Relating X-ray Absorption and Some Quality Characteristics of Mango Fruit (*Mangifera indica* L.)

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X-ray absorption was used as an index to detect the quality of mango based on its relationship with density, moisture content, soluble solids, titratable acidity, and pH. A regression equation was obtained between the computed tomography (CT) number and the physicochemical properties based on the principle of X-ray absorption capacities of the fruit. The CT numbers of intact mangoes were positively correlated with density, moisture content, and titratable acidity. The soluble solids and pH were inversely related with CT number. The results suggest that CT number measurements on intact fruit can be used as a nondestructive indicator of the quality of mango.

Keywords: *X-ray absorption; CT number; mango; Mangifera indica; quality*

INTRODUCTION

Consumers have placed an increasing emphasis on the quality of food products that they purchase. This has motivated the food industry to place an increased emphasis on the development of techniques that can be used for monitoring quality. Nondestructive sensing of fruit quality during harvesting, handling, ripening, and processing could lead to an added value of the product in the market. Ensuring quality of retail produce would improve consumer satisfaction, which would lead to a repeat buy of the product. Determination of the fruit internal quality often involves cutting and testing. A nondestructive on-line sensor that gives an indication of fruit quality in terms of sugar, acidity, pH, and moisture content would be of considerable value to the industry. Researchers have tried various techniques for internal quality evaluation such as nuclear magnetic resonance (NMR), optical, sonic, near-infrared radiation, and X-ray with some success. Some of the developed quality detection techniques are used successfully in the food industry, although they are usually specific to the kinds of products for which they are developed. X-ray absorption is one of the product properties that could be used as a basis for nondestructive quality analysis.

X-ray transmission, which depends on the mass density and absorption of the material, has been used to detect bruises and internal defects in apples (Diener et al., 1970; Schatzki et al., 1997), injury in papaya (Suzuki et al., 1994), maturity of lettuce (Lender and Adrian, 1971), maturity of peaches (Barcelon et al., 1999), hollow heart in potatoes (Finney and Norris, 1978), and granulation in oranges (Johnson, 1985). It also detected split pit in peaches (Han et al., 1992) and changes of peach internal structure during ripening (Barcelon et al., 1997). Ogawa et al. (1998) used X-rays to detect foreign materials in food based on density difference. Tollner et al. (1992) relate X-ray absorption with the density and moisture content of apples. Tollner (1994) observed that X-ray absorption at computed tomography (CT) modes could predict soil bulk density independent of water content. X-ray CT was used to detect the density change in tomato during maturation (Brecht et al., 1990). Zaltzman et al. (1987) presented a comprehensive literature review of studies related to quality evaluation of agricultural products based on density differences. X-ray absorbance is often associated with density and moisture content and has the potential to detect other quality factors in fruits. The objective of this study was to relate X-ray absorption with some physicochemical characteristics of mango fruit.

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MATERIALS AND METHODS

X-ray CT. An X-ray CT scanner TOSCANER-20000 (Toshiba Co.) designed for agricultural and industrial application was used in the study. The X-ray CT includes an X-ray tube, the collimators, the turntable, and the multichannel detector installed in a shield chamber. A reconstruction unit together with a console table and a cathode ray tube was connected to the computer. A collimated X-ray beam is directed on the product, and the attenuated remnant radiation is measured by a detector, the response of which is transmitted to a computer. A computer analyzes the signal from the detector, reconstructs an image, and displays the image on the monitor. Images were taken at an X-ray energy of 150 keV and an electron current of 3 mA. The standard unit for measuring X-ray absorption with CT systems is the Hounsfield unit or CT number. CT number is defined in equation form as

$$\text{CT number} = (\mu_S - \mu_W)k/\mu_W$$

where μ_S is the linear X-ray absorption coefficient of the sample (m^{-1}), μ_W is the linear X-ray absorption coefficient of water (m^{-1}), and k is a constant equal to 1000, if the scanner could measure down to a −1000 CT number. In the case of $k = 1000$, the CT number is called a Hounsfield unit. The CT number is based on linear X-ray absorption coefficients (Ogawa et al., 1998). CT numbers use a normalization of zero for water and −1000 for air. Some other dense materials such as aluminum alloy have a CT number of 2000 (Tanimoto et al., 1987). The CT number measuring the range of the X-ray scanner was from −1000 to +4000. The CT number measurement is expressed by brightness data in a reconstructed image. X-ray scanning was done radially through the middle portion and

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Table 1. Physicochemical Contents of Mango at Different Ripening Times

ripening time (week)	CT no.	density (g/cm^3)	moisture content (%)	soluble solids (°Brix)	acidity (g/kg)	pH
0	17.00 a	0.990 a	91.30 a	12.80 a	127.00 a	3.60 a
1	4.15 ab	0.981 b	89.95 a	13.45 ab	41.27 b	3.92 ab
2	−22.27 bc	0.962 c	87.82 b	14.29 bc	19.87 c	5.04 bc
3	−34.00 c	0.959 c	87.20 b	14.60 c	4.01 d	5.30 c

[a] Means in column having the same letter are not significantly different at $p \leq 0.05$.

in two other locations 15 mm from the middle of the fruit. CT number was measured on the flesh portion corresponding to the voxel area of 500 mm^2. The same portion of the fruit slice was used for the physical and chemical analyses.

Preparation of Mango. Mangoes (*Mangifera indica* L. cv. Carabao) were taken from a commercial farm in Cavite, Philippines. Fruits were selected from a single tree, mature, fully green, and free of disease. Harvested mangoes were placed in molded fiberboard packaging material and transported to the laboratory of the Tokyo University of Agriculture and Technology, Japan, by airfreight. The fruits were analyzed 2 days after harvest. A set of 32 fruits was X-ray scanned and ripened at room conditions (25 °C, 75% relative humidity). Fruits were evaluated analytically at weekly intervals for 3 weeks to get considerable changes of the fruit physicochemical characteristics.

Physical and Chemical Measurements. Composite samples of fruit portions (upper, middle, and lower) for each postharvest time interval was taken. Ten grams of flesh was titrated with 0.1 N NaOH to determine the total titratable acidity following AOAC Method 942.15. Results were expressed in terms of dominant acid as grams of citric acid per kilogram (AOAC, 1996). Total soluble solids content was determined on juice samples with an Abbe hand refractometer (Atago Co. Ltd., Tokyo) following AOAC Method 932.12, and the pH was determined using a digital pH meter following AOAC Method 981.12 (AOAC, 1996). The moisture content was determined on 5 g of flesh (mesocarp) by drying to a constant weight at 100 °C. Fruit density was measured by the displacement method (Kato, 1997). The physicochemical characteristics were measured from exactly the same sites as were used for the X-ray CT number measurements. All measurements were made in triplicate.

Statistical Analysis. Regression analysis was used to determine the relationship between the CT number and the physicochemical characteristics of mango. Analysis of variance technique was used to determine the effect of ripening time on the CT number and the physicochemical qualities of mango. Differences between means were determined by the Duncan multiple-range test at $p \leq 0.05$.

RESULTS AND DISCUSSION

The CT number and physicochemical properties of mango change over ripening time (Table 1). Physical and chemical changes of mango flesh cause the CT number to decline during ripening. The CT number decreased significantly to −34 after ripening from an initial value of 17. The negative CT number could be a reflection of less dense fruit tissue manifested by ripening. Physical and chemical responses at various ripening times changed at different rates, which resulted in the variation of X-ray CT number of the fruit. Density and moisture content followed the same decreasing trend with that of CT number. Density reduced significantly from an initial value of 0.99 to 0.96 g/cm^3, while moisture reduced significantly from an initial value of 91 to 87%. Titratable acidity decreased significantly with ripening, coinciding with an increase of soluble solids content and pH.

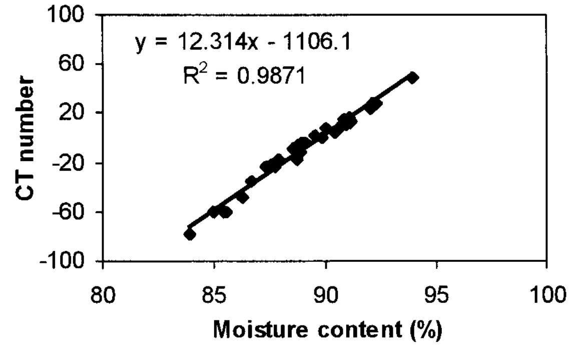

Figure 1. Relationship between CT number and moisture content of mango.

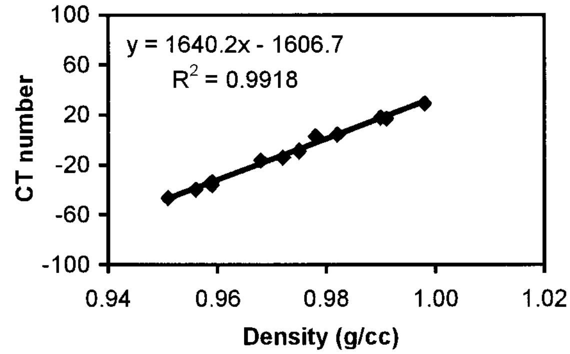

Figure 2. Relationship between CT number and density of mango.

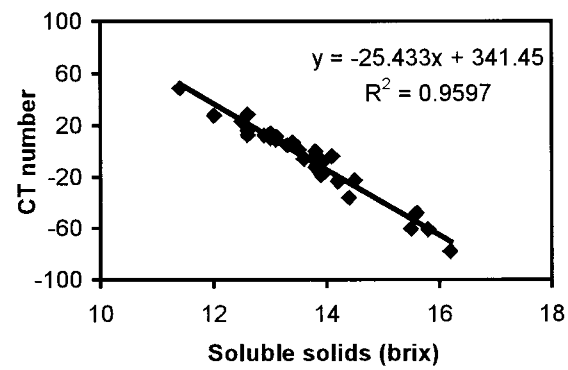

Figure 3. Relationship between CT number and soluble solids of mango.

Regression analyses were done to show the linkage between X-ray absorption and the values of the physicochemical indices of mango. Results indicated the presence of a strong correlation between measured X-ray absorption expressed in CT number and the physicochemical properties of the fruit (Figures 1−5). CT numbers were correlated with moisture content, density, and density-dependent properties such as soluble solids, titratable acidity, and pH of the fruit over the 3 week postharvest ripening time. Linear regression and correlation coefficients showed a high degree of association among the parameters.

Moisture content is the most dominant factor affecting the quality of fruit. A moisture regression equation based on CT number is highly significant ($R^2 = 0.98$). A positive linear relationship was observed between CT number and moisture content. Ai et al. (1988) found a similar positive correlation between CT number and moisture values. Tollner (1993) cautioned, however, that internal differences in X-ray absorption might occur within scans of fruit cross sections caused largely by the

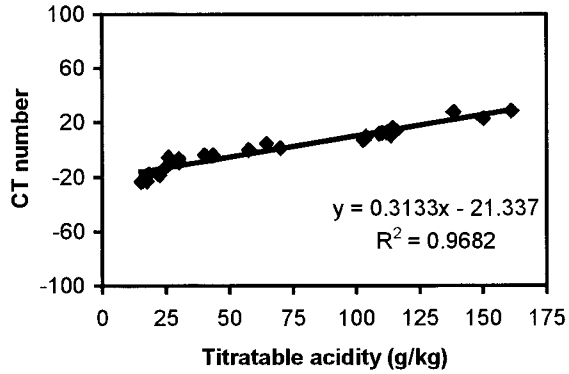

Figure 4. Relationship between CT number and titratable acidity of mango.

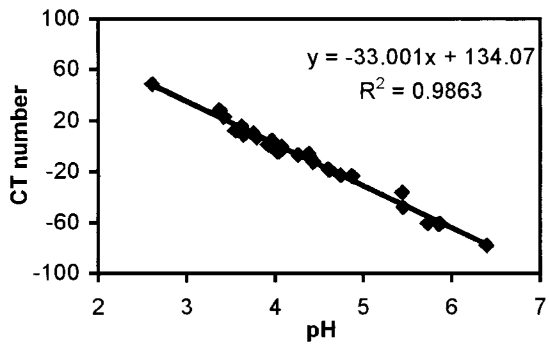

Figure 5. Relationship between CT number and pH of mango.

differences in volumetric water. Results suggest that the CT number could be used as an index for moisture content detection. This high correlation confirmed previous studies indicating that the CT number has been a good predictor of moisture (Tollner et al., 1992). Similarly, density had a positive linear relationship with CT number. Regression analysis indicated the presence of a strong correlation between X-ray absorption and the density (R^2 = 0.99). Density was an important variable because it can be objectively measured and is one of the properties that contains information relating to the internal quality of fruit. X-ray absorbance was proven to correlate with both density and moisture content. X-ray absorbance, however, depends on sample density and elemental composition of the product. Tollner et al. (1992) reported a highly positive correlation between X-ray absorption, moisture, and density of apples, which is in agreement with our results. The relationship between density and the quality of agricultural products has been recognized for a long time (Chen and Sun, 1991). Because X-ray absorbance was proven to correlate with density and water content, this parameter may also be applicable for the detection of other quality factors that are directly dependent on density.

The correlation coefficient between the CT number displayed by the scanner and soluble solids was highly significant, R^2 = 0.96. Soluble solids have a negative linear correlation with CT number. The soluble solids content is highly correlated with ripeness in most fruits and is an important indication of fruit taste (Kato, 1997). The acidity value, on the other hand, had a positive linear correlation with CT number (R^2 = 0.93), whereas the pH had a negative linear relationship with CT number (R^2 = 0.99). This strong relationship between X-ray absorption and chemical constituents might be due to the strong influence of the fruit density. Kato (1997) estimated the soluble solids content from the density and mass of watermelon. A change in density with damage and cultural practices could be due to fruit internal changes of chemical constituents, soluble solids content, or cell rupture (Zaltman et al., 1987). X-ray techniques could find possible application in fat, sugar, and starch differentiation of produce using density difference and could also be used to determine the structural properties of produce using scattered photons (Zwiggelaar et al., 1997). Karathanasis and Hajek (1996) explained that when X-rays encounter any form of matter, they are progressively attenuated as a result of a complex series of interaction with atoms of the attenuating or absorbing products. The X-ray absorption phenomenon and its extent are a function of the physical and chemical composition of the sample. The results indicate that the CT number could be used as reference to measure the internal constituents of fruit. This further suggests that X-ray absorption based techniques may be suitable for the analysis of fruit as an integral part of CT imaging analysis. Future study needs to be made on the influence of X-ray absorption on other physicochemical quality parameters not included in the current study.

CONCLUSIONS

Relationships between X-ray absorption and the physicochemical quality parameters of mango fruit have been obtained. There were strong correlations between X-ray CT numbers and the physicochemical properties of the fruit. In this study, it appears that the relationships that were considered turned out to be mostly linear. Moisture content, density, and acidity followed a positive linear relationship with CT number. On the other hand, soluble solids and pH followed a negative linear relationship with CT number. CT number was a satisfactory predictor of density and moisture content. It is also a satisfactory predictor of soluble solids, pH, and titratable acidity, which are considered to be density-dependent parameters. Results suggest that the CT number could be used as an index to estimate the physicochemical qualities of the fruit.

LITERATURE CITED

Ai, F.; Watanabe, K.; Mandang, T.; Kato, M.; Tojo, S.; Fujii, M.; Fukumoto, M. Computed tomographic analysis of soil structure. *Soil Phys. Conditions Plant Growth* **1988**, *63*, 1−16.

AOAC. *Official Methods of Analysis*, 16th ed.; Association of Official Analytical Chemists: Washington, DC, 1996.

Barcelon, E. G.; Tojo, S.; Watanabe, K.; Sorita, S. X-ray CT scanner for detecting internal changes in peach. *International Symposium on Agricultural Machinery and Automation*; National Taiwan University: Taipei, Taiwan, 1997; pp 227−232.

Barcelon, E. G.; Tojo, S.; Watanabe, K. X-ray CT imaging and quality detection of peach at different physiological maturity. *Trans. Am. Soc. Agric. Eng.* **1999**, *42*, 435−441.

Brecht, J. K.; Shewfelt, R. L.; Garner, J. C.; Tollner, E. W. Using X-ray computed tomography to nondestructively determine maturity of green tomatoes. *HortScience* **1990**, *26*, 45−47.

Chen, P.; Sun, Z. A review of nondestructive methods for quality evaluation and sorting of agricultural products. *J. Agric. Eng. Res.* **1991**, *49*, 85−98.

Diener, R. G.; Mitchell, J. P.; Rhoten, M. L. Using an X-ray image scan to sort bruised apples. *Agric. Eng.* **1970**, *51*, 356−361.

Finney, E. E.; Norris, K. H. X-ray scans for detecting hollow hearths in potatoes. *Am. Potato J*. **1978**, *55*, 95−105.

Han, Y. J.; Bowers, S. V., III; Dodd, R. B. Nondestructive detection of split-pit peaches. *Trans. Am. Soc. Agric. Eng*. **1992**, *35*, 2063−2067.

Johnson, M. Automation in citrus sorting and packing. *Agrimation Conference and Expo*, Chicago, IL, 1985; pp 63−68.

Karathanasis, A. D.; Hajek, B. F. Elemental analysis by X-ray fluorescence spectroscopy. In *Methods of Soil Analysis*; Soil Science Society of America: Madison, WI, 1996; pp 161−223.

Kato, K. Electrical density sorting and estimation of soluble solids content of watermelon. *J. Agric. Eng. Res*. **1997**, *67*, 161−170.

Lenker, D. H.; Adrian, P. A. Use of X-ray for selecting mature lettuce heads. *Trans. Am. Soc. Agric. Eng*. **1971**, *14*, 894−898.

Ogawa, Y.; Morita, K.; Tanaka, S.; Setoguchi, M.; Thai, C. N. Application of X-ray CT for detection of physical foreign materials in foods. *Trans. Am. Soc. Agric. Eng*. **1998**, *41*, 157−162.

Schatzki, T. F.; Haff, R. P.; Young, R.; Can, I.; Le, L.-C.; Toyofuku, N. Defect detection in apples by means of X-ray imaging. *Trans. Am. Soc. Agric. Eng*. **1997**, *40*, 1407−1415.

Suzuki, K.; Tajima, T.; Takano, S.; Asano, T.; Hasegawa, T. Nondestructive methods for identifying injury to vapor heat-treated papaya. *J. Food Sci*. **1994**, *59*, 855−857, 875.

Tanimoto, Y.; Tanaka, S.; Tomizawa, M. Application of X-ray CT scanner to nondestructive testing. *International Gas Turbine Congress*, Tokyo, Japan, 1987; pp 155−161.

Tollner, E. W. X-ray technology for detecting physical quality attributes in agricultural produce. *Postharvest News Inf*. **1993**, *4*, 149N−155N.

Tollner, E. W. Measurement of the density and water content in soils with X-ray linescan and X-ray computed tomography. *Trans. Am. Soc. Agric. Eng*. **1994**, *37*, 1741−1748.

Tollner, E. W.; Hung, Y. C.; Upchurch, B. L.; Prusia, S. E. Relating X-ray absorption to density and water content in apples. *Trans. Am. Soc. Agric. Eng*. **1992**, *35*, 1921−1929.

Zaltzman, A.; Verma, B. P.; Schmilovitch, Z. Potential of quality sorting of fruits and vegetables using fluidized bed medium. *Trans. Am. Soc. Agric. Eng*. **1987**, *30*, 823−831.

Zwiggelaar, R.; Bull, C. R.; Mooney, M. J.; Czarnes, S. The detection of soft materials by selective energy X-ray transmission imaging and computer tomography. *J. Agric. Eng. Res*. **1997**, *66*, 203−212.

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