# RESEARCH ON THE RHEOLOGICAL PROPERTIES OF SANBAI MELON JUICE TREATED WITH HIGH-VOLTAGE PULSED ELECTRIC FIELD PRETREATMENT
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# *高压脉冲电场预处理三白瓜汁流变性研究*

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**ABSTRACT**
*To clarify the impact of high-voltage pulsed electric field (HPEF) pretreatment on the rheological properties of Sanbai melon juice, experiments were conducted using two different juice concentrations. The study examined the effects of HPEF pretreatment on steady-state shear viscosity, the influence of temperature on steady-state shear viscosity, and the dynamic viscoelastic properties of the juice. The results showed that the shear stress increased with increasing shear rate, indicating that the juice exhibited pseudoplastic behavior. As temperature increased, the viscosity of the juice decreased gradually. Within the angular frequency range of 0.1–100 rad/s, both the storage modulus and the loss modulus increased with increasing angular frequency. Furthermore, the viscoelastic properties of the juice improved as the HPEF pretreatment intensity increased, with the elastic characteristics becoming more dominant than the viscous characteristics. These findings provide a theoretical basis for the processing and utilization of Sanbai melon juice.*

**摘要**
*为了解高压脉冲电场预处理（HPEF）对三白瓜汁流变特性的影响，本文对两种不同浓度的三白瓜汁进行试验，研究高压脉冲电场预处理对三白瓜汁稳态剪切黏度的影响、温度对三白瓜汁稳态剪切黏度的影响以及三白瓜汁动态黏弹性能研究。结果表明：三白瓜汁的剪切应力随着剪切速率的增加而增大，为假塑性流体；随着温度的升高，三白瓜汁所表现出的黏度值逐渐降低；在 0.1-100rad/s 的角频率范围内，果蔬汁的储能模量、损耗模量均随着角频率的增加而增大，随着高压脉冲电场预处理参数的增大，果蔬汁的黏弹性能参数均呈上升趋势，弹性特征均大于黏性特征。研究结果可为三白瓜汁果汁的加工利用提供理论依据。*

## INTRODUCTION
The global fruit and vegetable juice industry is booming and is expected to reach a revenue of USD 47.2 billion by 2026, growing at a compound annual growth rate of 5.2% *(Brito et al., 2024)*. Since fruits and vegetables are affected by seasonality and have a short shelf life, it is difficult to meet the demand for fruits and vegetables throughout all seasons. Therefore, for modern consumers, dietary choices are no longer just about solving the basic needs of food and clothing but also about nutritional value and a high standard of organoleptic quality to better promote human health. Against this backdrop, fruit and vegetable juices have become an ideal choice to meet people's needs. Sanbai melon is a traditional specialty of Wanrong County, Yuncheng City, Shanxi Province, and is a type of melon with a long history of cultivation in China. It is named "Sanbai" for its jade-like skin, fat-like flesh, and pearl-like seeds, and it contains abundant nutrients, including various mineral salts and vitamins. It also has good medicinal value, which can effectively clear heat and detoxify, and has a positive effect on the treatment of conditions such as nephritis and diabetes *(Wang, 2015)*. Despite its obvious nutritional value and high sensory quality, which contribute to promoting human health, the Sanbai melon has distinct seasonality, being available only from July or August (the same year) until January (the following year). Its storage conditions are very demanding; the temperature and humidity are extremely difficult to control.

Generally, it is challenging to preserve Sanbai melon intact until the Spring Festival, indicating a long gap period *(Li et al., 2020)*. To meet the demand for Sanbai melon, the development of Sanbai melon juice holds great potential value.

To ensure that Sanbai melon juice maintains its nutritional value while also possessing a pleasant taste and ease of preservation, rheological properties have become a crucial mechanical characteristic in fruit juice development. In the domain of fruit juice processing technology and product quality control research, this characteristic is of paramount importance. Studies on the rheological behavior of *Pyrus ussuriensis Maxim* juice *(Zhou et al., 2021)* and the influence of varying temperature conditions on its viscosity have demonstrated that *Pyrus ussuriensis Maxim* juice exhibits pseudoplastic behavior. Research into the viscosity trends of cactus juice *(Hou et al., 2018)* across different mass concentrations and temperatures, utilizing instruments such as a rotational viscometer and a rheometer, has confirmed that cactus juice is also a pseudoplastic fluid. Such fluids are commonly described by a power-law model to represent their rheological properties *(Wu et al., 2016)*. Experimental evidence indicates that liquid materials are substantially influenced by temperature, and their rheological properties undergo significant changes during processing under different temperature conditions *(Yuan et al., 2024)*.

The High-voltage Pulsed Electric Field pretreatment technology, an innovative non-thermal processing method, has garnered significant attention in the field of modern food processing due to its ability to substantially maintain the functional properties and nutritional composition of food (*Gargi, 2023; Ika et al., 2025; Mustafa et al., 2025*). This not only meets the dual demands of consumers for food safety and nutrition but also ensures the superiority of organoleptic quality *(Salinas et al.,2024; He 2022; Hélorie et al.,2025)*. Research on the application of this technology in food sterilization indicates that HPEF pretreatment technology is characterized by highly effective sterilization, low energy consumption, and high efficiency *(Yildiz et al., 2020; Ensieh et al., 2025)*. The primary mechanism of action is cell electroporation, where the HPEF induces a strong voltage effect on microbial cell membranes, causing membrane rupture, intracellular nutrient leakage, and ultimately microbial inactivation *(Zheng et al., 2023; Xiong et al., 2022; Jiang, 2018; Gabriela et al., 2025)*. For the specific product of Sanbai melon juice, studying the effects on its rheological characteristics under HPEF pretreatment is of significant importance. Research in this area could enhance the product's suitability for practical application in production, thereby improving its industrial viability and consumer appeal *(Li et al., 2023)*.

To date, international research exploring the effects of high-voltage pulsed electric field (HPEF) pretreatment on the rheological properties of Sanbai melon juice remains relatively limited in scope and depth *(Kobus et al., 2015; Ma et al., 2023)*. Therefore, this study aims to explore the effects of high-voltage pulsed electric field pretreatment on the rheological properties of Sanbai melon juice and the specific effects of temperature on its viscosity, providing theoretical analysis and data support for the performance of Sanbai melon juice through a detailed study of rheological properties and a systematic exploration of the temperature-viscosity relationship. This will provide a scientific basis for the innovation and quality monitoring of Sanbai melon juice products.

## MATERIALS AND METHODS

### Test material

Sanbai melons (as shown in Fig. 1) used in this study were harvested in August 2023 from Wanrong County, Yuncheng City, Shanxi Province. Immediately after harvest, they were stored in a cool location away from direct sunlight to preserve the freshness of the flesh. By December 2023, the melon flesh had reached an optimal solid-liquid mixture state, meeting the experimental requirements.

**Fig. 1 - Sanbai melon**

## Test apparatus and equipment

The HR-1 rheometer (Fig. 2), Manufactured by TA Instruments (USA), is equipped with computer control software (TA Instruments Trios v3.1.1.3538) for data acquisition and testing process control. It features a concentric cylinder fixture and a Patel temperature control system, allowing for precise temperature control and measurement of the sample during testing.

**Fig. 2 - HR-1 Rheometer**

The HPEF pretreatment system consisted of a BTX high-voltage pulsed electric field generator equipped with electrodes, a 630B MA1 45-0207 safety stand, BTX electroporation cuvettes, a trigger, and a voltage regulator. The HPEF device (model ECM830, BTX Corporation, USA) generates rectangular pulse waveforms with adjustable parameters, including a pulse intensity of 5–3000 V/cm, pulse duration of 10–200 μs, and pulse number ranging from 1 to 99.

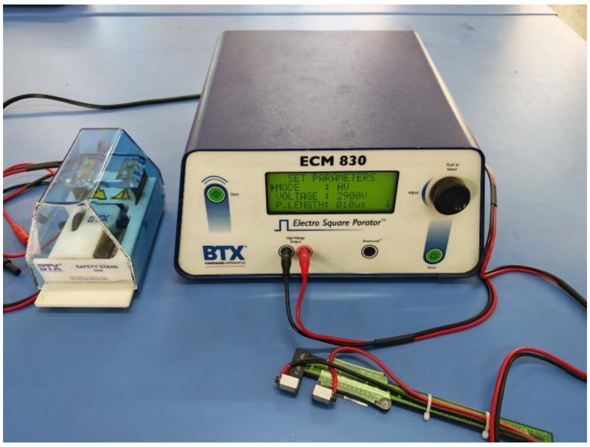



**Fig. 3 - High voltage pulsed electric field treatment device**

## Test Methods

### Sanbai Melon juice processing technology

The processing technique for Sanbai melon juice is as follows:

(1) Sanbai melon juice was scooped out using a stainless-steel spoon, transferred to a beaker, covered with plastic wrap, and stored in a refrigerator. This juice is referred to as "100% concentration" in this study.

(2) Seeds were removed from Sanbai melon flesh, which was then homogenized using a juicer to obtain juice. The juice was filtered through a 100-mesh sieve three times to remove impurities, then transferred to a beaker, covered with plastic wrap, and stored in a refrigerator. This juice is referred to as "50% concentration" in this study.

(3) To ensure the accuracy of test results, each experiment was repeated three times, and the average value was calculated.

### High-voltage pulsed electric field pre-treatment of Sanbai Melon juice

Sanbai melon juice was pretreated using a high-voltage pulsed electric field generator. Based on extensive preliminary tests, the pretreatment parameters were set as follows: pulse intensity ranging from 1000 to 1500 V/cm, pulse duration of 60 to 120 μs, and number of pulses from 40 to 60. Detailed pretreatment parameters are provided in Table 1.

Table 1

**Parameters of high voltage pulsed electric field pretreatment**

| Clusters | Pulse intensity | Pulse duration | Number of pulses |
|---|---|---|---|
| | [V/cm] | [μs] | [size] |
| **Control group** | 0 | 0 | 0 |
| **Process group1** | 1000 | 60 | 40 |
| **Process group2** | 1250 | 60 | 60 |
| **Process group3** | 1500 | 90 | 60 |
| **Process group4** | 1500 | 120 | 40 |

**Rheological test procedure**

To investigate the rheological properties of Sanbai melon juice, experiments were designed to measure data across four key aspects: steady-state shear viscosity, temperature effects, linear viscoelastic region, and dynamic viscoelasticity. The detailed procedures are as follows:

(1) Steady-State Shear Viscosity Test

The test was conducted at a constant temperature of 25°C with an equilibrium time of 600 seconds. Shear rates were varied from 0.1 to 100 $s^{-1}$, and corresponding data were recorded.

(2) Temperature Effect Test

Temperature was scanned from 5 to 85°C at a rate of 2°C per minute, with a fixed shear rate of 100 $s^{-1}$, to evaluate viscosity changes under varying thermal conditions.

(3) Linear Viscoelastic Region Test

This test was performed at 25°C with a constant shear angular frequency of 10 rad/s. Shear strain was adjusted within the range of 0.01% to 12% to determine the linear viscoelastic region.

(4) Dynamic Viscoelasticity Test

Based on results from the linear viscoelastic region test, the linear viscoelastic range was identified as 0.1% to 1% strain. The test was conducted with a fixed shear strain of 0.5% and a frequency scanning range of 0.1 to 100 rad/s.

All relevant data were automatically collected and recorded by the computer control program.

## Data analysis

Data was processed, analyzed, and plotted using SAS 9.4 and Origin 2022.

## RESULTS

### Steady-state shear viscosity test study of liquid-like Sanbai Melon

Fig. 4 presents the steady-state shear viscosity curves of Sanbai melon juice at 25°C for two concentrations: 100% (Sanbai melon juice 0-0) and 50% (Sanbai melon juice 1-0). As shown in the figure, the viscosity of both juice samples decreases with increasing shear rate, a characteristic consistent with pseudoplastic behavior (shear-thinning).

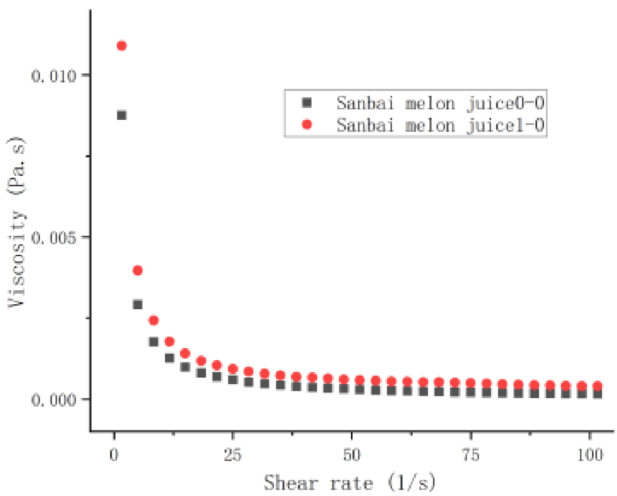



**Fig. 4 - Steady Shear Viscosity Curves of 100% and 50% Concentration Sanbai Melon Juice**

Notably, differences in viscosity between the two concentrations are more pronounced at lower shear rates. As the shear rate increases, these disparities gradually diminish. At any given shear rate, the 50% concentration juice exhibits higher viscosity compared to the 100% concentration sample. This phenomenon may be attributed to the processing method of the 50% concentration juice, where homogenization of melon flesh (including pulp) with juice introduces additional particulate matter or colloidal components, thereby increasing the overall viscosity of the system.

## Effect of HPEF on steady state shear viscosity of Sanbai Melon juice

### Analysis of Steady-State Shear Viscosity under HPEF Pretreatment (100% Concentration)

Fig. 5 illustrates the steady-state shear viscosity curves of 100% concentration Sanbai melon juice at 25°C, where "Sanbai melon juice 0-0" serves as the control group, and "0-1, 0-2, 0-3, 0-4" represent Treatment Groups 1 to 4, respectively. As shown in the figure, under all HPEF pretreatment conditions, the viscosity of Sanbai melon juice decreases with increasing shear rate, consistent with shear-thinning behavior.

Notably, viscosity differences between pretreated samples are most distinct at lower shear rates, but these disparities narrow as the shear rate increases. All treatment groups exhibit higher viscosity than the control group, with Treatment Group 2 showing the most significant elevation. This suggests that optimizing HPEF pretreatment parameters—specifically, a pulse intensity of 1250 V/cm, pulse duration of 60 μs, and 30 pulses—markedly enhances the viscosity of 100% concentration Sanbai melon juice.

### Power-Law Model Fitting Results

The power-law model, a nonlinear model widely applied to describe the viscosity of food materials, is particularly effective for analyzing the rheological behavior of liquid-like fruit and vegetable products. Table 2 presents the fitted power-law parameters for the steady-state shear viscosity of 100% concentration Sanbai melon juice.

Model Suitability:

For both the control and treatment groups, the correlation coefficients ($R^2$) of the fitted models exceed 0.90, and the p-values are less than 0.0001. These results confirm that the power-law model is highly suitable for fitting the steady-state shear viscosity curves of 100% concentration Sanbai melon juice.

Flow Behavior Classification:

The power-law model is defined by the equation (1):

$$\eta = K\dot{\gamma}^{n-1} \tag{1}$$

where: $K$ is consistency coefficient, reflects viscosity magnitude;

$n$ is flow behavior index, characterizes flow type, when:

$n$>1: Shear-thickening (dilatant fluid);

$n$<1: Shear-thinning (pseudoplastic fluid);

$n$=1: Newtonian fluid.

From Table 2, the flow behavior index $n$ of all fitted models is less than 1, confirming that 100% concentration Sanbai melon juice is a pseudoplastic fluid exhibiting shear thinning.

Effect of HPEF Pretreatment:

With increasing HPEF pretreatment intensity, the consistency coefficient K gradually increases, while the flow behavior index $n$ decreases. This indicates that HPEF pretreatment enhances the viscosity of the juice and exacerbates its shear-thinning behavior.

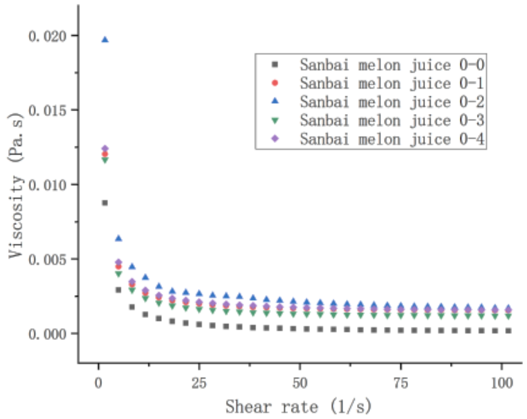



**Fig. 5 - Steady state shear viscosity profile of Sanbai Melon juice at 100% concentration**

**Table 2**

**Power-Law Equation Fitting Parameters for the Fluid Type of 100% Sanbai Melon Juice Concentration**

| Treat | *K* | n | P value | $R^2$ |
|---|---|---|---|---|
| 0 | 0.01434±1.43721E$^{-4}$ | 0.9856±9.10489E$^{-4}$ | <0.0001 | 0.999 |
| 1 | 0.01493±7.82139E$^{-4}$ | 0.59308±0.02442 | <0.0001 | 0.927 |
| 2 | 0.02633±0.00124 | 0.70418±0.02652 | <0.0001 | 0.947 |
| 3 | 0.01533±7.09454E$^{-4}$ | 0.67026±0.02457 | <0.0001 | 0.947 |
| 4 | 0.01543±7.47333E$^{-4}$ | 0.58905±0.02243 | <0.0001 | 0.937 |

Fig. 6 displays the shear viscosity curves of 50% concentration Sanbai melon juice at 25°C, where "Sanbai melon juice 1-0" serves as the control group, and "1-1, 1-2, 1-3, 1-4" correspond to Treatment Groups 1 to 4, respectively. As observed in the figure, following high-voltage pulsed electric field (HPEF) pretreatment, the viscosity of 50% concentration Sanbai melon juice decreases with increasing shear rate, consistent with shear-thinning behavior—similar to the trend observed in 100% concentration juice.

A notable feature is that viscosity differences between samples are most prominent in the low shear rate region, while these distinctions diminish as the shear rate increases. Compared to the control group, all HPEF-pretreated samples of 50% concentration juice exhibit higher viscosity, indicating that HPEF pretreatment enhances viscosity in this concentration as well.

Table 3 presents the power-law model fitting parameters for the steady-state shear viscosity curves of 50% concentration Sanbai melon juice.

Model Validity:

The correlation coefficients ($R^2$) of all fitted models exceed 0.90, and the p-values are less than 0.0001. These results confirm that the power-law model is highly suitable for describing the steady-state shear viscosity behavior of 50% concentration Sanbai melon juice, with the fitted models demonstrating strong reliability.

Flow Behavior Characteristics:

The flow behavior index (n) of all samples is less than 1, confirming that 50% concentration Sanbai melon juice is also a pseudoplastic fluid, exhibiting shear-thinning properties.

Effect of HPEF Pretreatment:

With increasing HPEF pretreatment parameters, the consistency coefficient (K) gradually increases, while the flow behavior index (n) decreases. This indicates that enhanced HPEF pretreatment intensifies both the viscosity and the shear-thinning phenomenon of 50% concentration juice. Compared to the control group, the treatment groups show a significant decrease in n and a significant increase in K, further validating the impact of HPEF on the rheological properties of the juice.

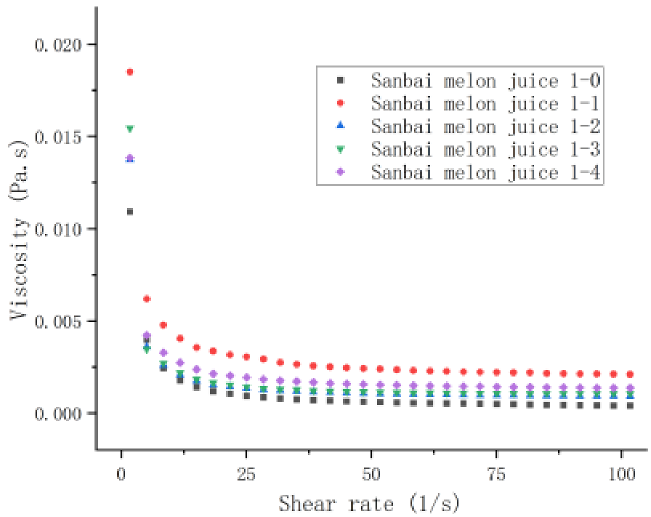



**Fig. 6 - Steady state shear viscosity profile of Sanbai Melon juice at 50% concentration**

**Table 3**

**Power-Law Equation Fitting Parameters for the Fluid Type of 50% Sanbai Melon Juice Concentration**

| Treat | $K$ | n | P value | $R^2$ |
|---|---|---|---|---|
| 0 | 0.01686±1.97888E-4 | 0.88418±0.00904 | <0.0001 | 0.997 |
| 1 | 0.02323±0.00122 | 0.619±0.02546 | <0.0001 | 0.929 |
| 2 | 0.02003±9.40346E-4 | 0.8424±0.03369 | <0.0001 | 0.954 |
| 3 | 0.02274±0.00123 | 0.87226±0.04083 | <0.0001 | 0.941 |
| 4 | 0.01812±9.56899E-4 | 0.68108±0.02857 | <0.0001 | 0.932 |

## Effect of Temperature on Steady State Shear Viscosity of Sanbai Melon juice

To investigate how temperature influences the viscosity of Sanbai melon juice after high-voltage pulsed electric field (HPEF) pretreatment, temperature-viscosity curves were generated for both 100% and 50% concentration juices (Fig. 7).

(1) 100% Concentration Juice

For 100% concentration juice, viscosity exhibited a consistent decreasing trend as temperature increased from 5 to 75°C. Quantitative analysis revealed the following viscosity reductions across the temperature range:

Control group: 0.0806 Pa

Treatment Group 1: 0.1128 Pa

Treatment Group 2: 0.2560 Pa (most significant reduction)

Treatment Group 3: 0.0917 Pa

Treatment Group 4: 0.1591 Pa

Notably, Treatment Group 2 showed the largest viscosity decrease, with a distinct difference from Treatment Group 4; the reductions in Treatment Groups 1 and 3 were comparable. As illustrated in Fig. 7(a), all HPEF-pretreated samples maintained higher viscosity than the untreated control group at any given temperature. This phenomenon may be attributed to cell membrane electroporation induced by HPEF: the electric field disrupts cell membranes, causing intracellular nutrients (e.g., polysaccharides, proteins) to leak into the juice, thereby increasing its viscosity.

(2) Model Fitting for Temperature-Viscosity Relationships

Table 4 presents the regression models describing the temperature-viscosity relationship. All models exhibited p-values < 0.0001, indicating a highly significant correlation between temperature and viscosity. Additionally, the coefficient of determination ($R^2$) for all models exceeded 0.99, reflecting excellent fit precision. These results confirm that the regression models effectively capture the influence of temperature on the viscosity of Sanbai melon juice.

**Table 4**

**Fitting Model of the Effect of Temperature on the Viscosity of 50% Sanbai Melon Juice Concentration**

| Treat | Fitting models | P value | $R^2$ |
|---|---|---|---|
| 0 | $y=0.0000168x^2-0.0025x+0.148$ | <0.0001 | 0.997 |
| 1 | $y=0.0000311x^2-0.0041x+0.211$ | <0.0001 | 0.993 |
| 2 | $y=0.0000627x^2-0.0087x+0.406$ | <0.0001 | 0.999 |
| 3 | $y=0.0000248x^2-0.0033x+0.176$ | <0.0001 | 0.998 |
| 4 | $y=0.0000428x^2-0.0056x+0.272$ | <0.0001 | 0.997 |

For 50% concentration Sanbai melon juice, viscosity exhibited a two-stage trend with increasing temperature: it gradually decreased within the range of 5 to 45°C and then stabilized between 55 and 80°C. Quantitative analysis of viscosity reductions across the entire temperature range (5 to 80°C) revealed the following:

Control group: 0.2160 Pa

Treatment Group 1: 0.1160 Pa

Treatment Group 2: 0.1470 Pa

Treatment Group 3: 0.0739 Pa (most gradual reduction)

Treatment Group 4: 0.1730 Pa (most significant reduction)

Notably, Treatment Group 4 showed the largest overall viscosity decrease, with a significant difference from Treatment Group 2. Treatment Group 3 exhibited the mildest reduction, indicating a more stable viscosity response to temperature changes.

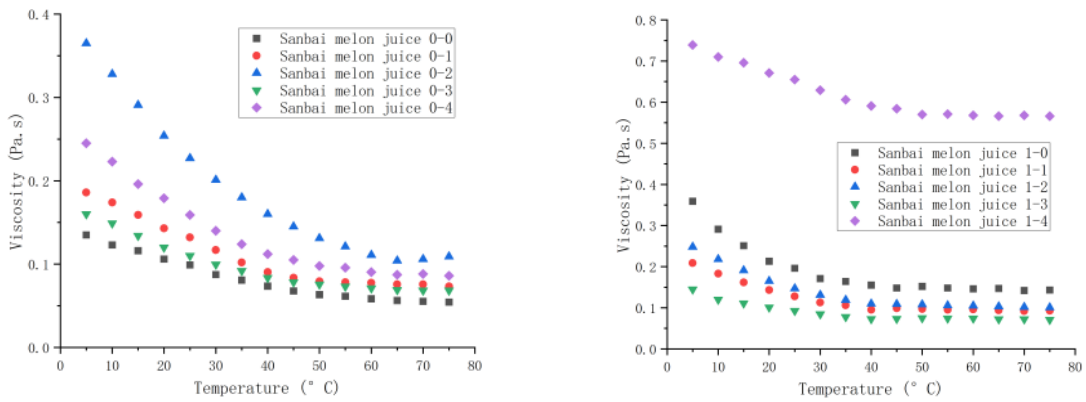
As shown in Fig. 7(b), the untreated control group had a higher viscosity curve than all treatment groups except Treatment Group 4. This observation may be attributed to the processing method of the 50% concentration juice: homogenization (via a homogenizer) could have caused the loss of certain viscosity-enhancing nutrients (e.g., insoluble fibers or colloidal particles), thereby reducing the viscosity of pretreated samples relative to the control—with the exception of Treatment Group 4, which may have retained more of these components due to specific HPEF parameters.

Table 5 presents the regression models describing the temperature-viscosity relationship for 50% concentration juice. All models demonstrated p-values < 0.0001, indicating a highly significant correlation between temperature and viscosity. The coefficient of determination ($R^2$) for all models exceeded 0.95, reflecting high fit precision. These results confirm that the regression models effectively capture the influence of temperature on the viscosity of 50% concentration Sanbai melon juice.

**Table 5**

**Fitting Model of the Effect of Temperature on the Viscosity of 100% Sanbai Melon Juice Concentration**

| Treat | Fitting models | P value | $R^2$ |
|---|---|---|---|
| **0** | y=0.0000759x2-0.0084x+0.371 | <0.0001 | 0.955 |
| **1** | y=0.0000415x2-0.0047x+0.225 | <0.0001 | 0.979 |
| **2** | y=0.0000508x2-0.0059x+0.268 | <0.0001 | 0.982 |
| **3** | y=0.0000252x2-0.0028x+0.150 | <0.0001 | 0.964 |
| **4** | y=0.0000478x2-0.0063x+0.774 | <0.0001 | 0.993 |




*(a) Concentration of 100%* *(b) Concentration of 50%*

**Fig. 7 - Temperature-viscosity curve of Sanbai Melon juice**

Consistent with the results of both 100% and 50% concentration experiments, the viscosity of Sanbai melon juice decreases with increasing temperature. This phenomenon can be explained by the following mechanisms:

As temperature rises, the thermal motion of molecules in the juice intensifies. This increases molecular activity weakens intermolecular forces (such as van der Waals forces and hydrogen bonds) that contribute to the structural integrity of the juice. Consequently, the average distance between molecules increases, reducing frictional resistance between adjacent molecules and weakening their interactions with other components (e.g., polysaccharides, proteins, or particulate matter) in the juice system. These changes disrupt the relatively dense network structure formed by the components, leading to a gradual decrease in viscosity.

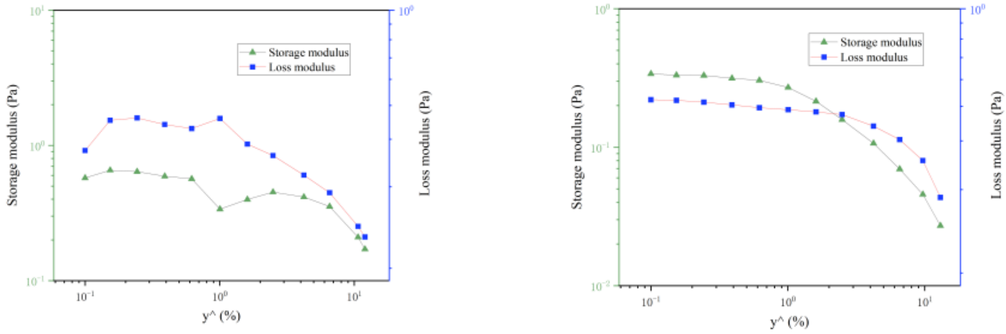
In essence, the thermal energy input at higher temperatures overcomes the cohesive forces that maintain the juice’s viscosity, resulting in the observed thinning effect. This mechanism aligns with the general rheological behavior of liquid systems, where temperature-induced molecular mobility typically reduces resistance to flow.

## Dynamic Viscoelastic Properties of Sanbai Melon juice in Liquid form

To identify the linear viscoelastic region (LVR) of Sanbai melon juice, tests were conducted using the control groups of 100% and 50% concentration juices. Fig. 8 presents the LVR test curves for these samples, where storage modulus (G') and loss modulus (G") were measured by scanning the applied shear strain.

The results show that within the shear strain range of 0.1% to 1%, both (G') (a measure of elastic behavior) and (G") (a measure of viscous behavior) remain relatively stable, with minimal fluctuations. This stability indicates that the material's viscoelastic properties are not significantly altered by strain within this range, confirming the presence of a linear viscoelastic region.

To ensure accurate assessment of dynamic viscoelastic properties across different concentrations and treatment conditions, a shear strain of 0.5% - within the identified LVR (0.1% to 1%) - was selected as the standard testing condition for subsequent dynamic viscoelasticity experiments. This choice ensures that measurements reflect the intrinsic viscoelastic characteristics of the juice without introducing strain-induced structural changes.




*(a) Concentration of 100%* *(b) Concentration of 50%*

**Fig. 8 - Linear viscoelastic zone test curve of Sanbai Melon juice**

Fig. 9 illustrates the dynamic viscoelasticity curves of 100% concentration Sanbai melon juice, characterized by the storage modulus (G') and loss modulus (G") across a range of angular frequencies.

Frequency-Dependent Trends:

As angular frequency increases, both (G') (which reflects elastic properties) and (G") (which reflects viscous properties) increase. Notably, (G") rises slowly in the low-frequency range but exhibits a more significant increase at high frequencies, indicating that viscous behavior becomes more prominent under higher shear rates.

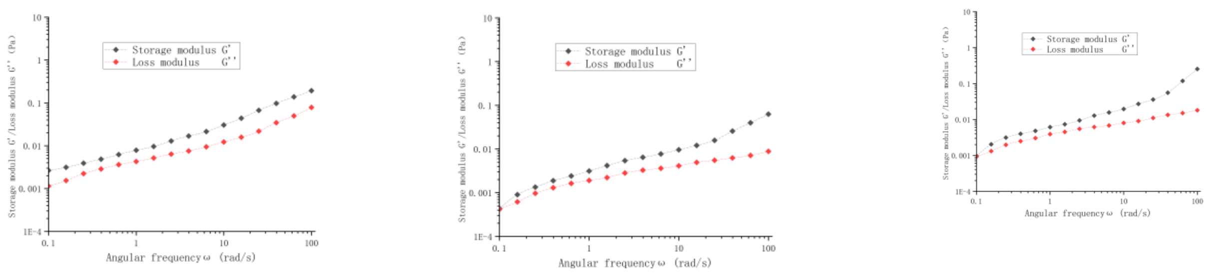
Predominance of Elastic Characteristics:

For both the control and treatment groups, (G') is consistently greater than (G") across all frequencies. This finding indicates that the elastic properties of 100% concentration Sanbai melon juice dominate over its viscous properties, a key feature of viscoelastic materials.

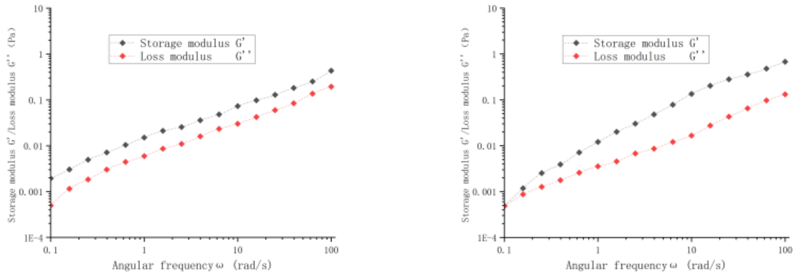
Effect of HPEF Pretreatment:

All HPEF-pretreated groups exhibit higher (G') and (G") values compared to the control group, with Treatment Group 2 showing the most marked increase. This suggests that HPEF pretreatment enhances both the elastic and viscous characteristics of the juice, with a more pronounced effect on elasticity.

These results reinforce that 100% concentration Sanbai melon juice behaves as a non-Newtonian fluid, and HPEF pretreatment further strengthens its viscoelastic properties - particularly elasticity - likely due to structural changes in its components (e.g., aggregated macromolecules or altered particle interactions) induced by the electric field.




*Control group* *Process group 1* *Process group 2*




*Process group 3* *Process group 4*

**Fig. 9 - Dynamic Viscoelasticity of 100% Concentration Sanbai Melon Juice**

Fig. 10 presents the dynamic viscoelasticity curves of 50% concentration Sanbai melon juice, characterized by the storage modulus (G') and loss modulus (G'') across varying angular frequencies.

Frequency-Dependent Trends:

Similar to the 100% concentration juice, both (G') (elasticity) and (G'') (viscosity) increase with rising angular frequency. However, the magnitude of this increase is relatively moderate, indicating a more gradual response of viscoelastic properties to changes in frequency.

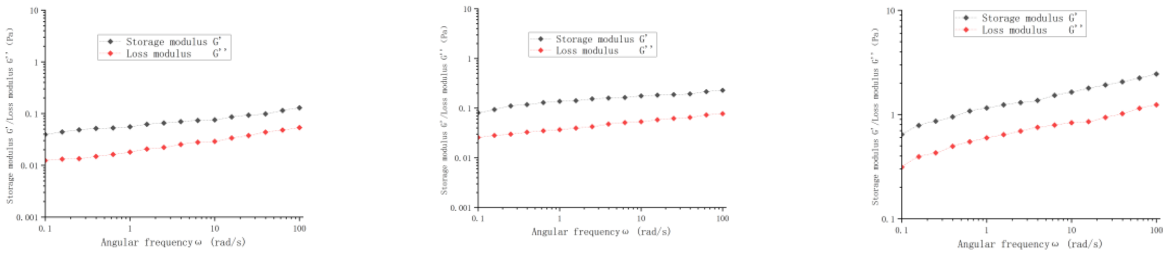
Predominance of Elastic Characteristics:

For both the control and HPEF-pretreated groups, (G') remains greater than (G'') across all measured frequencies. This confirms that, like the 100% concentration juice, the 50% concentration juice is dominated by elastic properties, reflecting its viscoelastic nature.

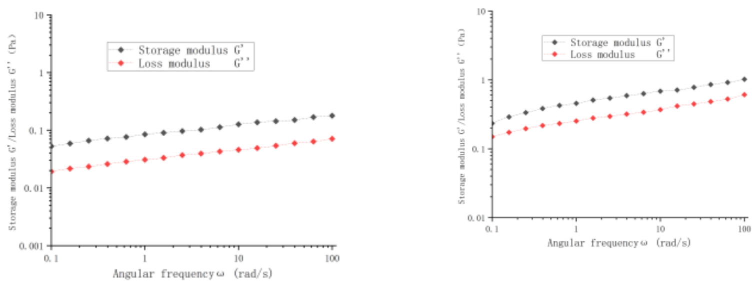
Effect of HPEF Pretreatment:

All treated groups exhibit higher (G') and (G'') values compared to the control group, with Treatment Group 2 showing the most significant enhancement in both moduli. This indicates that HPEF pretreatment strengthens both the elastic and viscous characteristics of 50% concentration juice, with a particularly notable improvement in elasticity.

These findings align with the trends observed in 100% concentration juice, demonstrating that HPEF pretreatment consistently enhances the viscoelastic properties of Sanbai melon juice—regardless of concentration—with a primary focus on boosting elastic behavior. This suggests that the structural changes induced by HPEF (e.g., altered intermolecular interactions or macromolecular aggregation) exert a similar influence across different concentration levels, reinforcing the technology's potential to modify the rheological properties of Sanbai melon juice for improved processing and product quality.




*Control group* *Process group 1* *Process group 2*




*Process group 3* *Process group 4*

**Fig. 10 - Dynamic Viscoelasticity of 50% Concentration Sanbai Melon Juice**

## CONCLUSIONS

This study investigates the rheological properties of Sanbai melon juice, yielding the following key findings:

(1) Pseudoplastic Behavior:

Under the tested conditions, Sanbai melon juice exhibits distinct pseudoplastic characteristics, as its rheological curves conform well to the power-law equation. A critical feature is shear thinning—viscosity decreases with increasing shear rate—consistent with the behavior of pseudoplastic fluids.

(2) Effect of HPEF Pretreatment on Steady-State Viscosity:

High-voltage pulsed electric field (HPEF) pretreatment significantly increases the viscosity of Sanbai melon juice. The power-law model provides an excellent fit to the steady-state shear viscosity curves, with correlation coefficients ($R^2$) exceeding 0.90 and $p<0.0001$, confirming its high applicability for describing the juice's rheological behavior.

(3) Temperature Dependence of Viscosity:

Viscosity tests across the temperature range of 5 to 80°C reveal that the viscosity of Sanbai melon juice decreases with increasing temperature. This trend is attributed to intensified molecular thermal motion, weakened intermolecular forces, and disrupted structural cohesion at higher temperatures.

(4) Dynamic Viscoelastic Properties:

Dynamic viscoelasticity tests show that both the storage modulus (G', reflecting elasticity) and loss modulus (G'', reflecting viscosity) increase with angular frequency. Notably, elastic properties dominate over viscous properties (G' > G'') in all samples. HPEF pretreatment enhances both G' and G'', with a more pronounced effect on elasticity, further strengthening the juice's viscoelastic characteristics.

These findings provide a scientific basis for viscosity regulation during the processing and storage of Sanbai melon juice. They also establish a theoretical foundation for optimizing production processes (e.g., selecting appropriate HPEF parameters) and implementing quality control measures under varying environmental conditions (e.g., temperature management). Ultimately, this research supports the development of high-quality Sanbai melon juice products with improved stability and sensory properties.

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