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Study on the Effect of Electromagnetic Pulse Combined with Low-Temperature Preservation Technology on Storage Quality of Cucumber

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Abstract. Aiming at the limitation that traditional low-temperature preservation of fruits and vegetables only relies on temperature to inhibit metabolism and can hardly inactivate endogenous enzymes and suppress the proliferation of surface microorganisms effectively, a pulsed magnetic field generation system was independently built to establish an experimental platform for synergistic preservation coupled with electromagnetic pulse and low temperature. The whole device generates pulsed current through rectification, full-bridge inverter and capacitor charge-discharge drive circuits, which is fed into frame coils to produce transient pulsed magnetic fields. Taking cucumber as test samples, comparative storage experiments were carried out to explore the preservation mechanism under the combined condition of pulsed magnetic field and low temperature. The test results showed that under 5-day storage at room temperature, low temperature, and low temperature combined with pulsed magnetic field, the pulsed magnetic field of 2.02mT and 50 Hz could further reduce the weight-loss rate and comprehensive pericarp color difference of cucumbers on the basis of low-temperature storage. Meanwhile, it partially alleviated oxidative stress damage induced by low temperature via up-regulating catalase activity. The results verify the preservation potential of pulsed magnetic field as a non-thermal physical treatment, and provide experimental support for the optimization of pulsed magnetic field generating equipment and its application in green preservation of agricultural products.

Keywords: pulsed magnetic field; low-temperature storage; physical-field coupling; non-thermal physical preservation; weight-loss rate.

1. Introduction

Cucumber is a widely-consumed fresh fruit and vegetable in China and occupies an important position in the fresh-food circulation system. Nevertheless, cucumber features high water content and vigorous respiratory metabolism, and is a typical chilling-sensitive fruit and vegetable. Postharvest water loss, wilting and chlorosis easily occur and lead to massive post-harvest losses. Hence, postharvest storage and preservation technologies for cucumbers are key research directions in the field of agricultural-product cold chains[1]. Low-temperature storage is the most widely adopted preservation method for postharvest fruits and vegetables. However, when the storage temperature falls below the chilling-injury threshold, cell-membrane damage and membrane lipid peroxidation will be triggered, accompanied by chilling-injury symptoms. Accordingly, single low-temperature preservation has obvious limitations[2].

Electromagnetic-pulse preservation is an innovative non-thermal physical preservation technology. It has become a research hotspot in recent years owing to its advantages including zero chemical residue and fast treatment. Transient strong magnetic fields act on biological tissues to modify cell-membrane permeability and inhibit microbial proliferation without obvious thermal damage, making it a highly promising novel preservation approach[3]. The combined application of electromagnetic pulse and low temperature can realize superposition effects of two preservation strategies. Low temperature slows down basal metabolism, while pulsed magnetic fields further delay cucumber senescence. Such combined treatment exhibits better application potential compared with single preservation modes[4]. In this paper, an experimental platform for synergistic preservation with

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electromagnetic pulse and low temperature was constructed. Fresh cucumbers were selected as research objects to investigate influences of this composite preservation scheme on cucumber storage quality, so as to provide experimental evidence for green physical preservation technologies for fruits and vegetables.

Current research on pulsed magnetic field preservation mostly focus on process performance tests, while studies on equipment aspects such as pulsed magnetic field generating circuits and coil magnetic field construction are relatively insufficient[5]. Starting from the construction of a pulsed magnetic field generation system, this paper designed and implemented a frame-type pulsed coil device that can be placed inside a low-temperature chamber, realizing stable output of pulsed magnetic fields under low-temperature conditions. Comparative storage experiments were performed with cucumbers as test samples. Special attention was paid to exploring biological effects of pulsed magnetic fields and verifying the synergistic preservation performance of pulsed magnetic field combined with low temperature, which offers a basis for structural optimization and parameter adjustment of pulsed magnetic field generating devices.

In this experiment, six cucumbers of the same batch and consistent maturity were used as materials. Three groups were set: room-temperature group (RT, 20 °C), low-temperature group (LT, 1.2 °C), and low-temperature plus pulsed magnetic field group (MF, 1.2 °C with 2.02 mT, 50 Hz pulsed train). Each group contained two cucumbers as biological replicates, and the storage period lasted for 5 days. Observation was conducted on appearance quality, water loss and pericarp color change. Physiological indicators including fruit-flesh firmness and antioxidant-enzyme activity were measured[6]. Combined with existing theories on biological effects of pulsed magnetic fields, the synergistic preservation mechanism of pulsed magnetic field and low temperature was analyzed. Regulatory rules of pulsed magnetic fields on storage quality and oxidative-stress responses of chilling-sensitive cucumbers were revealed, providing experimental data and theoretical references for equipment and process-parameter optimization of pulsed magnetic field physical preservation.

2. Test System and Scheme Design

2.1. Generation Principle of Pulsed Magnetic Field

A pulsed magnetic field generation system generally consists of an energy-storage module, a power-switch unit and excitation coils. During operation, mains electricity is rectified into direct current to charge energy-storage capacitors. After control signals trigger the conduction of power switches, energy-storage capacitors instantaneously release large current to excitation coils. According to the Biot-Savart law, transient pulsed current in coils generates pulsed magnetic fields inside the treatment cavity[7]. Adjustable control of magnetic-field magnetic-induction intensity can be realized by adjusting energy-storage voltage, pulse repetition frequency and pulse width. In this paper, a pulse generator discharges instantaneously to coils fixed around a gray PVC skeleton, producing transient high-intensity magnetic fields based on Ampère's law. A multi-dimensional Helmholtz coil array forms a three-dimensional coil system, which achieves highly uniform magnetic-field coverage in the central region where samples are placed. Pulsed magnetic field environments inside the low-temperature chamber can be formed by controlling the on-off of pulsed current.

The core of non-thermal preservation by pulsed magnetic fields lies in electromagnetic-induction effects of cells. External pulsed magnetic fields induce internal induced electric fields inside fruit-vegetable cells. When induced electric fields reach the threshold, reversible electroporation occurs on cell membranes, modifying transmembrane potential and membrane permeability, and further regulating cellular respiratory metabolism and intracellular signal transduction. Under appropriate parameters, this effect will not result in cell necrosis[8]. Meanwhile, pulsed magnetic fields can alter spatial conformations of enzyme proteins[9]. By improving catalase activity, cell-membrane integrity is enhanced and decay rates of fruits and vegetables are greatly reduced. Magnetic-field treatment also improves the capacity of tissues to eliminate reactive oxygen species and mitigates oxidative

damage to cell membranes induced by low-temperature stress. In addition, pulsed magnetic fields exert microbicidal effects and suppress proliferation of spoilage and pathogenic microorganisms on fruit-vegetable surfaces, thus extending shelf life.

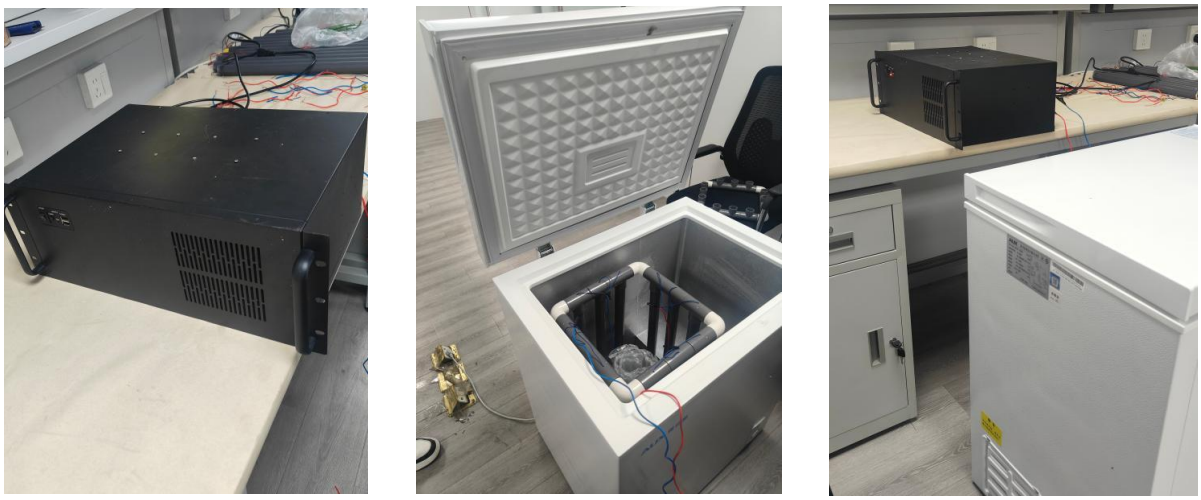
Traditional low-temperature storage mainly reduces environmental temperature to decrease rates of fruit-vegetable respiration and various biochemical reactions. Nevertheless, it cannot prevent membrane lipid peroxidation and reactive-oxygen-species burst of chilling-sensitive fruits and vegetables under sub-critical low temperatures[10]. When pulsed magnetic fields are coupled with low temperature, low-temperature conditions inhibit overall metabolic levels, while pulsed magnetic fields regulate the intracellular antioxidant system and alleviate oxidative damage at the cellular level, forming synergistic preservation effects[11]. Compared with single low-temperature treatment, coupled treatment triggers more complex physiological responses, which requires quantitative research via comparative tests.

2.2. Core Objectives of the Test

Primary objectives of this test are to build an experimental platform for synergistic preservation with electromagnetic pulse and low temperature, and carry out comparative storage experiments on cucumbers. Differences in weight-loss rate, pericarp chromaticity, fruit-flesh firmness, catalase activity and cell-membrane permeability among cucumbers in the room-temperature group, low-temperature group and low-temperature plus pulsed magnetic field group were quantitatively characterized[12]. Original physiological detection data under multiple working conditions were synchronously acquired to provide comparative evidence for theoretical verification of biological effects of pulsed magnetic fields and calibration of preservation-process parameters. Ultimately, influences of pulsed magnetic field parameters on cucumber storage quality were analyzed to offer direct experimental support for optimization of non-thermal physical preservation processes for fruits and vegetables.

2.3. Test System and Storage Conditions

A low-temperature refrigerator served as the constant-temperature carrier. Frame-type coils were fixed in the inner cavity of the low-temperature refrigerator, and connected to an external pulsed magnetic field generator via red and blue leads. Cucumber samples were placed in the central area of the coil cavity to ensure exposure to uniform pulsed magnetic fields, as shown in Figure 1.



(a) Pulsed magnetic field generator (b) Frame-type coil and refrigerator (c) Physical overview of the test system

Figure 1. Layout diagram of electromagnetic pulse and low-temperature preservation device

The power supply for the pulsed magnetic field generation system is composed of three-level hardware circuits: drive power-supply circuit, drive amplification circuit and full-bridge inverter circuit, realizing energy conversion from 220 V mains electricity to adjustable pulsed magnetic fields. The internal circuit of the pulsed magnetic field generator is shown in Figure 2.

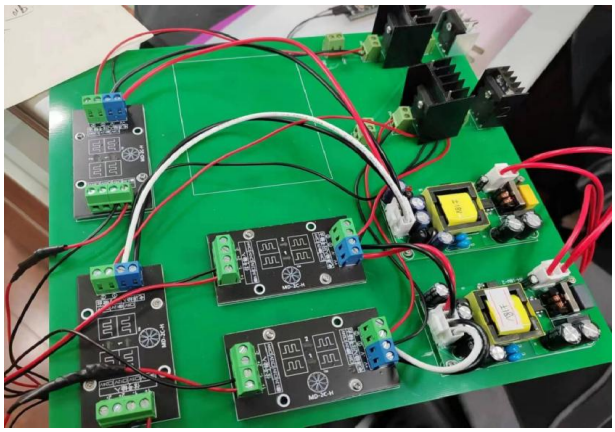


Figure 2. Internal circuit of the pulsed magnetic field generator

As the power source of the whole system, the drive power-supply circuit performs step-down, rectification, filtering and voltage-stabilization on 220 V mains electricity, outputting stable low-voltage direct current for power devices and control chips on circuit boards. The drive amplification circuit receives weak control pulse signals output by single-chip microcomputers, and amplifies these weak electric signals into strong drive signals capable of driving power switching tubes via drive chips, solving insufficient driving capacity of single-chip-microcomputer pins. The core power-conversion unit is the full-bridge inverter circuit. For power switching tubes, a topological scheme of parallel multi-tubes on a single circuit board and series connection of four-face modules was adopted: three power tubes are connected in parallel on one circuit board to increase current-carrying capacity of a single branch and reduce current stress of individual tubes; four tube-face modules are connected in series to improve overall voltage-withstand rating. Red wires are connected to positive poles and blue wires to negative poles for unified module polarity. Under control of output signals from the drive amplification circuit, the full-bridge inverter circuit converts direct current output by the drive power-supply circuit into high-frequency pulsed alternating current. Single-chip microcomputers can adjust pulse frequency and duty ratio in real time, outputting pulsed current with adjustable amplitude and frequency to excitation coils and finally exciting transient pulsed magnetic fields inside coil cavities.

Six long cucumbers harvested from the same batch, with intact appearance, no disease spots or mechanical injuries and basically consistent maturity, were selected as test materials. Single-fruit weight ranged from 186.47 g to 215.52 g, length from 298.8 mm to 317.9 mm, and maximum transverse diameter from 30.1 mm to 31.5 mm. They were divided into three groups for storage comparison. Temperature and relative humidity represent mean values and measured ranges continuously recorded at 1-minute intervals during storage. Temperatures of the three groups remained within their respective set ranges during the recording period. The grouping and treatment parameters are listed in Table 1. Control groups were stored at room temperature and corresponding low-temperature environments without pulsed magnetic field application. The experimental group was placed in the uniform-magnetic-field zone at the center of the coil cavity and treated with pulsed magnetic fields generated by this system.

Table 1. Experimental groups and treatment conditions

Group	Sample ID	Storage temperature/°C	Relative humidity	Pulsed magnetic field	Sample quantity
RT	RT-1, RT-2	20(19.1-20.9)	67.0%	None	2
LT	LT-1, LT-2	1.20(1.1-1.3)	85.0%	None	2
MF	MF-1, MF-2	1.22(1.1-1.4)	85.0%	2.02mT,50Hz pulsed train	2

The storage cycle was 5 days. Sample status was monitored, and test indicators included sensory changes, weight-loss rate, pericarp chromaticity and appearance, fruit-flesh firmness, catalase activity and cell-membrane permeability. Quality differences among samples from three groups were compared to evaluate preservation performance of pulsed magnetic fields[13]. Output parameters of

the pulsed-power main unit were recorded simultaneously, and magnetic-field-distribution characteristics inside coil cavities were monitored to assess working stability of the pulsed magnetic field device.

3. Analysis of Storage Quality and Test-indicator Results

3.1. Results of Storage Test Indicators

All six cucumbers were dark-green and plump without obvious differences on day 0. With prolonged storage time, appearance divergence emerged among the three groups. The appearance sequence of six cucumber fruits during storage is presented in Figure 3.

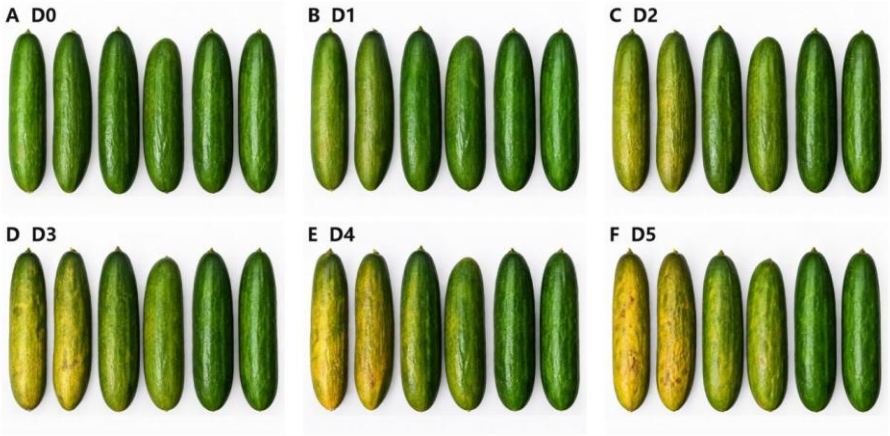
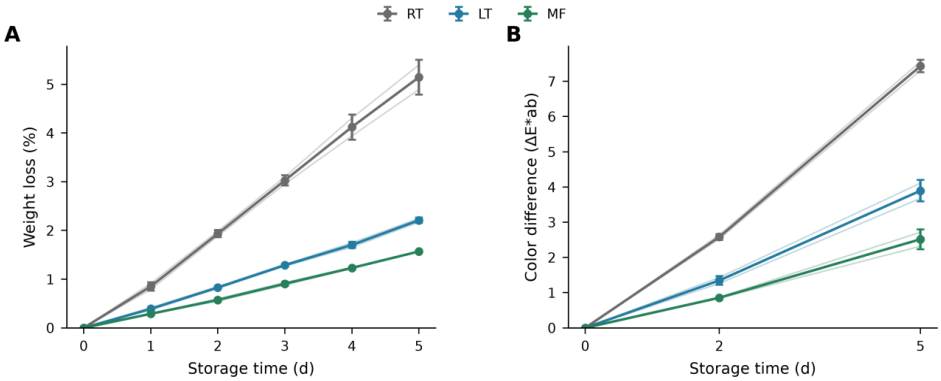


Figure 3. Appearance sequence of six cucumber fruits during storage
A-F represent D0-D5; from left to right: RT-1, RT-2, LT-1, LT-2, MF-1, MF-2

The room-temperature group exhibited weakened luster and partial chlorosis starting from day 2, and obvious pericarp yellowing together with slight wilting at both ends on day 5. The low-temperature group showed milder chlorosis; the middle part remained green but darkened on day 5. The low-temperature plus pulsed magnetic field group had the slightest color change and maintained favorable greenness and plumpness on day 5.

The weight-loss rate kept rising throughout storage. Differences among three groups appeared from day 1 and expanded day by day. The variations of weight-loss rate and comprehensive color difference with storage time are shown in Figure 4.



(a) Weight-loss rate (b) Comprehensive color difference

Figure 4. Changes of weight-loss rate and comprehensive color difference with storage time

On day 5, the weight-loss rate of the room-temperature group was 5.15 % ± 0.36 %, that of the low-temperature group decreased to 2.21 % ± 0.05 %, and that of the low-temperature plus pulsed magnetic field group further dropped to 1.57 % ± 0.02 %. Overall differences among three groups were significant. Pairwise comparison revealed that compared with the low-temperature group, the weight-loss rate of the low-temperature plus pulsed magnetic field group decreased by 0.641

percentage points, with a relative reduction of 29.0 %. The daily mean weight-loss rates of each group are summarized in Table 2.

Table 2. Daily mean weight-loss rates of each group

Storage time	RT/ %	LT/ %	MF/ %
D0	0	0	0
D1	0.85	0.39	0.29
D2	1.93	0.83	0.57
D3	3.03	1.29	0.91
D4	4.12	1.70	1.23
D5	5.15	2.21	1.57

On day 5, comprehensive color-difference values of the three groups were 7.43 ± 0.18 (RT), 3.89 ± 0.30 (LT) and 2.52 ± 0.28 (MF), with significant overall differences. Compared with the low-temperature group, the comprehensive color difference of the low-temperature plus pulsed magnetic field group decreased by 1.379, corresponding to a relative reduction of 35.4 %. Pericarp chromaticity components and comprehensive color difference on day 5 are listed in Table 3.

Table 3. Pericarp chromaticity components and comprehensive color difference on day 5

Indicator	RT	LT	MF
Lightness	33.67±1.13	34.79±0.16	35.60±0.33
Red-green chromaticity index	−7.09±0.29	−8.45±1.06	−10.27±0.67
Yellow-blue chromaticity index	21.99±0.02	19.82±0.36	19.04±0.78
Comprehensive color difference (relative to D0)	7.43±0.18	3.89±0.30	2.52±0.28

Fruit-flesh firmness values on day 5 were 6.62 ± 0.13 N (RT), 8.17 ± 0.02 N (LT) and 8.92 ± 0.69 N (MF), presenting significant overall differences. Catalase activity values were 261.6 ± 10.2 μmol/(min·g FW) (RT), 343.6 ± 5.0 μmol/(min·g FW) (LT) and 407.4 ± 5.5 μmol/(min·g FW) (MF), also with significant overall differences. Catalase activity of the MF group increased by 18.6 % relative to the LT group. Fruit-flesh firmness and catalase activity on day 5 are given in Table 4.

Table 4. Fruit-flesh firmness and catalase activity on day 5

Indicator	Unit	RT	LT	MF
Flesh firmness	N	6.62±0.13	8.17±0.02	8.92±0.69
Catalase activity	μmol/(min·g FW)	261.6±10.2	343.6±5.0	407.4±5.5

3.2. Effects of Low-Temperature Storage on Quality of Cucumbers

Low-temperature storage significantly delayed quality deterioration of cucumbers. Compared with the room-temperature group, the low-temperature group exhibited obvious preservation effects in multiple dimensions including appearance, water loss, color, firmness and antioxidant-enzyme performance. After 5-day storage, the weight-loss rate of the low-temperature group was $2.21\ \% \pm 0.05\ \%$, reduced by 57.1 % compared with $5.15\ \% \pm 0.36\ \%$ of the room-temperature group. Its pericarp comprehensive color difference dropped to 3.89 ± 0.30, decreasing by 47.6 % versus 7.43 ± 0.18 for the room-temperature group. Fruit-flesh firmness reached 8.17 ± 0.02 N, increased by 23.4 % compared with 6.62 ± 0.13 N of the room-temperature group. Catalase activity was 343.6 ± 5.0 μmol/(min·g FW), 31.4 % higher than that of the room-temperature group. Physiologically, low-temperature environments directly reduce transpiration and respiratory metabolic rates of cucumber fruits, mitigating water loss and consumption of internal nutrients. Meanwhile, they suppress reaction rates of enzymes related to chlorophyll degradation and cell-wall polysaccharide hydrolysis, delaying pericarp yellowing and fruit-flesh softening. This is consistent with general rules for low-temperature storage of chilling-sensitive fruits and vegetables[14].

Nevertheless, single low-temperature preservation still has inherent limitations. The 1.2 °C adopted in this test was below the chilling-injury threshold of cucumbers. Although appearance quality was

well maintained, low temperature can only decelerate overall biochemical reaction rates, instead of regulating the endogenous antioxidant system of fruits and vegetables at the cellular level. It cannot resist oxidative stress induced by sub-critical low temperatures, and massive accumulation of intracellular reactive oxygen species will trigger senescence-related damage processes. The self-built experimental platform for synergistic preservation with electromagnetic pulse and low temperature in this study inhibits macro-metabolism via low-temperature conditions, and superimposes non-thermal pulsed magnetic fields to regulate intracellular physiological responses, making up for shortcomings of single low-temperature preservation. Low-temperature and magnetic-field conditions can continuously act on cucumber fruits simultaneously, providing a hardware foundation for exploring their synergistic effects.

3.3. Synergistic Preservation Effects of Coupled Electromagnetic Pulse and Low Temperature

Based on the self-built test system, the experimental group was treated with 2.02 mT, 50 Hz pulsed train under 1.2 °C low-temperature conditions. Cucumber fruits were placed in this uniform magnetic-field zone for full and homogeneous magnetic-field exposure. Compared with the low-temperature group, superimposition of pulsed magnetic fields generated further gains in appearance quality, water-loss inhibition and color protection, and exerted significant regulatory effects on the antioxidant-enzyme system.

On day 5 of storage, the weight-loss rate of the low-temperature plus pulsed magnetic field group was 1.57 % ± 0.02 %, 29.0 % lower than that of the low-temperature group (2.21 % ± 0.05 %). Its comprehensive color difference decreased to 2.52 ± 0.28, with a 35.4 % reduction relative to the low-temperature group. Catalase activity rose to 407.4 ± 5.5 μmol/(min·g FW), 18.6 % higher than that of the low-temperature group. Fruit-flesh firmness of the MF group reached 8.92 ± 0.69 N, 9.2 % higher than that of the LT group.

Under test conditions in this study, the pulsed magnetic field of 2.02 mT and 50 Hz produced remarkable synergistic preservation gains on the basis of low-temperature storage. It further inhibited postharvest water loss and pericarp chlorosis-yellowing of cucumbers, significantly up-regulated catalase activity to enhance antioxidant capacity, and exerted positive effects on maintaining fruit-flesh firmness. Transient induced electric fields generated by pulsed magnetic fields inside coils modulate outward water-diffusion flux of epidermal cells and reduce transpiration water-loss rates, resulting in lower weight-loss rates for the low-temperature plus pulsed magnetic field group. Daily weight-loss data indicate that advantages in water-loss control of the MF group appeared as early as day 1 and expanded continuously with storage time, which demonstrates that magnetic-field-mediated regulation on water loss is a persistent effect rather than a one-off instantaneous treatment.

In addition, massive reactive-oxygen species such as hydrogen peroxide accumulate in cucumbers under cold-stress at 1.2 °C, which acts as a core inducement for fruit senescence and damage. Catalase serves as a key antioxidant enzyme for scavenging hydrogen peroxide. Low temperature can only slow down overall metabolic rates and cannot prevent reactive-oxygen-species burst. As a cell-level stimulus signal, pulsed magnetic fields induce up-regulation of cucumber antioxidant defense systems, improve catalase activity, accelerate elimination of hydrogen peroxide generated under low-temperature stress and mitigate oxidative damage.

4. Conclusions

An experimental platform for synergistic preservation with electromagnetic pulse and low temperature was constructed in this paper. A storage system coupling 2.02 mT, 50 Hz pulsed magnetic field and 1.2 °C low temperature was established. Taking cucumbers as test materials, quality variations within the 5-day storage period were compared among three conditions: room-temperature storage, single low-temperature storage, and low-temperature storage combined with pulsed magnetic fields.

Test results show that 1.2 °C low-temperature storage effectively alleviates postharvest water loss and yellowing of cucumbers, and maintains fruit-flesh firmness and antioxidant levels. Further superimposition of 2.02 mT, 50 Hz pulsed magnetic fields achieves favorable synergistic preservation performance. On day 5 of storage, compared with the single low-temperature group, combined treatment with pulsed magnetic field and low temperature reduced cucumber weight-loss rate by 29.0 %, lowered pericarp comprehensive color difference by 35.4 %, and increased catalase activity by 18.6 %, thus better preserving green appearance and plump texture of fruits. By up-regulating catalase activity, pulsed magnetic fields help mitigate oxidative-stress damage of chilling-sensitive cucumbers during low-temperature storage.

This study confirms the application potential of non-thermal physical treatment using pulsed magnetic fields in cucumber low-temperature preservation. Limited by sample size in this experiment, relevant action mechanisms remain speculative. Future work will expand sample scales, supplement detections of physiological indicators such as reactive-oxygen-species metabolism and cell-wall-degrading enzymes, and further reveal regulatory mechanisms of pulsed magnetic fields on chilling-sensitive fruits and vegetables. It will provide theoretical support for process-parameter optimization of pulsed magnetic field preservation equipment and practical preservation applications for agricultural products.

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