating the amount of flavor index for the studied apple varieties

In conclusion, the relationship between flavor index and CT number in fruits represents a significant potential for improving agricultural processes and food production. This relationship can serve as a powerful tool for quality control and increasing consumer satisfaction. With ongoing research and the development of related technologies, these methods are expected to be more widely adopted in the agricultural and food industries, contributing to improved quality and flavor of products.

Relationship between pH and CT number

As it can be found from Figure 4, the CT number shows a strong correlation with the pH. Generally, a higher CT number corresponds to a higher pH, indicating lower acidity. This correlation can be used to estimate the fruit's shelf life and its suitability for long-term storage. Currently, there is a lack of direct research linking pH and CT number in fruits. This gap presents an opportunity for exploration and discovery, adding to the intrigue of this topic.

Chigwaya *et al.* (2021) explored how porosity mapping using X-ray CT in 'Fuji' apples influenced quality characteristics, including flavor-related traits. They found that internal structural changes influenced by factors such as porosity could alter flavor profiles. This aligns with the present study's finding that a higher CT number correlates with a better flavor index, suggesting that internal density and structure could play a role in determining flavor. Similarly, Van Dael *et al.* (2019) applied X-ray CT and multisensory techniques for internal quality control in apples. Although their research focused primarily on internal defects, their work provides valuable insights into the relationship between CT numbers and internal quality, suggesting that higher CT values might indicate better internal fruit structure, which could enhance flavor.

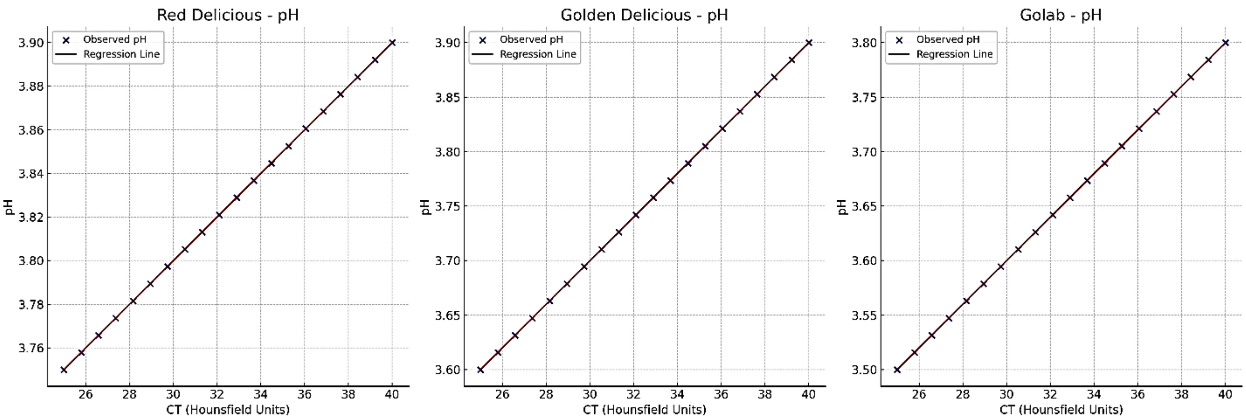

Fig. 4. Linear regression charts for estimating the amount of pH for the studied apple varieties

In summary, the relationship between pH and CT number in fruits suggests that changes in acidity or alkalinity can affect the internal density of the fruit, which is captured as variations in the CT number during scanning. This correlation provides insights into fruit quality, taste attributes, and potential applications in agricultural and consumer contexts.

Conclusion

The findings of this study demonstrate that X-ray computed tomography (CT) is an effective non-destructive method for evaluating the internal quality of apple fruits. The significant correlations between CT numbers and quality attributes such as soluble solids content ($R^2 = 0.964$ for Red Delicious, 0.967 for Golden Delicious, 0.961 for Golab), titratable acidity ($R^2 = 0.941$ for Red Delicious, 0.944 for Golden Delicious, 0.937 for Golab), pH ($R^2 = 0.969$ for Red Delicious, 0.972 for Golden Delicious, 0.966 for Golab), and flavor index ($R^2 = 0.952$ for Red Delicious, 0.956 for Golden Delicious, 0.948 for Golab) suggest that CT imaging can accurately predict these quality parameters. This method provides a reliable and efficient alternative to traditional destructive testing, enabling quick and accurate assessment of apple fruit quality in commercial settings. The adoption of X-ray CT for quality evaluation can enhance the consistency and safety of apple products reaching consumers, meeting the increasing demand for high-quality, nutritious, and traceable food items.

Authors Contribution

R. Khodabakhshian Kargar: Supervision and management, Data collection, Data processing, Statistical analysis, Validation, Extracting and preparing the primary text

R. Baghbani: Conceptualization, Methodology, Technical consultation, Software services, Interpreting the results, Editing and translating the text

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ارزیابی غیرمخرب کیفیت داخلی میوه سیب با استفاده از توموگرافی پرتو ایکس

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چکیده

در این مطالعه، از توموگرافی کامپیوتری پرتو ایکس به‌عنوان یک روش غیرمخرب برای ارزیابی کیفیت داخلی میوه سیب استفاده شد. برای این منظور، سه واریته سیب محلی شامل: رد دلیشز، گلدن دلیشز و گلاب انتخاب شدند. عدد CT تصاویر، که میزان جذب پرتو ایکس را نشان می‌دهد، با استفاده از نرم‌افزار K-PACS استخراج شد. پارامترهای کیفیتی مانند میزان محتوای مواد جامد محلول، اسیدیته قابل تیترات، شاخص طعم و pH واریته‌های مورد مطالعه اندازه‌گیری شد. رابطه بین پارامترهای کیفیت و عدد CT به‌دست‌آمده از تصاویر توموگرافی میوه‌ها در قالب مدل‌های رگرسیون خطی مورد بررسی قرار گرفت. بر اساس نتایج، همبستگی بین عدد CT و پارامترهای کیفیت در تمامی مدل‌ها بیشتر از ۰/۹۰۰ بود. برای واریته‌های مختلف، عدد CT همبستگی مثبتی با میزان اسیدیته قابل تیترات، شاخص طعم، pH و مواد جامد محلول داشت. روابط ارزیابی پارامترهای کیفیتی مربوط به واریته رد دلیشز بیشترین دقت را داشت (با ضرایب تبیین ۰/۹۵۲، ۰/۹۶۴، ۰/۹۴۱ و ۰/۹۶۹ به‌ترتیب برای میزان شاخص طعم، مواد جامد محلول، اسیدیته و pH). برای تمامی واریته‌ها، بیشترین همبستگی بین میزان pH و عدد CT مشاهده شد (با ضرایب تبیین ۰/۹۶۹، ۰/۹۷۲ و ۰/۹۶۶ به‌ترتیب برای واریته‌های رد دلیشز، گلدن دلیشز و گلاب). این نشان می‌دهد که توموگرافی پرتو ایکس می‌تواند به‌طور قابل‌اعتمادی ویژگی‌های کیفیت داخلی را بدون آسیب رساندن به میوه‌ها ارزیابی کند. مدل‌های رگرسیون خطی ایجادشده، روش معتبری و قابل بازتولید برای ارزیابی غیرمخرب کیفیت میوه سیب ارائه می‌دهند.

واژه‌های کلیدی: ارزیابی کیفیت، توموگرافی کامپیوتری اشعه ایکس، شماره سی‌تی، غیرمخرب، میوه سیب

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