

Effects of High Temperature on Pak Choi Quality and Simulation Study Postprint

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Abstract

To investigate the effects of high temperature stress on quality indicators of Chinese cabbage, a split-plot sowing experiment was conducted from October 2015 to May 2016 using the ‘Huawang’ cultivar as test material. Three day/night temperature gradients of 32°C/22°C, 35°C/25°C, and 38°C/28°C were established, with treatment durations of 3 d, 6 d, 9 d, and 12 d, using 25°C/18°C as the control (CK). Two days after the conclusion of each treatment, morphological appearance, SPAD values, dry and fresh weights per plant, and contents of crude fiber, soluble sugar, soluble protein, and vitamin C were measured. Regression models relating leaf rolling rate and yield per unit area to maximum temperature, minimum temperature, mean temperature, and treatment duration were established, and model simulation accuracy was verified using measured data. The results demonstrated that dry weight per plant, fresh weight per plant, leaf fresh weight, leaf length, leaf width, petiole width, SPAD values, and yield per unit area of Chinese cabbage all exhibited decreasing trends with intensifying high temperature stress and prolonged stress duration. With increasing temperature and extended duration, leaf petiole length and leaf rolling rate gradually increased. High temperature stress elevated crude fiber content in Chinese cabbage. Under short-term high temperature stress, soluble sugar, soluble protein, and vitamin C contents showed no significant changes, but gradually decreased with prolonged stress duration and increased stress temperature. Using multiple regression methods, separate models were constructed relating leaf rolling rate and yield per unit area to maximum treatment temperature, minimum treatment temperature, mean treatment temperature, and corresponding treatment duration. Model validation results indicated that the model for leaf rolling rate constructed using minimum treatment temperature and duration of minimum temperature showed optimal simulation performance, with regression standard error and relative error of 7.59% and 0.1894, respectively. The model for yield per unit area constructed using maximum treatment temperature and duration of maximum temperature showed optimal simulation performance, with regres-

sion standard error and relative error of $274.02 \text{ g} \cdot \text{m}^{-2}$ and 0.073%, respectively. The study concluded that with intensified high temperature stress and prolonged stress duration, Chinese cabbage yield decreased, palatability deteriorated, and nutrient content diminished, indicating that high temperature stress degrades Chinese cabbage quality.

Full Text

Abstract

To investigate the effects of high-temperature stress on quality indicators of pakchoi (*Brassica campestris* L. chinensis L.), batch sowing experiments were conducted from October 2015 to May 2016 using the 'Huawang' cultivar. Three temperature gradients were established: $32^{\circ}\text{C}/22^{\circ}\text{C}$, $35^{\circ}\text{C}/25^{\circ}\text{C}$, and $38^{\circ}\text{C}/28^{\circ}\text{C}$ (day/night), with treatment durations of 3, 6, 9, and 12 days, using $25^{\circ}\text{C}/18^{\circ}\text{C}$ as the control (CK). Two days after each treatment concluded, measurements were taken for plant morphology, SPAD values, fresh and dry weights per plant, and contents of crude fiber, soluble sugar, soluble protein, and vitamin C. Regression models were developed to relate leaf rolling rate and yield per unit area to maximum temperature, minimum temperature, mean temperature, and duration of exposure, with model performance validated using measured data. The results demonstrated that dry weight, fresh weight, leaf fresh weight, leaf length, leaf width, petiole width, SPAD values, and yield per unit area all decreased with intensifying high-temperature stress and prolonged exposure duration. Conversely, petiole length within the blade and leaf rolling rate increased with rising temperature and extended duration. High-temperature stress elevated crude fiber content. While short-term high-temperature stress produced no significant changes in soluble sugar, soluble protein, or vitamin C contents, these parameters gradually declined with prolonged stress and higher temperatures. Using multiple regression analysis, models were constructed to relate leaf rolling rate and yield per unit area to maximum processing temperature, minimum processing temperature, mean processing temperature, and corresponding duration. Model validation indicated that the leaf rolling rate model based on minimum processing temperature and duration of minimum temperature performed best, with a root mean square error of 7.59% and relative error of 0.1894. The yield per unit area model based on maximum processing temperature and duration of maximum temperature showed optimal performance, with a root mean square error of $274.02 \text{ g} \cdot \text{m}^{-2}$ and relative error of 0.073%. The study concludes that increasing high-temperature stress intensity and duration reduces pakchoi yield, deteriorates taste, and decreases nutrient content, indicating that high-temperature stress degrades pakchoi quality.

Keywords: High-temperature stress; Pakchoi; Quality; Growth period; Simulation model

Introduction

Pakchoi (*Brassica campestris* L. *chinensis* L.), a member of the Brassicaceae family, is an annual or biennial herbaceous crop cultivated for its green leaves. Also known as non-heading Chinese cabbage, common cabbage, or green vegetable, it originated in China and represents the most popular vegetable in southern China, accounting for 30–40% of total annual vegetable production in large and medium-sized cities along the Yangtze River basin. High-temperature stress is the most common adverse factor affecting pakchoi production in southern regions, where summer heat causes quality deterioration, bitter taste, yellowing, and premature aging, resulting in significantly reduced yield and economic benefits.

Previous research has documented similar effects in other crops. For instance, Wang et al. reported that pepper (*Capsicum annuum* L.) exposed to temperatures above 35°C exhibits lighter leaf color and reduced above-ground and below-ground fresh and dry weights, as well as decreased fruit mass. High temperature also affects leaf coloration, with studies showing that heat stress reduces SPAD values and relative chlorophyll content in rice (*Oryza sativa* L.) during both seedling and heading stages. High-temperature stress increases cell membrane permeability, leading to electrolyte leakage. To prevent excessive electrolyte loss, plants adjust the types and contents of osmotic regulation substances. Soluble sugars and soluble proteins are important osmotic substances in plant cells that accumulate under water stress accompanying high-temperature conditions, altering cell sap concentration and osmotic potential.

Currently, crop quality research primarily focuses on developing ecological models to predict internal quality based on environmental effects on quality indicator accumulation using mathematical regression methods. Stenzel et al. simulated the accumulation of soluble sugars, organic acids, and sugar-acid ratios during citrus development, establishing fruit maturity curves based on deoxy acid quality calculations. Slaughter developed non-destructive methods for assessing mango maturity through color and aroma evaluation. Domestic and international experts have achieved significant progress in greenhouse crop research based on crop growth and development modeling theory, quantitatively describing and predicting crop growth processes and their relationships with environmental factors.

However, few studies have examined the effects of high temperature on pakchoi quality and related simulation models. This study established different high-temperature levels and durations to investigate their impacts on pakchoi yield and quality, constructing regression models relating yield per unit area and leaf rolling rate to daily minimum, maximum, and mean temperatures, and comparing model performance. The research defines a high-temperature stress index and classifies stress levels, providing a theoretical basis for predicting pakchoi yield and appearance quality.

Materials and Methods

Experimental Design

Experiments were conducted in October 2015 at the Nanjing University of Information Science and Technology Venlo controlled greenhouse using artificial climate chambers (TPG-2009, Australian), with six batch sowings performed over the study period. The ‘Huawang’ pakchoi cultivar was grown in nutrient pots (12 cm diameter). When plants reached 8–9 leaves, high-temperature treatments were initiated: 32°C/22°C, 35°C/25°C, and 38°C/28°C (day/night) for durations of 3, 6, 9, and 12 days. Each treatment comprised 16 plants with three replicates, with water and fertilizer maintained within normal ranges. During the experimental period, relative humidity was controlled at 75% and photosynthetically active radiation at $800 \text{ mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. A control group (CK) was maintained under optimal conditions (24°C/18°C day/night). Two days after each treatment concluded, measurements were taken for fresh and dry weights per plant, water content, appearance quality, and nutrient content, with leaf rolling rate and yield per unit area calculated.

Measurement Methods

Leaf Rolling Rate Determination. For each treatment, the maximum width of all leaves was measured when fully expanded and in their natural curled state. Following Qiao et al., the rolling standard was defined as leaf width/projected width after curling -1 , with rolling rate subsequently calculated.

SPAD Measurement. Three pakchoi plants were randomly selected from each treatment, and SPAD values were measured using a SPAD chlorophyll meter.

Leaf Morphology and Plant Fresh/Dry Weight Determination. Fresh weight was determined using destructive sampling. Petioles were separated from leaf blades using a clean blade to measure leaf weight, leaf length and width, petiole length and width, and petiole length within the blade. Samples were then placed in an oven at 105°C for 2 hours for deactivation, followed by drying at 80°C to constant weight for dry weight determination.

Yield per Unit Area Determination. Nutrient pots were arranged at 5 pots per square meter. For each treatment, three random 1 m² areas were selected, plants were washed with distilled water, surface moisture was absorbed, and the mass of pakchoi produced per square meter of projected area was weighed using a 0.001 g precision electronic balance.

Quality Determination. Three plants were randomly selected per treatment as replicates. Crude fiber content was determined using the anthrone colorimetric method, soluble sugar by anthrone colorimetry, vitamin C by the 2,6-dichlorophenol indophenol method, and soluble protein by Coomassie brilliant blue colorimetry.

Stress Level Classification

The high-temperature stress index (IHT) was determined based on leaf rolling rate (A) and yield reduction rate (R). Stress levels were classified as: $IHT < 3$ (mild stress, Level I); $IHT = 3-6$ (moderate stress, Level II); $IHT > 6$ (severe stress, Level III).

Data Processing and Statistical Analysis

Data were organized and analyzed using Microsoft Excel 2010 and SPSS 22.0.

Results

Effects of High Temperature on Plant Fresh and Dry Weights

presents changes in dry weight, fresh weight, and leaf fresh weight under different high-temperature stress treatments. At the same treatment duration, all weight parameters in CK exceeded those in temperature treatments. As temperature increased, dry weight, fresh weight, and leaf fresh weight decreased, with differences from CK widening as duration extended. Under $32^{\circ}\text{C}/22^{\circ}\text{C}$ for 3 days, these parameters showed no significant difference from CK. However, under $38^{\circ}\text{C}/28^{\circ}\text{C}$ for 12 days, dry weight, fresh weight, and leaf fresh weight decreased by 64.23%, 84.32%, and 82.89% compared to CK, respectively.

Effects of High Temperature on Leaf Morphology

shows that leaf length, width, and petiole width were greatest in CK, gradually decreasing with rising temperature and showing greater reductions with extended duration. The $38^{\circ}\text{C}/28^{\circ}\text{C}$ treatment for 12 days produced the most significant effects, reducing leaf length and width by 50.1% and 45.8% compared to CK, respectively. Leaf length showed greater variation and was more sensitive to high-temperature stress. Petiole length began to decrease significantly under $38^{\circ}\text{C}/28^{\circ}\text{C}$ for 9 days, showing reductions of 14.6% and 30.7% at 9 and 12 days compared to CK. After 9 days at $38^{\circ}\text{C}/28^{\circ}\text{C}$, some leaves yellowed and even died, causing petiole length reduction. Within the $25-35^{\circ}\text{C}$ daytime temperature range, petiole length within the blade increased with temperature and showed more pronounced increases with extended duration. Compared to $35^{\circ}\text{C}/25^{\circ}\text{C}$ for 12 days, $38^{\circ}\text{C}/28^{\circ}\text{C}$ for 12 days reduced petiole length by 6.58%.

Effects of High Temperature on Leaf Rolling Rate, SPAD, and Yield per Unit Area

illustrates changes in leaf rolling rate, SPAD, and yield per unit area under different temperatures. Rolling rate increased with temperature and showed greater divergence from CK as duration extended, reaching 100% under $38^{\circ}\text{C}/28^{\circ}\text{C}$ from 9 days onward. SPAD values were consistently highest in CK, decreasing with rising temperature and showing greater differences from CK with prolonged treatment. Compared to CK, SPAD values under $38^{\circ}\text{C}/28^{\circ}\text{C}$ decreased

by 19.95%, 31.09%, 40.28%, and 53.82% at 3, 6, 9, and 12 days, respectively. Yield per unit area decreased with increasing temperature and showed greater divergence from CK with extended stress duration, with reductions of 52.31%, 68.9%, and 86.38% under 32°C/22°C, 35°C/25°C, and 38°C/28°C for 12 days, respectively.

Effects of High Temperature on Pakchoi Quality

shows changes in internal quality under different temperature treatments. Crude fiber content increased with stress intensity and showed greater increases with prolonged duration, with CK values lower than all temperature treatments. The 38°C/28°C treatment showed the most significant difference, increasing crude fiber content by 14.47%, 21.51%, 22.88%, and 18.75% at 3, 6, 9, and 12 days compared to CK.

Soluble sugar content was lowest under 38°C/28°C at all durations. At 3, 6, and 9 days, soluble sugar content showed an initial increase followed by a decrease with rising stress temperature, with 38°C/28°C showing significant differences from CK (reductions of 0.16%, 7.79%, and 32.69%). At 12 days, soluble sugar content decreased with increasing temperature, with 38°C/28°C showing a significant reduction of 61.33% compared to CK.

Vitamin C content decreased with increasing stress temperature, with CK values highest at all treatment durations. Changes were significant at 9 and 12 days, with 38°C/28°C showing the most pronounced differences (reductions of 11.54%, 10.97%, 32.22%, and 60.84% at 3, 6, 9, and 12 days, respectively).

Soluble protein content showed significant changes with temperature stress. At 3 days, content increased with temperature (increases of 2.83%, 4.92%, and 5.63% under 32°C/22°C, 35°C/25°C, and 38°C/28°C, respectively). At 6, 9, and 12 days, content decreased with temperature, showing reductions of 9.13%, 41.94%, and 80.52% under 38°C/28°C compared to CK.

Relationship Between Leaf Rolling Rate, Yield, and Temperature/Duration

Using multiple regression analysis with data from the first three experimental batches, models were constructed relating leaf rolling rate and yield per unit area to maximum processing temperature (T_{max}), minimum processing temperature (T_{min}), mean processing temperature (T_{mean}), and treatment duration (t). The remaining three batches were used for model validation to identify optimal models, with fitting equations and validation results shown in .

The model based on minimum processing temperature and duration performed best for leaf rolling rate, with the smallest standard error (7.59%) and relative error (0.1894). The model using maximum processing temperature and duration performed worst, with errors 1.23 times greater. The mean temperature model showed intermediate performance.

For yield per unit area, the model based on maximum processing temperature and duration performed best, with the smallest standard error ($274.02 \text{ g} \cdot \text{m}^{-2}$) and relative error (0.073). The minimum temperature model performed poorest, with errors 1.6 times greater. The mean temperature model showed intermediate performance.

High-Temperature Stress Level Classification

High temperature affects pakchoi quality and yield. Since leaf rolling rate (A) is the primary indicator of appearance quality and yield reduction rate (R) evaluates stress impact, the high-temperature stress index was defined using these parameters to classify damage levels. shows that yield reduction rate increased with temperature and stress duration. From day 9 onward, all temperature treatments reached Level II or III stress (moderate to severe), with yield reductions of 44.54%, 47.42%, 47.85%, 52.31%, 68.90%, and 86.38%. The stress index exceeded 5 (except $32^{\circ}\text{C}/22^{\circ}\text{C}$ at 9 days). Overall, Level II stress was most common.

Discussion and Conclusion

This study found that leaf length, width, plant fresh and dry weights, and leaf fresh weight decreased with increasing temperature and prolonged duration, consistent with previous reports. Under high-temperature stress, reduced leaf water uptake causes transpiration to exceed absorption, leading to wilting. Continued stress results in leaf scorching, extended growth cycles, elongated stems, narrowed and thinned leaves, premature senescence, and rapid quality deterioration. SPAD values decreased with rising temperature and extended duration, aligning with Tao et al.'s findings that SPAD values in spring maize varieties decline with stress duration, with greater reductions under longer stress.

Plants regulate osmotic substances to adapt to stress. Soluble sugars and proteins are primary osmotic regulators. High temperature accelerates protein decomposition, with slower rates in heat-tolerant varieties. This study found that short-term high-temperature stress increased soluble protein content, possibly due to heat shock protein synthesis participating in heat resistance responses. However, as stress intensified, soluble protein content decreased, likely because high temperature impaired membrane system function, reducing protein release from membranes or other bound forms. The consistent, regulated decrease compared to CK demonstrates the close relationship between soluble protein content and stress resistance.

Soluble sugars regulate intracellular osmotic balance and maintain protein hydration to prevent protoplasm dehydration. The trend of soluble sugar content under high-temperature stress was similar to soluble protein, with initial increases under short-term stress followed by decreases with prolonged duration and higher temperatures. This pattern aligns with Li et al.'s research on eggplant, where soluble sugar content increased significantly during early heat stress

(possibly due to starch decomposition) but decreased markedly later (likely due to impaired photosynthetic capacity reducing photosynthates).

This study defined a high-temperature stress index and classification system based on yield and leaf rolling rate. Stress reached Level II or higher from day 9 onward. Leaf rolling rate was more sensitive to high-temperature stress than yield reduction, exceeding 40% under 38°C/28°C at all durations.

In conclusion, high-temperature stress degrades pakchoi appearance and nutritional quality while causing severe yield losses under intensified stress. The models based on minimum temperature/duration for leaf rolling rate and maximum temperature/duration for yield per unit area performed optimally, providing decision-making support for cucumber production management. However, this study did not differentiate genotypic responses and had limited temperature treatments. Further research should investigate effects of different high-temperature gradients on various heat-tolerant pakchoi cultivars.

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