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HYPERSPECTRAL SURFACE ANALYSIS FOR RIPENESS ESTIMATION AND QUICK UV-C SURFACE TREATMENTS FOR PRESERVATION OF BANANAS

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This study aimed to determine the ripeness of bananas using hyperspectral surface analysis and how a rapid UV-C (ultraviolet-C light) surface treatment could reduce decay. The surface of the banana fruit and its stages of maturity were studied using a hyperspectral imaging technique in the visible and near infrared (370–1000 nm) regions. The selected color ratios from these spectral images were used for classifying the whole banana into immature, ripe, half-ripe and overripe stages. By using a BP neural network, models based on the wavelengths were developed to predict quality attributes. The mean discrimination rate was 98.17%. The surface of the fresh bananas was treated with UV-C at dosages from 15–55 μW/cm^2. The visual qualities with or without UV-C treatment were compared using the image, the chromatic aberration test, the firmness test and the area of black spot on the banana skin. The results showed that high dosages of UV-C damaged the banana skin, while low dosages were more efficient at delaying changes in the relative brightness of the skin. The maximum UV-C treatment dose for satisfactory banana preservation was between 21 and 24 μW/cm^2. These results could help to improve the visual quality of bananas and to classify their ripeness more easily.

Keywords: *ultraviolet irradiation, visual quality, neural network, hyperspectral, ripeness.*

Introduction. Bananas are produced in large quantities in tropical and subtropical areas. In 2003, global production of the genus Musa (bananas and plantains) was estimated at 102 million MT, about 68% bananas and 32% plantains [1]. The appropriate ripeness of bananas is typically estimated visually for personal consumption or for export. Several quantitative approaches have been demonstrated such as measuring mechanical firmness by destructive analysis, total solid soluble content, ethylene content, and aromatic composition using gas chromatography.

The banana fruit cannot be stored for prolonged periods at temperatures below 12–14°C because of the symptoms of chilling injury (CI): rapid peel blackening, failure to ripen, hardening of the central placenta, and loss of flavor [2, 3]. However, serious diseases can also affect the quality and yield of banana, so sterilization has become a very important topic. Effective sterilization can significantly reduce the incidence of disease in bananas and prolong storage time and shelf life. Clean bananas will maintain their taste and flavor and reduce the risk to human health. The current method of preventing decay is to use chemicals such as fungicides [4]. However, this sterilization process does not produce bananas of uniform quality and also is not sufficient to ensure their safety. Therefore, research is now focusing on new sterilization technology and preservation techniques [5, 6].

In recent years, ultraviolet-C light (UV-C) has become more popular as a safe, green method to replace the traditional thermal sterilization methods for fruits and vegetables. UV-C treatment can improve the disease resistance of fresh agricultural products, delay senescence, and inhibit the growth of pathogenic microorganisms. It has now become an important topic of research into the harvesting and storage of fresh agricultural products. Recently, sub-lethal doses of UV-C have been investigated as a possible strategy in postharvest technology as they can reduce decay in many fruits. UV-C irradiation has also been shown to be useful for delaying some processes associated with ripening and reducing chilling injury in peppers [7]. Cuvi et al. treated red peppers with UV-C radiation, then stored them at 0°C for 21 days and showed that UV-C exposure prevented CI and reduced weight loss [8]. It was suggested that this might be related to the increased activity of antioxidant

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enzymes. The centers of broccoli heads treated with UV-C light were analyzed for chlorophyll-degrading peroxidase, chlorophyllase, and Mg-dechelatase activities [9]. The results suggested that UV-C treatments could be a useful nonchemical method for broccoli to delay chlorophyll degradation, reduce tissue damage and disruption, and maintain antioxidant capacity. One study examined the effects, before packaging, of four levels of UV-C illumination on quality changes of watermelon cubes stored for up to 11 days at 5°C [10]. UV-C radiation did not significantly affect the vitamin C content but catalase activity and total polyphenols content declined considerably during storage. However, total antioxidant capacity markedly increased independently of the UV-C dose. Therefore UV-C radiation can be considered a promising tool for maintaining the overall quality of fresh-cut watermelon. Pongprasert et al. treated banana fruits (Musa (AAA group), Cavendish subgroup cv. Cavendish) with UV-C before storage at 8 or 25°C. They concluded that UV-C treatment may play an important role in maintaining membrane integrity and inhibiting PPO (polyphenoloxidase) activity, thus reducing the severity of CI symptoms and delaying ripening.

The color of banana skin, determined by its chlorophyll content, can indicate its ripeness. At the immature stage, the banana skin is green, becoming yellow when ripe. Bacterial infections can cause bananas to decay, leading to many black spots, so the area of the black spots can be used to measure the degree of decay. Immature bananas contain the original pectin, which is insoluble in water. This holds the cells together individually, so that the banana is solid. As the bananas ripen, the water-soluble pectin increases gradually and the insoluble pectin decreases gradually. At this time, the pectinase activity has increased to make the banana soft, so the process of ripening softens bananas. Therefore, firmness can be an index of banana quality.

Overall, this study aims to quantify the ripeness level of the whole banana from its immature to its overripe stages by using hyperspectral-imaging with a color feature extraction algorithm and an artificial neural network (ANN) for classifying the maturity levels of the banana [11]. It will analyze the visual quality of bananas after UV-C treatment. The study will use different dosages of ultraviolet light radiation to treat the banana surface for 10 min and measure their effect on visual quality using the images, firmness, color, and area of black spot of bananas and hence their shelf life.

Materials and Methods. *Plant material and selection of treatment.* Banana fruits from Gaozhou (Guangdong Province, China) were obtained from a wholesale market at the immature, ripe, and overripe stages for hyperspectral analysis and at the immature green stage for UV-C treatment. Uniform, undamaged fruits were selected, separated, and randomized for use in experiments.

Fruits were illuminated from above and below by UV-C light from a UV lamp (wavelength 254 nm) positioned at different distances to provide dosages of 55, 43, 37, 29, 24, 21, 18, and 15 μW/cm^2 at the banana surface. Both sides of the banana fruits were illuminated with UV-C at each nominal illumination period to obtain a uniform exposure as shown in Fig. 1a. The illumination dosages were determined using a photo-radiometer (ZQJ-254, China). To understand the treatment process, we used a real-time monitor, which displayed the optical emission spectrum (OES) of UV-C light. A typical optical emission spectrum is shown in Fig. 1b. The emission intensity at a particular wavelength from an excited state is proportional to the concentration of species in that excited state.

Hyperspectral image acquisition system. The hyperspectral image acquisition system (Fig. 2) consisted of four important components: a charge-coupled device (CCD) camera, a spectrograph fitted with a standard C-mount zoom lens, a fruit holding platform surrounded by a white nylon cube tent, and two 50 W halogen lamps fitted at an angle of 45° to illuminate the camera's field of view. The exposure time for data acquisition in the sensitivity range of 370–1000 nm was fixed at 20 ms for the whole experiment. The distance between the CCD camera lens and the surface of the banana was fixed at 25 cm.

The acquired images were processed using spectra SENS software. Initially, the acquired images were corrected using white and dark references. The corrected image (I_c) was estimated as follows:

$$I_c = (I_A - I_D)/(I_W - I_D)\cdot 100 ,$$

where I_A is the acquired hyperspectral image, I_D is the dark image recorded by closing the camera lens completely and turning off the external light source, and I_W is the white reference image with 99% reflectance using a Teflon white board. The experiment was replicated three times to obtain standard deviations. The corrected images were used to extract information about spectral properties, to select effective wavelengths, and to develop models to predict biochemical composition [12].

Artificial neural networks (ANNs) have been developed to find unknown correlations between a given input data set and its target set. In the present study a feed forward back-propagation (FFBP) ANN has been devised to refine the prediction of hyperspectral data. ANNs require training to "learn" how to correlate inputs with outputs. Therefore proper datasets have to be selected to complete the training phase [13].

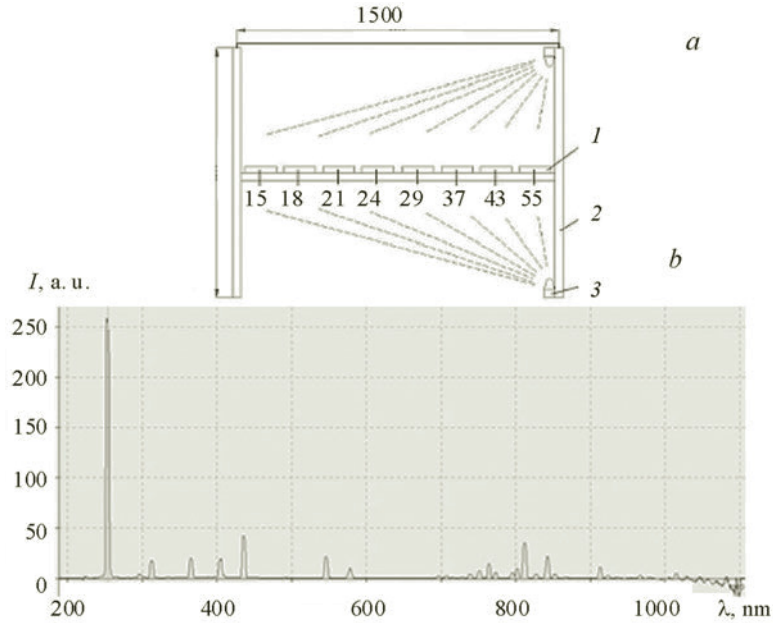

Fig. 1. The banana trial platform schematic diafragm of UV irradiation (a) [1) the banan sample, 2) the holder of the trial platform, 3 – UV-C light] and the spectra of UV-C light (b).

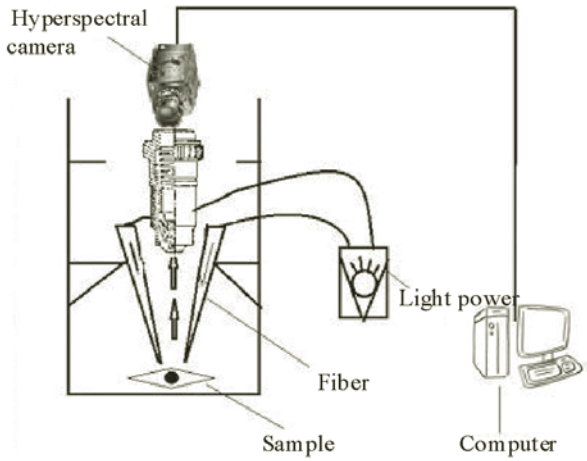

Fig. 2. Hyperspectral imaging system in operation.

Results and Discussion. *Spectral reflectance of the banana.* The average spectral reflectance in the range of 370–1000 nm collected from the banana fruits at different maturity stages from 1 to 4 (1 – immature, 2 – half-ripe, 3 – ripe, 4 – over-ripe) is shown in Fig. 3. The presence of chlorophyll pigment could be observed in the spectral range of 670–710 nm for banana fruits at maturity stage 1, and in the 650–680 nm range for those at maturity stage 2. However, the content of chlorophyll pigment was higher in fruits at maturity stage 1 than in those at maturity stage 2. No absorption was observed in bananas at maturity stages 3 and 4 because the fruit had turned yellow and the chlorophyll had completely degraded [14].

The spectral bands from 800–960 nm indicate the water content of the fruit, thus clearly demarcating the maturity stages based on the amount of moisture available in the fruits. As the moisture content of the unripe fruit skin was higher, the reflectance was also correspondingly higher for the unripe fruits from stages 1, 2, and 3. The reflectance was lower in fruits from stage 4 because of the lower moisture content in the fruit skin, water being the most abundant constituent in the pulp and skin of banana [15].

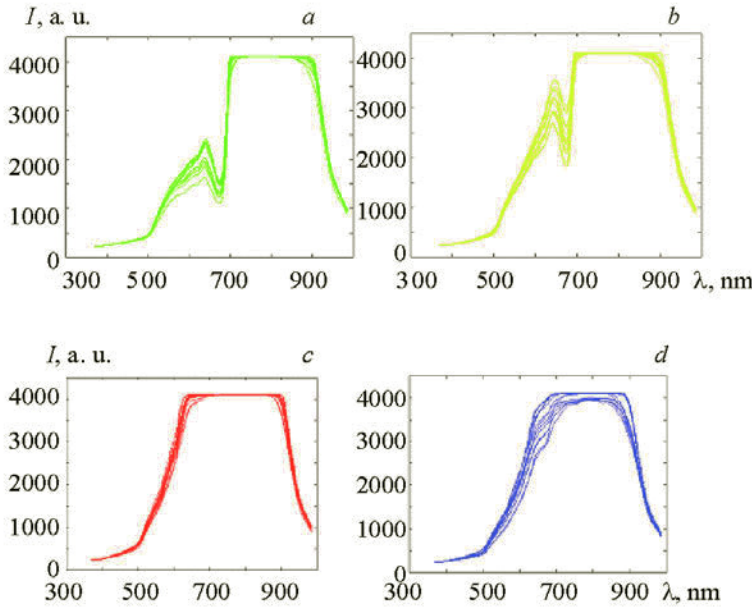

Fig. 3. Spectral profile from the hyperspectral image of bananas at different stages of ripeness: a) immature (stage 1), b) half-ripe (stage 2), c) ripe (stage 3), d) over-ripe (stage 4).

TABLE 1. ANN Training and Predicted Results

Actual maturity stage	Predicted maturity stage				The mean discrimination rate
	1	2	3	4	
1	142	0	0	0	98.17%
2	2	149	0	0	
3	0	0	147	9	
4	0	0	0	151	

Thirty samples were drawn randomly for training. The remaining 30 samples were used for testing. To reduce errors, the training and test samples were exchanged 20 times. The mean discrimination rate was 98.17%. The predicted outputs and actual outputs are shown in Table 1.

Table 1 shows that two samples at stage 2 were considered by the ANN as stage 1 and nine samples at stage 3 were considered as stage 4, both emerging at adjacent stages. The spectral data from these samples is similar and can overlap between stages 3 and 4. The actual stage is mainly judged by the naked eye and can be affected by subjective factors. Therefore, these differences between the output (predicted) and the actual stages are acceptable.

Analysis of the relative brightness of the UV-C treated bananas. The images of bananas treated by UV-C at different dosages shows that the banana skin was damaged at a high UV-C dosage, 55 μW/cm^2, but stayed green at a lower UV-C dosage of 15 or 24 μW/cm^2. With no UV-C treatment, the banana became mature and yellow. The color of banana skin is determined by the chlorophyll content. Some studies have reported that UV-C treatment maintains a significantly higher level of chlorophyll compared with no UV-C treatment [16].

The fresh GaoZhou bananas were treated using different UV-C dosages. The relative brightness, L, and the relative color aberration, A and B, of the fresh banana skin were measured and are shown in Fig. 4a–c. The relative brightness value, L, ranges from zero for black to 100 for white. Figure 4a shows that, for bananas treated with UV-C, L rises initially then falls. This indicates that initially the banana skin is brilliant green, then becomes dark green, then yellow, and finally black due to decay. By the 11th day, the relative brightness was high after treatment with low dosages of UV-C (15–24 μW/cm^2). At dosages of 29–55 μW/cm^2, L was low, similar to those with no UV-C treatment. These results

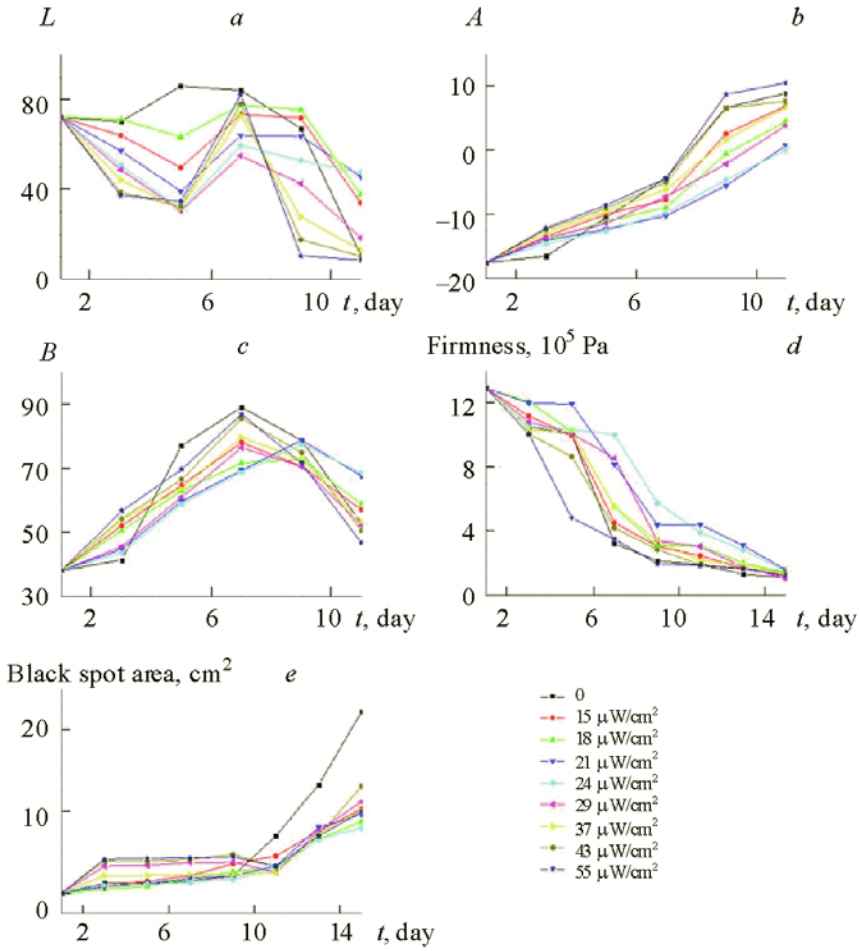

Fig. 4. Change in quality of bananas after UV-C treatment: a) the relative bridhtness *L*; b) the relative color aberration *A*; c) the relative color aberration *B*; d) the firmness; e) the banan skin black spot.

show high dosages of UV-C damaged the banana skin, while low dosages were more efficient and could delay changes in relative brightness.

The relative color aberration, *A*, represents red at positive values and green at negative values. Figure 4b shows that the value of *A* increased with time. These measurements are consistent with the observations: the banana ripens and the color changes from green to yellow. While it emerges that the value of A was low for UV-C treatments at dosages of 24 and 21 μW/cm^2, it was large at 0.55 μW/cm^2. These results show that a safe intensity of UV-C treatment can delay change in the relative color aberration *A*.

The relative color aberration, *B*, represents the yellow at positive values and blue at negative values. Figure 4c shows that the value of *B* increased initially then decreased with time. Similarly, this is based on the fact that when bananas ripen, the yellow color becomes darker. While the value of *B* was large after UV-C treatment at dosages of 24 and 21 μW/cm^2, it was small at other dosages. These results show a low intensity UV-C treatment can also delay changes in the relative color aberration *B*.

Analysis of banana skin firmness after UV-C treatment. The firmness of the skin of fresh GaoZhou bananas, treated with different dosages of UV-C skin, was measured (Fig. 4d). The bananas became mature with time with their firmness decreasing continuously. The firmness after treatment at dosages of 24 and 21 μW/cm^2 was higher from the 5 to 13 days. Finally after the 15 day, the firmness of all bananas became similar. So it can be concluded that a safe intensity UV-C treatment can promote the firmness of the banana.

Analysis of the area of black spots on the skin of UV-C treated bananas. The area of black spots on the skins of fresh GaoZhou bananas treated with different dosages of UV-C was measured (Fig. 4e). As the bananas matured, the area of black

spots on all banana skins increased continuously. The area of black spots on untreated bananas was low up to the 9 day and also low after treatment with dosages of 18, 24, and 21 $\mu W/cm^2$ after 9 days, compared with no UV-C treatment. So it can be concluded that a safe intensity of UV-C treatment can delay the generation of black spots which corresponds to PPO activity [17]. Other studies have also shown that UV-C treatment significantly reduced PPO activity and decreased the area of black spots [18].

UV-C light in the range of 240–260 nm has been approved in the USA for use on food as a surface sanitizing treatment, being as effective as NaClO or O_3. UV-C light damages the nucleic acids of some microorganisms, thus affecting their growth. The crucial issue is whether a safe dose of UV-C can be found which would greatly impair pathogen growth without damaging the product.

Some authors have suggested that UV-C treatment can reduce both the incidence and severity of damage to banana fruits stored at low temperatures [19]. UV-C treatment reduced membrane damage as indicated by the lower activity of lipoxygenase and lower malondialdehyde content. In addition, *in vitro* PPO activity was initiated when fruits were stored at CI temperature, but UV-C treatment could inhibit this. UV-C treatment also delayed yellowing and chlorophyll degradation because it inhibited chlorophyllase and chlorophyll-degrading peroxidase activities. The reduction in ethylene production and respiration rate by UV-C treatment also results in extending the postharvest shelf life of bananas. These findings suggest that the loss of cellular compartments from membrane degradation, combined with the increase in PPO activity, might contribute to the development of CI in banana peel [19].

In commercial trials, exposing packaged watermelons cubes to UV-C light at 4.1 kJ/m^2 produced more than a 1 log reduction in microbial populations by the end of the product shelf life without affecting juice leakage, color, and overall visual quality. In further experiments, a lower UV-C dose (1.4 kJ/m^2) reduced microbial populations to a lesser degree and only when the surface was completely exposed. Higher UV-C doses made no difference to microbial populations (6.3 kJ/m^2) or resulted in quality deterioration (13.7 kJ/m^2) [20]. For fresh bananas, the safe doses of UV-C at 21 and 24 $\mu W/cm^2$ in the present study delayed yellowing and chlorophyll degradation to produce high visual quality.

Conclusions. The banana surface was analyzed using hyperspectral image technology and treated with UV-C light. Whole bananas were classified into immature, ripe, half-ripe, and overripe stages. By using a BP neural network, models were established based on the wavelengths from hyperspectral images to predict the quality attributes. The mean discrimination rate was found to be 98.17%.

Fresh bananas were also treated with UV-C at dosages in the range 15–55 $\mu W/cm^2$. The effect of UV-C treatment on the visual qualities of bananas was assessed using images, the chromatic aberration test, the firmness test, and the area of black spots on the banana skin. The effect of low radiation doses on banana sterilization was not obvious, but high radiation doses damaged the banana skin. It was concluded that the safe UV-C treatment doses were 21 and 24 $\mu W/cm^2$ and that it could prolong the shelf life of the bananas.

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