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Effects of Environmental Variations on Droplet Deposition Patterns in Feng-flavor *Baijiu*

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Abstract: Droplet evaporation is currently widely used in medical diagnosis, materials and other aspects, but there is still little research on *Baijiu*. Previous research found that the deposition pattern of feng-flavor *Baijiu* was highly sensitive to temperature and humidity conditions. Therefore, this study explored the best temperature and humidity environment and materials in the evaporation process of feng-flavor *Baijiu*. The findings reveal that the temperature significantly modulates the evaporation rate of feng-flavor *Baijiu* droplets, while elevated humidity leads to incomplete deposition patterns. Furthermore, substrates with varying hydrophilic properties produce markedly different deposition morphologies. Optimal conditions were identified as 25 °C, 60% relative humidity (RH), and an indium tin oxide (ITO) substrate. These insights provide a novel approach for quality assessment in feng-flavor *Baijiu* production.

Keywords: Droplet Evaporation; Deposition Pattern; Environmental Condition; Feng-flavor *Baijiu*.

1. Introduction

Baijiu, a traditional Chinese distilled spirit with a millennium-long history, has distinguished by its unique aromatic and sensory profile, earning global recognition as one of the world's six major distilled spirits—alongside brandy, whisky, vodka, rum, and gin [1]. Classified into 12 distinct flavor categories based on regional traditions and production techniques (e.g., sauce-flavor, strong-flavor, feng-flavor, and light-flavor styles)" [1-4]. Its production utilizes high-quality sorghum as the primary grain, fermented with medium-to-high-temperature *Daqu* (a starter culture comprising barley, peas, and wheat), aged in traditional *Jiuhai* (earthenware storage vessels for aging), and meticulously blended to achieve balance. This intricate process generates a chemically diverse matrix, with over 2,000 compounds identified to date [5], establishing feng-flavor *Baijiu* as a highly complex colloidal system.

Droplet evaporation, a ubiquitous physical phenomenon, governs diverse real-world processes—from oil spill drying to water droplet dissipation on superhydrophobic surfaces. Sessile droplets, in particular, form characteristic residual patterns upon evaporation, most notably the "coffee-ring effect", where solutes migrate to at the droplet periphery [6]. Beyond this classic phenomenon, evaporation-driven self-assembly serves as a versatile platform for particle organization [7,8], enabling the fabrication of functional materials such as colloidal crystals and nanostructured assemblies [9,10]. For multicomponent droplets containing non-volatile components, evaporation dynamics are dictated by internal Marangoni flows, capillary forces, and solute interactions, leading to distinct drying regimes. Building on this principle, researchers have engineered tailored deposition patterns through strategic control of solute chemistry (e.g., ionic species [10], surfactants [11,12]), environmental parameters, and substrate properties. These insights underpin advancements in spray cooling [13], coatings [14], inkjet printing [15], and medical diagnostics [16],emphasizing the critical interplay of multifactorial variables—including substrate material, temperature, and humidity—in shaping deposition outcomes.

In this work, we systematically explored the evaporation dynamics and deposition patterns of feng-flavor *Baijiu* droplets under control conditions: temperature gradient (10°C, 25°C, 37°C) paired with four humidity levels (30% RH, 50% RH, 60% RH, 80% RH, relative humidity). Subsequent substrate optimization experiment identified ideal conditions for capturing the unique deposition signatures of feng-flavor *Baijiu*.

2. Materials and Methods

2.1. Material and Reagents

2.1.1. Material

The experimental *Baijiu* samples were categorized as follows: The standard samples of feng-flavor *Baijiu* and for professional sensory evaluation 2 (55% ABV, alcohol by volume) certified by the China Alcoholic Drinks Association (CADA).

2.1.2. Reagents

Anhydrous ethanol (analytical grade): Chengdu Kelong Chemical Co., Ltd. Ultrapure water. Acid cleaning solution (Prepared by dissolving 120 g potassium dichromate ($K_2Cr_2O_7$) in 200 mL concentrated sulfuric acid (H_2SO_4, 98%), followed by dilution with 200 mL distilled water.

2.2. Instruments and Equipments

Inverted fluorescence biological microscope, effective magnification 40-200 ×. Optical Measuring Instrument Theta Lite: Baolin Technology Co., LTD. Hydrophilic slides ($\theta < 90°$), conductive glass indium tin oxide (ITO, (a) for laboratory use only South-China Xiangcheng Technology Co., LTD, Size: 100 mm × 100 mm × 1.1 mm). Glass slides ((b): Saga Flagship Store Size: 76.2 mm × 25.4 mm × 1 mm).

Shitai slides positive charge anti-detachment 188105w ((c): Youkang Biological Consumables Wholesale City, Size: 75 mm × 25 mm × 1 mm). Constant temperature and humidity intelligent precision dedicated air conditioner (HFW-75, Beijin Zksh Tec.Co., Ltd).

2.3. Methods

2.3.1. Substrate Cleaning Protocols

ITO and Shitai glass slides: Rinse with laboratory tap water followed by deionized water (3 ~ 5 times or cycles) until fully hydrated and free of contaminants.

Glass slides: Soak in the acid wash solution (H_2SO_4:H_2O_2 = 7:3 v/v) for 12 hours. Rinse with tap water and deionized water (3~5 cycles) to ensure complete wettability and cleanliness.

Dry in an oven at 60 °C for 1 hour, then air-dry overnight at ambient conditions.

2.3.2. Deposition Patterns Analysis under Controlled Conditions

Experiments were conducted in a temperature- and humidity-controlled chamber at three temperatures (10 °C, 25 °C, 35 °C) and four relative humidity (RH) levels (30%, 50%, 60%, 80%). A 1 μL *Baijiu* droplet was deposited onto the substrate using a calibrated micropipette. Ten droplets were dispensed per slide, with three replicate slides per experimental condition. Deposition patterns exhibiting the highest morphological consistency across replicates were selected as representative for subsequent analysis. Triplicate experiments were performed to ensure statistical robustness.

2.3.3. Evaporation Dynamics Characterization

The Theta Lite optical tensiometer (Biolin Scientific), was employed to quantify evaporation parameters: the static contact angle by the lying droplet. A 4 μL droplet was deposited vertically onto the substrate using the sessile drop method. After allowing the solid-liquid system to stabilize (~30 s), time-lapse imaging captured: contact angle evolution, droplet base diameter and droplet height. Data acquisition spanned 650 s, with measurements recorded at 2s intervals. Image analysis was performed using the instrument's proprietary software (OneAttension v4.3) to extract dynamic evaporation profiles.

3. Results and Discussion

3.1. Evaporation Dynamics of Feng-Flavor *Baijiu* under Different Environmental Conditions

The evaporation dynamics of droplets exhibit strong dependence on temperature-humidity conditions. For the standard sample of feng-flavor *Baijiu* (from CADA), the droplet evaporation models exhibit certain differences across tested environmental parameters, as illustrated in Fig. 1.

3.1.1. Temperature-dependent Evaporation Dynamics

At low-to-moderate temperatures (10 °C, 25 °C), the evaporation predominantly follows the constant contact radius (CCR) model. At lower temperature condition (10 °C), reduced thermal energy results in slower evaporation rates, while the hydrophilic Shitai glass substrate stabilizes droplet spreading, aligning with internal Marangoni flow dynamics. Elevated temperature (37 °C): Evaporation transitions to a mixed mode characterized by "stick-slip" behavior, where intermittent pinning-depinning cycles alter droplet morphology. This shift correlates with accelerated evaporation rates, particularly under low humidity (30% RH), which shortens total evaporation time by ~ 40% compared to 25 °C at low humidity.

3.1.2. Humidity-modulated Evaporation Dynamics

High humidity (80% RH) suppresses evaporation rates significantly at 25 °C and 37 °C. Despite this, the CCR mode persists at 37°C/80% RH, suggesting humidity-driven stabilization of the contact line. Low humidity (30% RH) enhances evaporation efficiency, though temperature remains the dominant factor in mode transition (e.g., stick-slip initiation at 37°C). Fig. 1 quantitatively demonstrates the pronounced temperature sensitivity of evaporation rates, with humidity acting as a secondary modulator of droplet geometry.

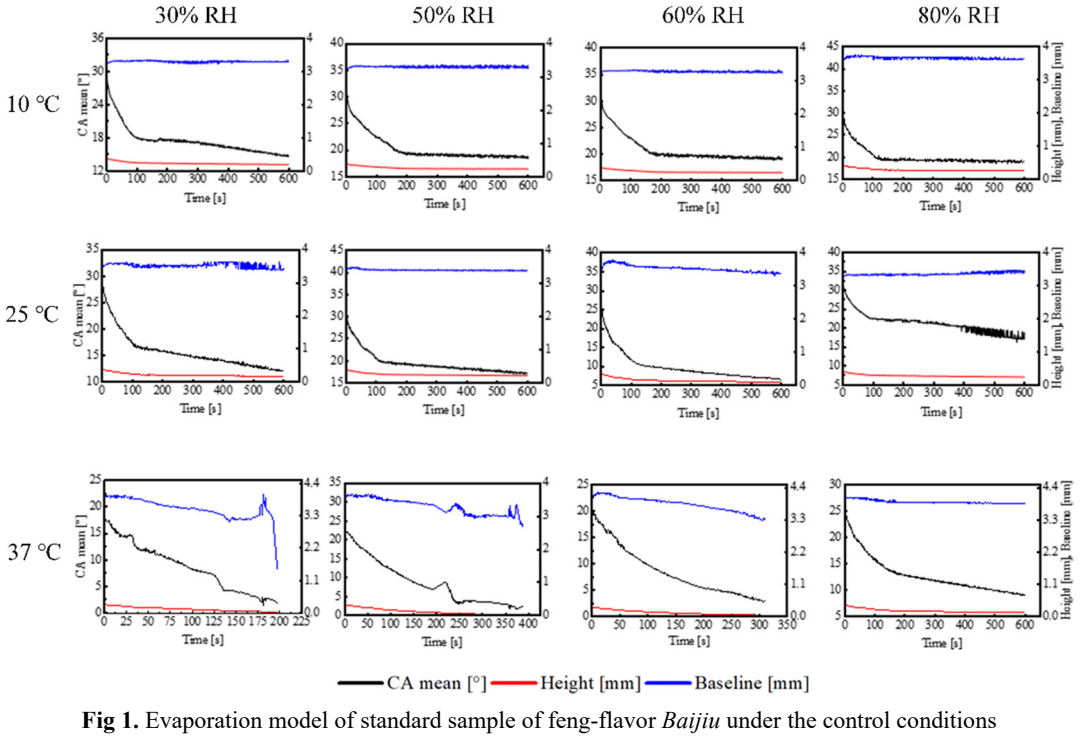


Fig 1. Evaporation model of standard sample of feng-flavor *Baijiu* under the control conditions

3.2. Environmental Influence on Deposition Patterns of Feng-Flavor *Baijiu*

Upon examining droplet evaporation models, we compared the corresponding deposition patterns of feng-flavor *Baijiu* and observed that at lower temperatures, these patterns remained relatively intact, featuring coffee-ring structures (Fig. 2). Low-temperature regimes (10°C) structurally complete deposition patterns with pronounced coffee-ring structures. Optimal pattern integrity observed at 30 and 50% RH, attributed to slower evaporation rates allowing full solute redistribution. Under elevated temperature (37°C), the high humidity (80% RH) induced moisture absorption by hygroscopic flavor compounds such as hexanoic acid and ethyl hexanoate, leading to partial dissolution of deposition pattern.

Similar humidity levels (e.g., 30% vs. 50% RH) produced morphologically analogous patterns, while transitions to 80% RH induced abrupt structural collapse (Fig. 2). Distinct pattern differentiation across temperature gradients, underscoring thermal control over solute assembly (Fig. 2). Maximal pattern integrity occurred at 10 °C/ (30%RH、50% RH） and 25 °C/60% RH. Notably, temperature had a more pronounced effect on the deposition patterns—each of the three temperature gradients produced entirely different patterns. The findings indicate that both temperature and humidity significantly impact patterns, particularly the individual conditions of 80% RH and 37 °C. Through comparison, the deposition patterns were most intact under conditions of 10 °C with 30 or 50% RH and 25 °C with 60% RH. Among these, the 25 °C/60% RH was prioritized for subsequent studies due to its experimental practicality.

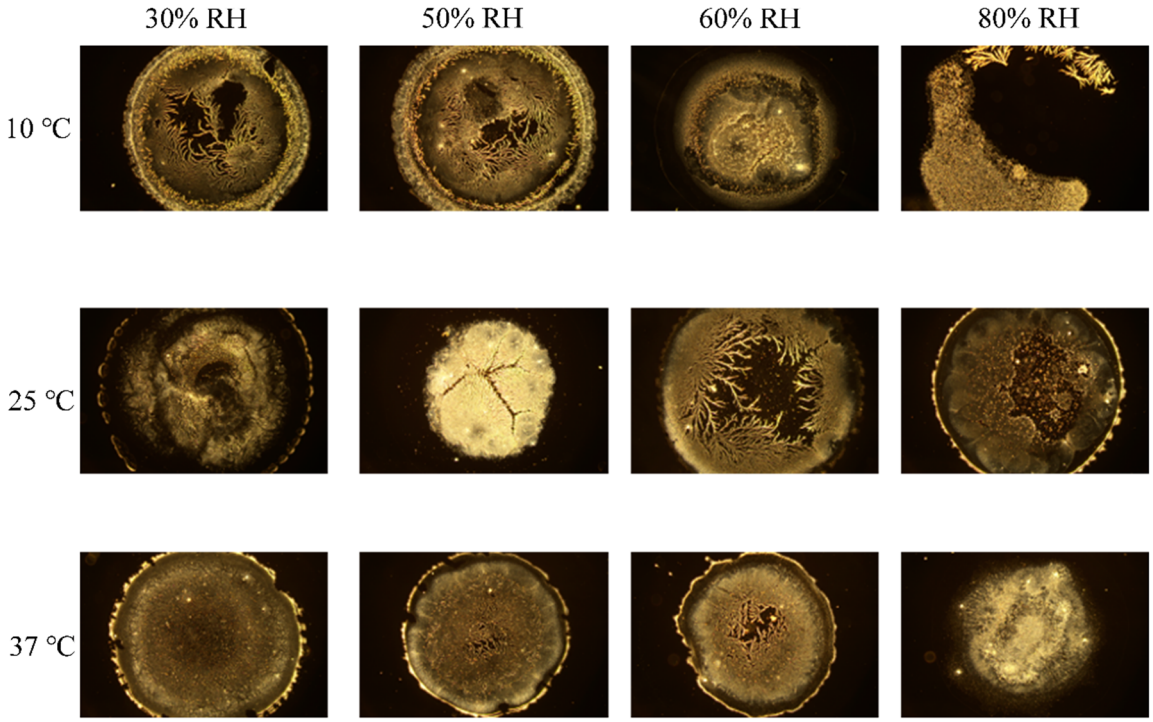


Fig 2. Deposition patterns of standard sample of feng-flavor *Baijiu* under the control conditions

3.3. Influence of Substrate Wettability on Deposition Patterns in Feng-flavor *Baijiu*

Building on the optimal environmental conditions (25°C, 60% RH), substrate materials were systematically evaluated for their impact on deposition pattern formation. Fig. 3 demonstrates distinct deposition patterns across three substrates. As shown in Fig. 3, material a (ITO, θ = 85°) produced structurally intact deposition patterns. Material c (Glass, θ = 36°) yielded morphologically similar patterns to ITO but exhibited marginally reduced edge definition under high-resolution imaging. However, ITO exhibits a larger contact angle compared to material c (Glass). Material b generated incomplete patterns. When droplets evaporate on hydrophilic surfaces (with a small contact angle), the contact radius and evaporation area increase, which accelerates the evaporation rate. Conversely, on hydrophobic surfaces (with a large contact angle), the smaller contact radius results in a slower evaporation rate.

Hydrophilic surfaces (e.g., Glass, θ = 17°) promoted rapid evaporation via the constant contact radius (CCR) model, driven by increased droplet spread and enhanced liquid-substrate interactions (Fig. 3 b). Moderately hydrophobic ITO (θ = 85°) maintained CCR-dominated evaporation but at a reduced rate, favoring gradual solute assembly (Fig. 3 a). Strong Marangoni convection on hydrophilic Glass (θ = 36°) enhanced solute transport to the contact line, amplifying coffee-ring formation (Fig. 3 c). Moreover, evaporation rates decrease with reduced surface wettability, with superhydrophobic surfaces exhibiting the lowest rates. The wettability of the substrate also affects internal droplet flow dynamics: for example, Marangoni flow is typically stronger on hydrophilic materials, whereas radial flow dominates on superhydrophilic surfaces [18]. Considering these factors, ITO emerged as the superior substrate due to pattern reproducibility (minimal batch-to-batch variation, <5% feature density difference), controlled evaporation and analytical compatibility (electrochemical inertness supporting potential downstream compositional analysis).

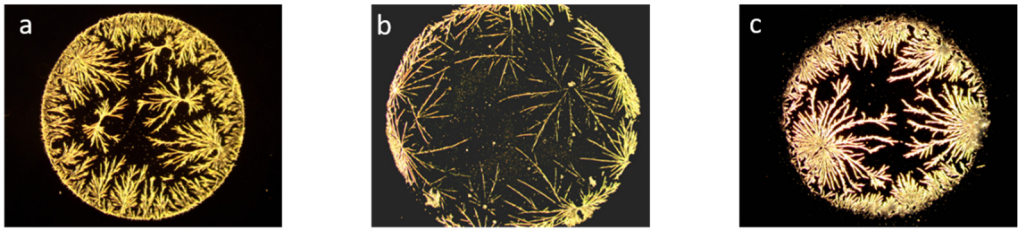


Fig 3. Deposition patterns of feng-flavor *Baijiu* on different substrate materials. Note: a-ITO (water θ= 85 °± 2 °), b-glass (water θ=17 °± 2 °), c-Shitai slide (water θ=36 °± 5 °)

4. Summary

In the context of droplet evaporation in feng-flavor *Baijiu*, parameters such as temperature, humidity, and substrate material all influence the evaporation model and final deposition patterns. Comparisons across three temperature conditions demonstrated that droplet volatilization is severely affected under extreme environmental conditions. Therefore, the optimal range was determined to be 10–25 °C for temperature and 30–60% RH for humidity. Among these, the deposition patterns formed at approximately 25 °C and 60% RH were the most intact, and these conditions are relatively easy to replicate. This indicates that moderate temperature and moderate-to-low humidity (avoiding excessively high values) are preferable. Interestingly, at relatively high temperatures, the deposition pattern is affected, and the evaporation rate of the droplets is significantly faster. Therefore, it is not advisable to have a relatively high temperature. Therefore, the evaporation environment should be appropriate (25 °C, 60% RH). Using these optimized conditions, we compared materials with different hydrophilic properties. Although the deposition pattern of feng-flavor *Baijiu* was consistent across materials, significant differences in hydrophilicity led us to select ITO as the final substrate due to its balanced performance. Nonetheless, this method provides a preliminary framework for quality evaluation of feng-flavor *Baijiu* through droplet evaporation analysis.

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Conflicts of Interest

The authors declare no conflict of interest.

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