Modeling Post-harvest Quality by StanSAT, Applied to Cucumis Sativus L.

Chen Cheng (✉ chengsir1993@lsu.edu.cn)

Lishui University

Xinxing Xu

Ocean University of China

Chaoyang Dong

Tianjin Climate Center

Zhihong Gong

Tianjin Climate Center

J. Fernando Bienvenido Barcena

UAL/ University of Almeria

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1 **Modeling post-harvest quality by Stan_{SAT}, applied to *cucumis sativus* L.**

2 Chen Cheng ^{a, b*}, Xinxing Xu ^c, Chaoyang Dong ^d, Zhihong Gong ^d, J. Fernando Bienvenido Barcena ^e

3 ^aInstitute of Ecology, Lishui University, Lishui, Zhejiang, 323000, China

4 ^bCollege of Resources and Environment Sciences, China Agricultural University, Beijing 100193, China

5 ^cCollege of Food Science and engineering, Ocean University of China, Qingdao 266100, Shandong, China

6 ^dTianjin Climate Center, Tianjin 300074, China

7 ^eComputer Science Department, UAL/ University of Almeria, Almeria, 04120, Spain

8 **ABSTRACT**

9 Crop post-harvest quality model is designed to dynamically and accurately simulate the quality change process. In this study, the relationship
10 between morphological indices and fruit quality (external quality and internal quality) were quantitatively simulated, and the post-harvest quality
11 and quality evaluation value simulation model were established for the first time with standardized stress accumulated temperature (Stan_{SAT}). The
12 results showed: 1) There were significant linear relationships between the fresh weight and the volume, the darker value and the color value, the
13 tan H and the color value, and the water content and the soluble solid content. There was a significant quadratic relationship between fruit density
14 and fruit shape index. There was a significant logarithmic relationship between the tan H and the darker value. 2) The quality indices, including
15 quality evaluation value, darkness value, color value, darker value, shape index, tan H and density, showed a linear change trend with Stan_{SAT}.
16 The soluble solid content showed a quadratic function variation trend with Stan_{SAT}. 3) For each quality index, normalized root mean square error
17 (NRMSE) of each quality index and its evaluation simulation model based on Stan_{SAT} were from 1.58 % to 17.85 %, which showed the post-
18 harvest quality index and quality evaluation simulation have high accuracy. Generally, the model could systematically and quantitatively express
19 the dynamic process of post-harvest quality of cucumber.

20 *Key words:* *cucumis sativus* L.; standardized stress accumulated temperature; simulation model; external morphology quality; internal quality;
21 quality evaluation

22 *Corresponding author E-mail address:chengsir1993@lsu.edu.cn (Chen Cheng)

1. Introduction

Cucumber (*Cucumis sativus* L.) was one of the most widely cultivated facilities of melon-fruit vegetable crops in the world, and the annual cultivated area in China had exceeded one million hectares (Wang B.H. et al., 2017). With the improvement of people's living standard, people had higher and higher requirements on fruit quality. Fruit quality was the combination of external and internal quality (Ballistreri G. et al., 2013), which need to be considered comprehensively and evaluated. Postharvest fruit quality was necessary to accurately simulate based on crop model principle used computer technology and physical and mathematical methods (Sinnathamby S. et al., 2017). The accurate post-harvest quality evaluation model not only had important significance for quantitative evaluation of post-harvest fruit quality, but also provided reference for the research of post-harvest storage of melon-fruit in dynamic environment.

Some scholars had carried out quantitative simulation research on morphological (Voigt F.A. et al., 2004; Hong K. et al., 2013; Xanthopoulou A. et al., 2017), optical (Yang X. et al., 2014), and mechanical properties (Jiang S. et al., 2007). There were also quantitative simulation studies of intrinsic quality elements, including soluble solids, water, and vitamin content (Danilo C.C. et al., 2011). However, there were few reports on whether there was a quantitative relationship between external and internal quality indicators. In production, often affected by the shortage of human and material resources, the fruit needs to be stored for a short time, which the storage environment was unstable (Lukasse and Polderdijk, 2003). Therefore, we need to explore whether unstable environmental factors could be used as intermediate variables to connect two kinds of indicators. Potential application areas for post-harvest quality evolution models are the evaluation of real cold-chains (non-constant temperatures) and the use of these models in model predictive control (MPC) (Lukasse and Polderdijk, 2003). Some scholars used different evaluation criteria and methods to comprehensively evaluate and score fruit quality, such as analytic hierarchy method (Li S.F. et al., 2009), Borda evaluation method, Copeland method, Entropy weight method (Marchant T., 1998; Hu T.T. et al., 2019). However, the optimal value of different quality indicators was inconsistent, which will directly affect the rationality of the score, so it was necessary to divide different types of indicators. Meanwhile, the environmental conditions of storage had an important effect on the quality of post-harvest fruit. The environmental conditions contained temperature,

humidity, light, CO₂ concentration, and ethylene (Tian S.P. et al., 2005; Hübner and Lang, 2012; Hong K. et al., 2013; Kim M.J. et al., 2017; Li Y. et al., 2018), and among which temperature was the key factor. There were many scholars use of accumulated temperature model algorithm had carried on the quantitative simulation to the growth of horticultural crops (Meiyan Y. et al., 2013; Cheng C. et al., 2021). Combined with the crop growth and development characteristics, accumulated temperature principle showed that high temperature had stress but not blocking effect on crop growth and development, while low temperature had blocking effect on crop growth and development. However, for the fruit storage process, both high temperature and low temperature had a stress on the change of fruit quality but do not block (Tsipouridis and Thomidis, 2005), so it was necessary to consider the accumulation of high temperature and low temperature at the same time and simulate the fruit quality.

This study collected two growing season experiment observation data, drove by temperature as cucumber post-harvest quality simulation and evaluation, and standardized the accumulated temperature. According to the classification and weight setting of quality indices, established the quantitative simulation between cucumber appearance and inner quality and environmental elements. A cucumber post-harvest quality evaluation and simulation model based on standardized stress accumulated temperature ($Stan_{SAT}$) was established for the first time.

2. Materials and methods

2.1 Sample preparation

The experiment was conducted in the Agricultural Science and Technology Innovation Base (39°25'48" N, 116°58'12" E, altitude 8 m) in Wuqing, Tianjin from November 2018 to July 2019. The experiment crop variety was "Jinsheng 206" with high productive and low temperature resistance characteristic. The initial state of the physical properties of the fruit before the experiment was relatively consistent. Cucumber samples with basically the same maturity and no surface damage were selected on the day of harvest in each growing season. About 90~180 cucumber samples were sampled once for 3~10 days, and six cucumber samples were taken each time. Three of them were mainly used for the determination of dry and fresh weight, and the other three were mainly used for the determination of soluble solids. The average value of the three

69 measurements was taken. In the two growing seasons conducted 13 sample collections, of which 90 samples were collected
70 on 10 times and 180 samples were collected on 3 times, making a total of 1440 samples.

71 In order to increase the amount of data and improve the representativeness of data, three storage locations under different
72 environmental conditions, including inside solar greenhouse, outside the solar greenhouse and inside living room, were
73 selected during the harvest period of two growing seasons. It can be seen from Fig. 1, during the whole experiment period, the
74 daily temperature inside of greenhouse varied from 12.9°C to 35.4°C, which the temperature change indicated the most stable.
75 The daily temperature outside of greenhouse varied from -6.6°C to 31.9°C, which the temperature change expressed the most
76 unstable. The daily temperature inside of laboratory varied from 9.8°C to 28.4°C, which the temperature change showed
77 relatively stable.

78 *2.2 Crop data*

79 Table 1 listed the determination and calculation methods of post-harvest cucumber fruit quality indicators. Fresh weight
80 was the fruit weight within three hours after sampling. The fruit was first dehydrated at 105°C for 0.5 hour, dried at 80°C to
81 a constant weight, and then weighed. The fully mature fruits were randomly selected, and 3 points were taken (2~3cm from
82 the fruit shoulder, the middle of the fruit, and 2~3cm from the fruit apex). Chroma L, a and b were obtained and the average
83 values were taken. Wash and dry the fruit and juice it in order to measure soluble solid content. All experiments were carried
84 out in triplicate.

85 *2.3 Meteorological data*

86 Inside solar greenhouse air temperature and relative humidity and other meteorological data automatically every 10
87 minutes recorded by DZN1 microclimate observatory (Beijing Huayun Shangtong Technology Co. LTD). The Hobo
88 microclimate observatory (ONSET Corporation, USA) was used to conduct cryptographic auxiliary observation, and the
89 meteorological data such as air temperature and humidity inside and outside the greenhouse and inside the living room were
90 automatically recorded every five minutes.

2.4 Quality evaluation value (QE)

First of all, combined with the determined measurement value of each quality indices, the evaluation value of a single index should be determined, which could be divided into three types. The efficiency index was the higher the value, the better. The cost index was the lower the value, the better. The moderate index was the closer to a fixed value (V_s), the better (Formula (1)). Then, set the weight of each evaluation index (Formula (2)). Finally, the comprehensive evaluation value of fruit storage quality was solved and scored (Formula (3)).

$$FV_{ij} = \begin{cases} \frac{V_{ij}-V_{\min}}{V_{\max}-V_{\min}}, & \text{Efficiency index} \\ \frac{V_{\max}-V_{ij}}{V_{\max}-V_{\min}}, & \text{Cost index} \\ \frac{V_s}{V_s+|V_{ij}-V_s|}, & \text{Moderate index} \end{cases} \quad (1)$$

$$E_{ij} = FV_{ij} * W_{ij} \quad (2)$$

$$TE_i = E_{i1} + E_{i2} + \dots + E_{im} \quad (3)$$

where, V_{ij} was the measured value of index. $V_{\max}$ was the maximum value of index. $V_{\min}$ was the minimum value of index. W_{ij} was the weight of index. TE_i was the comprehensive quality evaluation value index.

2.4 Standardized stress accumulated temperature, $Stan_{SAT}$

In order to quantify the quality changes of fruit storage in non-constant temperature cold storage environment and distinguish it from the mechanism of crop growth and development, stress accumulated temperature (SAT) theory should be considered (Formula (4)). Because of the difference between the index and accumulated temperature, if the accumulated temperature was used to simulate the index directly, the parameters would be too small and had little significance. Therefore, the stress accumulated temperature was standardized in this study, and standardized stress accumulated temperature ($Stan_{SAT}$) was Formula (5).

$$SAT_i = \begin{cases} Tb - Td_i, & Td_i < Tb \\ 0, & Tb \leq Td_i \leq Tm \\ Td_i - Tm, & Td_i > Tm \end{cases} \quad (4)$$

$$Stan_{SAT} = \frac{\sum_{i=0}^n SAT_i}{\sum_{i=0}^N SAT_i} \quad (5)$$

where, $i = 0, 1, \dots, n, \dots, N$, represented the storage days, 0 represented the collection date, n represented the storage days,

d, and N was the maximum storage days for the whole experiment, d. Td_i was the daily average temperature, obtained by instrument observation, °C. Tb was the lower limit temperature of storage, set 10°C. Tm was the upper limit temperature of storage, set 13°C. $\sum_{i=0}^n SAT_i$ was stress accumulated temperature for n days, °C. $\sum_{i=0}^N SAT_i$ was the total stress accumulated temperature in the entire experiment stored, °C.

2.6 Model establishment and verification

Based on Excel 5.0 (Microsoft Software Company, USA), regression analysis and significance analysis were carried out on the data to establish the model, and independent test data were used to test the model. The statistical criteria for the validation of the models mainly include mean ($\bar{X}$), standard deviation (SD), linear regression coefficient (α), intercept (β), decision coefficient (R^2), P(t*) values, root mean square error (RMSE), normalized root mean square error (NRMSE), and compliance index (D) (Cheng C. et al., 2021).

3. Results

3.1 The relationship between quality indicators

According to Fig. 2, the quantitative relationship between morphological indicators showed that there was a very significant linear change relationship between fresh weight (W_f) and fruit volume (V) ($R^2=0.696$), that was, W_f increased with the increase of V at an increase rate of 0.32 g/cm³. There was an extremely significant quadratic function change relationship between fruit density (ρ) and shape index (SI) ($R^2=0.425$), which SI decreased first and then increased with the increase of ρ . As for the quantitative relationship between color indices, there was a very significant logarithmic change relationship between $\tan H$ and darker value (DV) ($R^2=0.634$), that was, $\tan H$ decreases with the increase of DV. There was a very significant linear change relationship between $\tan H$ and color value (CV) ($R^2=0.719$), which CV decreased with the increase of $\tan H$, and the decline rate was 1275. In regard to the quantitative relationship between internal quality indices, there was a very significant linear relationship between fruit water content (FW) and soluble solid content (SSC) ($R^2=0.563$), which the FW decreased with the increase of SSC at a rate of 1.14 %/%.

3.2 Quality and evaluation value simulation model

According to Table 2, the indices were divided into three types according to the most favorable change trend of each quality index with the increase of storage time. Fruit water content, color value, volume, darker value, density, firmness and fresh weight were set as efficiency indices, which the higher the index value, the better the quality. Fruit shape index, $\tan H$ and radian were set as the cost indices, which the lower the index value, the better the quality. Fruit soluble solid content, length and diameter were set as moderate indices, when the index value was maintained at the level at the time of harvest, the quality was more favorable. In this study, the moderate value was set as the index mean when stress accumulated temperature (SAT) was lower than 10°C, and the initial moderate value of fruit soluble solid content, length and radian were 3.5%, 29.9cm and 35.0mm, respectively. According to the classification of the weight of each index, the weight of quality evaluation value of each quality indices was set (Li S.F. et al., 2009; Hu T.T. et al., 2019). The weights of fruit water content, darker value, firmness, fresh weight, shape index, radian and soluble solid content were set as 0.1, and the weights of other quality indices were set as 0.05. Based on the comprehensive evaluation and grading of fruit quality index, the value of comprehensive quality index was obtained. The maximum score was 100.

From Table 3 showed, quality evaluation value (QE), darker value (DV), firmness (F) and density (ρ) with standardized stress accumulated temperature (Stan_{SAT}) all showed a direct linear declining trend, decline rate followed by ρ (150.2 kg/m³)> QE (15.5)> DV (4.6)>F (3.2 N). The CV of cucumber fruit showed an indirect linear decreasing trend with Stan_{SAT} . Color value (CV) was related to Stan_{SAT} , chroma a and b, and the decline rate with Stan_{SAT} was 1736. Both shape index (SI) and $\tan H$ showed an indirect linear upward trend with Stan_{SAT} . SI was associated with Stan_{SAT} and ρ , $\tan H$ was associated with Stan_{SAT} , chroma a and b, along with the increased rate of Stan_{SAT} numerical size in the order by SI (1.3)> $\tan H$ (0.5). The soluble solid content (SSC) of cucumber fruit showed a direct quadratic function change trend of first increasing and then decreasing with Stan_{SAT} , and began to decrease when Stan_{SAT} up to 0.56.

In order to observe the effect of the simulation model, this study used independent experiment data to experiment the quality index and evaluation simulation model based on Stan_{SAT} , and compared the simulated value of each quality index

and evaluation simulation model with the measured value of cucumber fruit. Fig. 3 illustrated that the simulated value and the measured value were close to the 1:1 line, and close to the error range, which the simulated value and the measured value were relatively consistent. The simulation accuracy of standardized accumulative temperature simulation model for simulating different quality indices and evaluation was in order DV (1.63 %)> CV (3.72 %)> SI (4.22 %)> F (4.85 %)> QE (5.49 %)> tan H (5.55 %)> ρ (11.70 %)> SSC (18.35 %). It could be seen that the simulation model of quality and evaluation value based on Stan_{SAT} had high simulation accuracy.

As illustrated by Table 4, showed that for each quality index, based on Stan_{SAT} of cucumber fruits of each quality index (F, ρ , SI, tan H, DV, CV, SSC and QE) simulation model. The normalized root mean square error (NRMSE) between simulation values and the observed values, respectively, were 4.71 %, 11.77 %, 4.20 %, 5.59 %, 1.58 %, 3.61 %, 17.85 % and 5.30 %, and the root mean square error (RMSE) respectively were 0.99 N, 36.15 kg/m³, 0.75, 0.24, 1.39, 449.40, 0.75 % and 3.63. The SSC and ρ simulation model of the simulation precision were high, the rest of the simulation model of the simulation precision were very high. The α value ranged from 0.65 to 1.01, β value ranged from -70.76 to 18.82, and R² ranged from 0.27 to 0.97, indicated a good linear relationship between the simulated value and the measured value. P(t*) was between 0.04 and 0.41, showed that there was no significant difference between the simulated value and the measured value. D value was between 0.70 and 0.99, expressed that the model had a high simulation consistency. The average accuracy of Stan_{SAT} simulation model was 6.83 %, showed that the model of Stan_{SAT} simulation had well simulation effect and practicability.

4. Discussion

Some studies showed that fruit growth was a function of volume (or weight) increase, and calculating fruit volume by geometric principle could accurately fit fruit weight (Arzani K. et al., 1999). The current research had rarely reported whether there was a very significant relationship between SI and ρ calculated based on the principles of physics. The hue, saturation, and value (HSV) color space has been studied as a quantitative analytical parameter for bitonal optical sensors (K. Cantrell et al., 2010). Studies had shown the optical properties of strawberries and their relationship with SSC and FW, and established a partial least squares model for predicting the SSC and FW of strawberry based on the optical parameter spectrum (Xie D.D.

et al., 2021). The results were similar to this study.

For the first time, this study used meteorological environmental factors (stress accumulated temperature) as the driving quantity, and was not limited to simulation under constant temperature or small temperature change conditions, such as incubator storage conditions. During cucumber storage, the suitable temperature range was relatively small, and the temperature range for storing cucumbers at room temperature tends to fluctuate greatly, which was more likely to be higher than the upper biological temperature of storage or lower than the lower biological temperature of storage. Combined with the characteristics of crop growth and development, the effective accumulated temperature and active accumulated temperature showed that high temperature had a stressful but not blocking effect on crop growth and development, while low temperature will block the growth and development of crops. Therefore, these two types of accumulated temperature could simulate crop growth and development well (Bartholomew and Williams, 2013; Liu Y. et al., 2015). But for the cucumber fruit storage process, both high temperature and low temperature had a stressful but not blocking effect on the change of fruit quality (Kim M.J. et al., 2017). Therefore, it was necessary to consider the influence of the accumulation of high and low temperature on the quality of cucumber fruit at the same time, so the stress accumulation method had more production significance. Finally, a Stan_{SAT} -based simulation model of cucumber postharvest quality (appearance shape, fruit color and internal quality) was established. The quality indices were divided into three types, and normalized, evaluated and scored. For fruits that cannot be frozen at constant temperature in time, this model was conducive to quantitatively and more accurately simulating the various quality indicators of cucumber, provided technical support for cucumber post-harvest storage management, and at the same time providing a reference for the research on post-harvest storage of greenhouse fruits.

The model also needed to obtain a large amount of experimental data, and consider the effects of air humidity, CO_2 concentration and light conditions (Tian S.P. et al., 2005; Jones R.B. et al., 2006; Kim M.J. et al., 2017; Li Y. et al., 2018) on the post-harvest quality of cucumber fruits. The corresponding software system could be further developed and nested into the real-time monitoring system to estimate the quality loss (Roque T.S. et al., 2020). Correct and validated the model to improve the universality of the model. When performing quality evaluation values, it was also necessary to consider the

changes of other key internal quality element components (Hong K. et al., 2013). In future research, evaluation methods were diversified to establish a systematic and comprehensive QE simulation model (Marchant T., 1998; Hu T.T. et al., 2019), and provided theoretical and mathematical basis for the classification of fruit quality.

5. Conclusion

QE, DV, F and ρ of cucumber fruit showed a direct linear decline with Stan_{SAT} . CV expressed an indirect linear decrease trend with Stan_{SAT} , which was related to Stan_{SAT} , chroma a and chroma b. SI and $\tan H$ displayed an indirect linear increase trend with Stan_{SAT} , furthermore, SI was related to Stan_{SAT} and ρ , and $\tan H$ was related to Stan_{SAT} , chroma a and chroma b. SSC appeared a direct upward and then downward quadratic function trend with Stan_{SAT} . For each quality index, the NRMSE of each quality index (F, ρ , SI, $\tan H$, DV, CV, SSC and QE) simulation model of cucumber fruit based on Stan_{SAT} were respectively 4.71 %, 11.77 %, 4.20 %, 5.59 %, 1.58 %, 3.61 %, 17.85 % and 5.30 %. The simulation accuracy of SSC and ρ simulation models were high, and the simulation accuracy of the other quality index simulation models were very high. The dynamic changes of various quality indicators could be calculated more accurately through the calculated Stan_{SAT} . The dynamic quality change process of fruit quality simulation could reasonably and timely save the resource consumption in the management process, such as human, material resources and storage resources.

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Figures

Figure 1

Trend of temperature change inside of greenhouse, outside of greenhouse and inside of laboratory.

Figure 2

The quantitative relationship between measured fruit quality indexes, including morphology, color and interior quality

Figure 3

Comparison between the simulated values and the measured values of fruit quality and evaluation value simulation model based on StanSAT

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