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Research on Image Enhancement of Crisp-Ripe Stage Red Jujube Based on Particle Swarm Optimization Algorithm

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Abstract: Machine vision technology plays a crucial role in non-destructive detection and online monitoring of deep processing for red dates during the crisp-ripe stage. However, due to factors such as uneven illumination in the collection environment and illumination attenuation on the curved surface of quasi-spherical objects, the collected images of red dates during the crisp-ripe stage often suffer from issues such as low overall image quality, difficulty in recognizing epidermal fruit spots and fine textures, low contrast between fruit surface crack defects and normal fruit surfaces, and blurred fruit body edges, which increase the difficulty of accurately identifying fruit surface features. In response to the common problems of over-enhancement and loss of details in current image enhancement methods when processing images of red dates during the crisp-ripe stage, this paper combines the practical requirements of preserving details of the fruit body and crack edges, enhancing epidermal texture clarity, balancing contrast and noise, and constructs a multi-dimensional image enhancement fitness function. A method for enhancing images of red dates during the crisp-ripe stage based on the Particle Swarm Optimization (PSO) algorithm is proposed. Through comparative experiments on image enhancement of red dates during the crisp-ripe stage, the effectiveness and superiority of the proposed image enhancement method are verified from both subjective visual effects and objective evaluation indicators.

Keywords: Red dates; Multi-dimensional image enhancement fitness function; Image adaptive enhancement.

1. Introduction

Image Contrast Enhancement (ICE) is a technique that eliminates the impact of adverse factors during image acquisition by optimizing the gray levels of updated images to reduce image degradation, thereby enhancing image quality [1]. In recent years, researchers have formulated image enhancement technology as a complex nonlinear optimization problem, employing intelligent optimization algorithms inspired by physical, natural, and biological systems to solve the ICE problem.

The southern Xinjiang region is the core production area for high-quality red dates in the world, and red dates serve as a pillar industry for local workers and residents to increase their income and achieve prosperity. However, images of red dates at the crisp-ripe stage generally suffer from issues such as low contrast, weak surface wrinkles and cracks, uneven illumination, strong noise interference, and unclear boundaries between the fruit body and the background. These issues lead to decreased stability in traditional machine vision systems for extracting apparent defects and grading quality, making it difficult to accurately identify subtle defects such as low-contrast cracks and light-colored scars [2]. Image enhancement is an important image preprocessing method before conducting quality diagnosis, target segmentation, and multi-dimensional feature extraction of red date images at the crisp-ripe stage. Currently, scholars both domestically and internationally commonly adopt linear or nonlinear transformations, but there is no specific method for image enhancement tailored to red date images at the crisp-ripe stage. Most image enhancement methods applied to red date images at this stage can degrade image quality. Therefore, this paper proposes an image enhancement method for red dates at the crisp-ripe stage based on the Particle Swarm Optimization (PSO) algorithm. This method uses the PSO algorithm to adaptively select the optimal parameters of the transformation function and evaluates the enhancement effect through a multi-dimensional fitness function, thereby achieving adaptive enhancement of low-contrast red date images at the crisp-ripe stage and avoiding the problem of over-enhancement present in existing image enhancement methods.

2. Image Enhancement Method for Jujubes at the Crisp-ripe Stage Based on PSO Algorithm

2.1. PSO algorithm

The PSO algorithm is an intelligent optimization algorithm inspired by the behavior of bird flocks [3]. This algorithm simulates the process in which particles within a group search for the optimal solution through information sharing and cooperation. In each iteration, the velocity of particles is updated according to the following formula:

$$v_i^{(t+1)} = w \cdot v_i^{(t)} + c_1 \cdot r_1 \cdot (pBest_i - x_i^{(t)}) + c_2 \cdot r_2 \cdot (gBest - x_i^{(t)}) \quad (1)$$

Update the position according to the following formula:

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \tag{2}$$

In the formula, $v_i^{(t)}$ and $x_i^{(t)}$ represent the current velocity and position of the particle, respectively. *w* denotes the inertia factor, c_1 and c_2 represent the learning factors, r_1 and r_2 represent random numbers between 0 and 1, and $pBest_i$ and $gBest$ represent the historical optimal position found by the *i*-th particle and the global optimal position of the population, respectively.

2.2. Bilateral gamma correction

The principle of gamma correction involves performing nonlinear tone editing on the image that needs adjustment, and its formula is as follows [4]:

$$I_o = cI_i^{\gamma} \tag{3}$$

In the formula, I_o and I_i represent the corresponding grayscale values of the enhanced and original images, respectively, while the two parameters *c* and γ control the overall brightness of the image and the shape of the conversion curve.

When the value of parameter *c* is equal to 1, the grayscale values of the image are normalized to the range of 0 to 1. The gamma functions $g_a(z)$ and $g_b(z)$ form the basis of the Bilateral Gamma Correction (BGC) function based on global brightness. The formulas for the two functions are as follows:

$$g_a(z) = z^{1/r} \tag{4}$$

In the formula, $g_a(z)$ is a convex function used to enhance the dark areas of the processed image, where *z* represents the grayscale value of the input image. *r* is an adaptive parameter that adjusts the enhancement amount of the input image, and this parameter is usually equal to 2.5.

$$g_b(z) = 1-(1-z)^{1/r} \tag{5}$$

In the formula, $g_b(z)$ is a concave function used to suppress the bright areas in the processed image.

$$g(z) = \alpha g_a(z) + (1-\alpha) g_b(z) \tag{6}$$

In the formula, the adjustment function *g*(z) is generated by a weighted combination of a convex function $g_a(z)$ and a concave function $g_b(z)$. *a* is an adjustment variable with a value in the range of [0,1].

The specific process of enhancing an image using the BGC function is as follows: First, normalize the image using formula (7). Next, correct the image using formula (8). Finally, map the values back to the range of 0 to 255 using formula (9). The above formulas are as follows:

$$I_1(x,y) = I(x,y) \ / \ 256 \tag{7}$$

$$I_2(x,\ y) \ = \ g(I_1(x,\ y)) \tag{8}$$

$$I(x,y) = I_2(x,y) \times 256 \tag{9}$$

2.3. Incomplete Beta function

Tubbs proposed a normalized incomplete Beta function (IBF) to automatically fit these four different types of transformation functions [5], with the mathematical expression as follows:

$$F(u) = B^{-1}(\alpha,\beta) * \int_0^u t^{\alpha-1}(1-t)^{\beta-1}\,dt \tag{10}$$

In the formula, $F(u)$ represents the normalized IBF, where $0 \leqslant u \leqslant 1$. α and β are parameters of IBF, where $0<\alpha$，$\beta<10$. $B(\alpha, \beta)$ denotes the Beta function, and its formula is defined as follows:

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}\,dt \tag{11}$$

In the formula, different values of α and β parameters will result in different types of transformation curves.

2.4. Construction of fitness function

Addressing the prevalent issues in images of crisp-ripe red dates, such as low contrast, faint features like surface wrinkles and shallow cracks, uneven illumination, and blurred fruit boundaries, this paper constructs an adaptability function tailored for image enhancement of crisp-ripe red dates. The aim is to enhance contrast while simultaneously strengthening crack edges and maintaining the stability of the fruit contour. This adaptability function encompasses the sum of edge intensity, image entropy, peak signal-to-noise ratio, average image gradient, and the number of edge pixels. The formula for this adaptability function is defined as follows:

$$\begin{aligned} G(E) = {} & 0.2 * \log(N(E)) + 0.2 * \log(\log(S(E))) + 0.2 * H(E) + \\ & 0.2 * PSNR(I,E) + 0.2 * \log(AG(E)) \end{aligned} \tag{12}$$

In the formula, *I* and *E* represent the original and enhanced images, respectively, and $G(E)$ represents the fitness function value. In formula (10), $N(E)$ represents the number of edge pixels in the enhanced image, and a larger value of $N(E)$ indicates a clearer image.

$S(E)$ and $H(E)$ represent the sum of image edge intensities and the entropy of the enhanced image, respectively. The formula for $H(E)$ is as follows:

$$H(E) = \sum_{i=0}^{255} p_i \log_2(p_i) \tag{13}$$

In the formula, p_i represents the probability of the i-th intensity value appearing in the image.

PSNR is used to calculate the Peak Signal-to-Noise Ratio between images, and its calculation formula is as follows:

$$PSNR = 10 \times \log_{10}\left(\frac{(2^n - 1)}{MSE(I,E)}\right) \tag{14}$$

In the formula, *MSE* is defined as follows:

$$MSE(I,E) = \frac{\sum_{i=1}^{H}\sum_{j=1}^{W}(I(i,j) - E(i,j))^2}{H \times W} \tag{15}$$

In the formula, H and W represent the height and width of the image, respectively, and $I(i, j)$ and $E(i, j)$ represent the grayscale values of the original and enhanced images at position (i, j), respectively.

The average gradient $AG(E)$ is a key indicator for evaluating image clarity, and the specific formula for $AG(E)$ is as follows:

$$AG(E) = \frac{1}{H \times W}\sum_{i=1}^{H}\sum_{j=1}^{W}\sqrt{\frac{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2}{2}} \tag{16}$$

In the formula, $\frac{\partial f}{\partial y}$ and $\frac{\partial f}{\partial x}$ represent the vertical and horizontal gradients, respectively.

2.5. Adaptive enhancement method for jujube image based on PSO algorithm during the brittle-ripe stage

The traditional IBF has extremely limited improvement effect when dealing with situations where both ends are stretched, and the middle is compressed [6]. In the BGC function, $g_a(z)$ is a convex function to enhance the dark areas, while $g_b(z)$ is a concave function to suppress the bright areas. Using the BGC function to preprocess the original image can adjust the overly bright or dark areas in the TRUS image to avoid excessive enhancement. Inspired by the literature [4], this paper first applies the BGC function to preprocess the input original image, thereby enhancing the dark details of the original image and suppressing overexposure, while retaining the bright information. This step ensures that the image is preliminarily corrected in extreme areas, providing a more balanced input for subsequent optimization. Secondly, the BGC-corrected image is used as input, and the PSO algorithm is employed to adaptively optimize the transformation function parameters, achieving global contrast stretching.

The PSO algorithm is utilized to adaptively optimize the parameters α and β, aiming to obtain an enhanced image of crisp and ripe red dates and to a certain extent overcome the issue of over-enhancement. The flowchart of the PSO algorithm for adaptive image enhancement is illustrated in Figure 1.

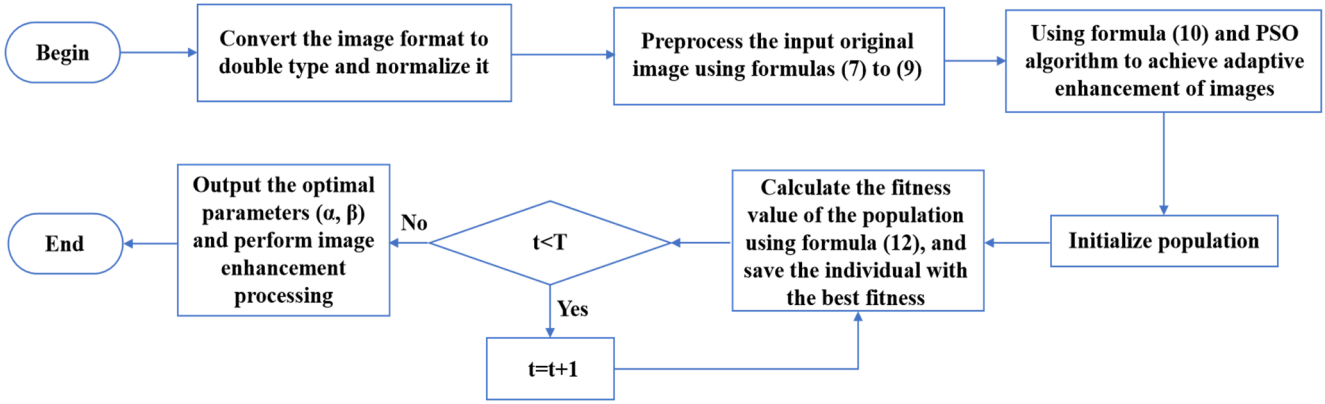


Figure 1. Flowchart of adaptive image enhancement based on PSO algorithm

3. Experiment and Discussion

3.1. Experimental Data

In this paper, an image dataset of red dates at the crisp-ripe stage was collected in the laboratory, and one image was randomly selected for experimentation.

3.2. Evaluation Metrics

This article employs three widely used metrics in the field of image enhancement to assess algorithm performance, namely: Structural Similarity Index Measure (SSIM), H(E), and PSNR. PSNR and H(E) have been briefly outlined above. A higher H(E) value indicates more image details, while a higher PSNR value signifies less distortion between the enhanced result and the reference image. In this section, we briefly summarize SSIM.

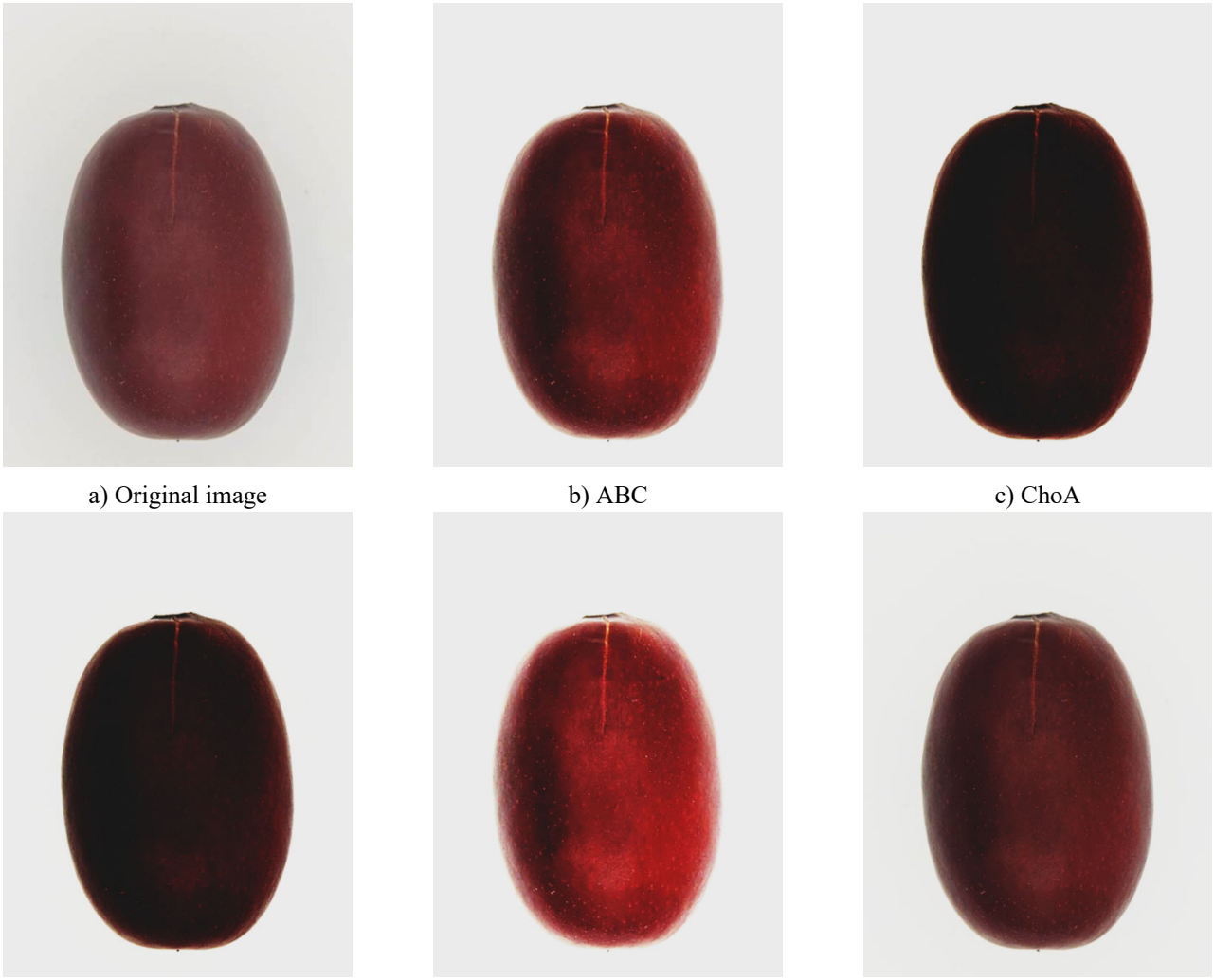
SSIM, as a measure of similarity between the original image and the enhanced image, has a value range of 0 to 1. The higher the SSIM value, the greater the similarity between the two images. The formula for this index is as follows:

$$\mathrm{SSIM}(I,E)=\frac{(2\mu_I\mu_E+c_1)(2\sigma_{IE}+c_2)}{(\mu_I^2+\mu_E^2+c_1)(\sigma_I^2+\sigma_E^2+c_2)} \quad (17)$$

In the formula, c_1 and c_2 are constants, which serve to prevent the denominator from being 0; μ represents the brightness of the image, σ represents the RMS contrast of the image, and σ_{IE} represents the covariance between two images.

3.3. Analysis of experimental results

To verify the effectiveness of the method proposed in this paper, we compared it with currently popular image contrast enhancement methods, including the ChoA [4], ABC [7], Ei^{2}PO [1], and AEFA [9]. Figure 2 presents the visual comparison results of the method proposed in this paper and the comparative algorithms in the image enhancement of red dates during the crisp-ripe stage.



a) Original image b) ABC c) ChoA

d) Ei^{2}PO e) AEFA f) Proposed Method

Figure 2. Visualization results of the proposed method and the comparative method

As can be seen from Figure 1 b) and Figure 1 e), the contrast of the red jujube images enhanced by the ABC and AEFA algorithms has been improved to some extent. Although the longitudinal cracks on the fruit surface are more prominent, the images enhanced by these two algorithms exhibit local over-enhancement issues. The edges of the fruit body's curved surface and the top of the cracks near the fruit stem appear significantly whitened and distorted, and the pericarp around the cracks is overly saturated, resulting in a certain degree of loss of pericarp details and transition information at the edge of the cracks. As shown in Figure 1 c) and Figure 1 d), the images enhanced by ChoA and Ei^{2}PO excessively reduce the overall brightness of the fruit body area, causing large areas of the red jujube fruit surface to appear blackened. The longitudinal cracks on the fruit surface become extremely dim and blurry, and the fine extension segments at the lower end of the cracks are completely engulfed by the dark part. The epidermal texture and fruit dot details are almost completely lost. As can be seen from Figure 1 f), the method proposed in this paper not only makes the external boundary contour and fruit stem of the red jujube fruit body clearer, but also preserves the continuity and boundary sharpness of the fine cracks from the top to the end of the longitudinal cracks on the fruit surface. The contrast between the light-colored areas inside the cracks and the surrounding normal pericarp, the shaded and illuminated areas on the fruit surface, and the small epidermal fruit dots is effectively enhanced, making the defect characteristics and three-dimensional sense of the fruit surface more distinct. The overall brightness of the image is moderate, without local overexposure or underexposure in the dark part. The enhanced red jujube images have full color, and the overall visual perception is more natural compared to the contrast methods. Table 1 presents the PSNR, SSIM, and H(E) results

obtained from five image contrast enhancement methods, with the optimal values for each indicator highlighted in bold.

Table 1. PSNR, SSIM, and H(E) results obtained by the method proposed in this paper and other methods

Algorithm	Entropy	SSIM	PSNR
ABC	3.2676	0.8970	22.5905
ChoA	2.2532	0.6925	18.0290
Ei^2PO	2.6067	0.7318	18.4898
AEFA	3.3170	0.8437	19.9300
Proposed Method	**4.6516**	**0.9422**	**23.9415**

The experimental results indicate that the image enhancement method proposed in this paper not only enhances the contrast of red dates during the brittle ripening stage but also effectively suppresses noise amplification. It preserves the external contour of the fruit body, the fruit stem, and the details of longitudinal crack edges. Additionally, it performs adaptive equalization adjustment on the brightness distribution of the brightly lit areas and the darkly shadowed areas on the fruit surface. While highlighting weak contrast features such as fine cracks at the ends of cracks and tiny fruit spots on the epidermis, it effectively avoids issues such as local white overexposure, dark underexposure, and color oversaturation distortion. The method proposed in this paper balances optimal objective quantitative performance and subjective visual quality. The PSNR, SSIM, and H(E) values of the enhanced images obtained are significantly better than those of the comparative algorithms, ranking first among all comparative methods in terms of these three evaluation indicators.

4. Conclusion

Addressing issues such as low image contrast, faint longitudinal crack tips and epidermal fruit spot features, uneven brightness distribution due to illumination attenuation on the curved surface of the fruit, and blurred fruit boundaries in the crisp-ripe stage of red dates, this paper proposes an image enhancement method based on the PSO algorithm. This method constructs a multi-dimensional fitness function consisting of the sum of edge intensities, image entropy, peak signal-to-noise ratio, image average gradient, and the number of edge pixels. It effectively suppresses noise gain while enhancing the features of fruit surface cracks and fruit body contours. Additionally, it adaptively adjusts the brightly lit areas, dark shaded areas, and curved surface edges on the fruit surface, thereby improving the resolvability of image details while effectively avoiding excessive enhancement phenomena such as local white overexposure or dark underexposure blackening.

The image enhancement and comparison experiment of red dates at the crisp-ripe stage shows that the red date images enhanced by the method proposed in this paper exhibit fuller color, a more natural visual appearance, and a more balanced transition between light and dark areas on the fruit surface. Details such as longitudinal cracks on the fruit surface and tiny fruit spots on the epidermis are fully preserved, while the external contour, fruit stem, and edge areas of the fruit body are clearly highlighted, which is beneficial for subsequent segmentation of surface defects, multi-dimensional feature extraction, and quality grading of red dates. The PSNR, SSIM, and H(E) values obtained by the method proposed in this paper are 23.9415, 0.9422, and 4.6516, respectively, which are significantly better than those of the comparison algorithm, providing the best objective quantitative performance and subjective visual quality.

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