Received: 9 April 2025 | Revised: 18 July 2025 | Accepted: 10 September 2025 | Published online: 30 September 2025

RESEARCH ARTICLE

Journal of Optics and Photonics Research
2025, Vol. 00(00) 1–8
DOI: 10.47852/bonviewJOPR52025878

BON VIEW PUBLISHING

Study on the Aging of Sauce-Flavored Baijiu Based on Light Irradiation

Xiang Gao[1], Ri Zeng Tao[1], Chun Feng Guo[1,*], Qi Fei Zhu[1], Bobo Yang[1] and Jun Zou[1,2,*]

[1]*School of Science, Shanghai Institute of Technology, China*

[2]*Institute of New Materials & Industrial Technology, Wenzhou University, China*

Abstract: Aging is a crucial process that enhances the quality of Chinese Baijiu production. This paper investigates the aging of sauce-flavored Baijiu through light irradiation. LED light sources with central wavelengths of 365, 395, and 455 nm are employed to age Baijiu samples. The total acid content is determined by titration, while the total ester content is obtained through saponification. Aged Baijiu samples are subjected to sensory evaluation, and their aroma profiles are analyzed using an electronic nose. The total acid and total ester content in the aged Baijiu samples meets the first-grade Baijiu standards established by national regulations. Principal component analysis of the electronic nose data indicates that the flavor profile of the aged samples closely resembles that of Maotai, a renowned sauce-flavored Baijiu. The experimental results demonstrate that irradiation with light at a central wavelength of 395 nm for 2 weeks represents an optimal aging solution, which may be beneficial for the aging of sauce-flavored Baijiu.

Keywords: Chinese Baijiu, light irradiation, chemical composition, electronic nose test

1. Introduction

The sauce-flavored Baijiu is popular due to its unique aroma and holds a big share of Chinese liquor [1]. The aroma of sauce-flavored Baijiu comes from the acids and esters in it [2]. Aging is an important process in producing high-quality sauce-flavored liquor to increase the contents of acids and esters and remove new flavors [3]. Traditionally, maturation in ceramic jars lasts between 3 and 5 years, during which gradual esterification and the slow loss of volatile compounds contribute to a mellow and harmonious spirit. However, with annual production of sauce-flavor Baijiu now exceeding 500,000 liters and consumer demand increasing by 15% per year, this lengthy natural aging process has become a critical bottleneck for industry expansion [4]. Multiple artificial aging methods, such as chemical aging, biological aging, and physical aging, are developed to speed up the aging process [5].

Chemical aging includes the oxidation method [6] and the catalytic method [2]. These methods depend on the chemical reagents, which will result in high costs and bring potential safety risks. For example, oxygen aging requires explosion protection, and the decomposition of potassium permanganate may affect the taste of the Baijiu. Biological aging is realized by secreting various biological enzymes [7]. However, the interactions among various enzymes are challenging to control quantitatively. Additionally, inhibitory effects may arise between different enzymes, which could mitigate the aging process [8].

*Corresponding authors: Chun Feng Guo, School of Science, Shanghai Institute of Technology, China. Email: cfguo@sit.edu.cn and Jun Zou, School of Science, Shanghai Institute of Technology, China, and Institute of New Materials & Industrial Technology, Wenzhou University, China. Email: zoujun@sit.edu.cn

While biological aging methods can closely mimic natural maturation, each approach presents notable limitations. Microbial-enhanced fermentation effectively promotes ester synthesis; however, the complex interactions among strains and the difficulty in precisely controlling fermentation conditions often result in batch-to-batch quality inconsistencies [8]. Koji-enhanced aging is compatible with traditional processes, but prolonged koji preparation cycles and the susceptibility of microbial communities to environmental fluctuations lead to unstable product quality [1]. Ceramic-jar micro-ecological aging can generate abundant flavor compounds; nevertheless, it still requires a lengthy aging period, occupies substantial space, and suffers from low production efficiency [9]. Bioreactor technology can drastically shorten aging time; however, it is hampered by high capital investment, elevated operating and maintenance costs, and challenges in scaling up [5]. These drawbacks underscore the urgent need for a safer and more controllable alternative aging strategy.

Physical aging is completed by using high temperature [10], microwave, high pressure [11], ultrasonic waves [12], light irradiation, etc. [13, 14]. For high temperature and microwave aging, it is easy to cause Baijiu volatilization and affect the Baijiu flavor [15]. The cost of high-pressure treatment equipment is high. The ultrasonic aging method can easily lead to the appearance of small molecules that may not exist in natural aging.

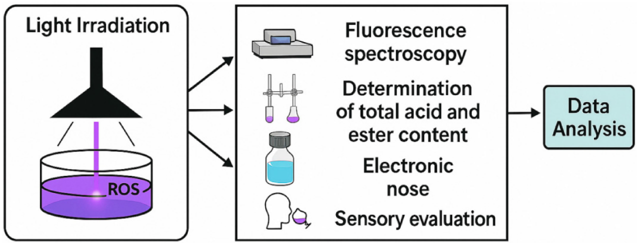
As a physical aging method, light aging is considered to be a relatively safe solution and has attracted wide attention. Light illumination is exploited to accelerate the REDOX reaction and esterification reaction to shorten the aging period. Irradiation from ultraviolet (UV) light can effectively inactivate polyphenol oxidase and reduce the content of volatile acids. It can also effectively reduce the amount of sulfur dioxide used in the wine-making process [14]. Kim et al. [16] proposed that fluorescence irradiation greatly reduced the volatile content in red wine and had a certain aging effect. When the wine is irradiated with a continuous light source with wavelengths from 360 to 800 nm, fatty esters in wine will degrade, and pH will change [13].

While the light aging of wine and red wine has been successfully explored, the light aging of sauce-flavored Baijiu remains under-researched. The application of 365 nm near-UV light (approximately 3.4 eV) can induce electronic transitions in specific organic molecules, such as phenols and aldehydes, found in liquor, thereby triggering photo-oxidation reactions. Research indicates that this wavelength can excite electron carriers, resulting in the generation of reactive oxygen species, such as superoxide radicals, which accelerate the oxidation and degradation of organic matter [17]. In contrast, 395 nm light, situated at the near-UV-visible boundary, possesses slightly lower energy than 365 nm light but offers superior penetration, making it more suitable for exciting molecules in the deeper layers of liquor. Experimental evidence demonstrates that 395 nm light can effectively excite specific organic pollutants during fluorescence detection and exhibits selective excitation capabilities for aromatic compounds, such as phenols present in sauce-flavored liquor [18]. This wavelength can directly excite chromophores, particularly conjugated structures in brown carbon (BrC), thereby initiating radical chain reactions and accelerating ester synthesis or aldehyde condensation [19]. Furthermore, 455 nm blue light, which lies within the visible spectrum and has lower energy (approximately 2.7 eV), can selectively excite specific molecular orbitals. For instance, this wavelength can effectively identify nitrogen- or oxygen-containing heterocyclic compounds, such as pyrazines, which are key flavor components in sauce-flavored liquor [20]. Blue light may facilitate the rearrangement or polymerization of these heterocyclic compounds via $\pi \rightarrow \pi^*$ electronic transitions, thereby forming more complex flavor substances [3]. Given the advantages of these three light sources and to mitigate the harmful effects of deep-UV light on human health, this study employs near-UV light at 365 and 395 nm, along with blue light at 455 nm, to irradiate sauce-flavored liquor [21]. The fluorescence spectra before and after 1 week of aging are measured to capture subtle changes in composition and to identify the optimal aging light source. The saponification and acid-base titration methods are employed to reflect the changes in total acids and total esters over 1 month. Sensory assessment and principal component analysis (PCA) of the electronic nose data demonstrate a positive effect of light aging on sauce-flavored Baijiu.

2. Methods

Figure 1 illustrates the schematic diagram of the maturation analysis system for sauce-flavored Baijiu. A sauce-flavored Baijiu, designated as "Dong Zhi Jia," with an alcohol content of 53% (v/v) and a total volume of 1500 ml, is selected and evenly distributed into three transparent glass containers. These containers are sealed with thermoplastic film to ensure airtightness. Each container is illuminated by LED light sources with central wavelengths of 365, 395, and 455 nm, respectively. The original liquor and the irradiated samples are sequentially labeled as samples 1, 2, 3, and 4. The system is placed in a dark room maintained at a constant temperature of 25 °C, where the samples in the containers are irradiated for 12 h each day over a period of 4 weeks. At the conclusion of each week, the total acids, total esters, and sensory evaluations of the Baijiu samples are conducted. To accurately determine the optimal maturation

Figure 1
System diagram of Baijiu aging analysis



time for light irradiation, all experiments are performed in triplicate, and the results presented are the averages of the three trials.

2.1. Fluorescence spectroscopy

An FS5 fluorescence spectrometer (Edinburgh Instruments Ltd., Germany) is used to measure the fluorescence spectrum of sauce-flavored Baijiu. The tested Baijiu samples are placed in a 1 × 1 × 4 cm sealable quartz colorimeter. The quartz cuvette is washed with deionized water before each test and rinsed with a small amount of the liquid sample to be tested. Then, 5 mL of the liquid sample is aspirated with a pipette gun. The tested sauce-flavored Baijiu sample is placed into a 1 × 1 × 4 cm sealable quartz cuvette. The cuvette's lid is closed and placed into a fluorescence spectrometer. The emission slit (Em) of the fluorescence spectrometer is set to 2 nm, the excitation slit (Ex) is set to 3 nm, and the scanning speed is set to 300 nm/min. The optimal excitation-emission wavelength of the sample is 330/430 nm [22].

2.2. Determination of total acid and ester content

The equipment for the determination of the total acid and total ester mainly includes beakers, glass bottles, round-bottom flasks, thermometers, buret pipettes, cow horn tubes, weighing paper, conical flasks, condensing tubes, Mettler Toledo AL204 electronic analytical balance, and Shanghai Yiheng HWS-24 water bath.

Here is the translation of the procedure for determining total acidity:

Before the determination, it is necessary to prepare a 10 g/L phenolphthalein indicator and a 0.1 mol/L sodium hydroxide standard titration solution. The preparation of all solutions should be carried out in accordance with the Chinese National Standard GB 12456-2021 [23]. A 50 mL sample and two drops of phenolphthalein indicator are added to the flask, and the mixture is stirred well. The sample is then titrated with the sodium hydroxide standard titration solution until a pink color is observed, and the volume of the sodium hydroxide standard titration solution consumed is recorded. The total acidity content is calculated using the following formula:

$$X_1 = \frac{c \times V \times 60}{50} \quad (1)$$

X_1 is the mass concentration of total acid (acetic acid) in the sample, in g/L; c is the actual concentration of sodium hydroxide standard titration solution, in mol/L; V is the volume of sodium hydroxide standard solution consumed, in mL; 60 is the numerical value of the molar mass of acetic acid, the unit is g/mol; and 50 is the volume of the sample drawn, in ml.

Here is the translation of the procedure for determining total esters:

Before the determination, it is necessary to prepare 0.1 and 3.5 mol/L sodium hydroxide standard titration solutions, 0.1 mol/L sulfuric acid standard solution, 10 g/L phenolphthalein indicator solution, and 40% volume fraction ethanol (ester-free) solution in accordance with the national standard. A 50 mL sample and two drops of phenolphthalein indicator are added to the flask, and the mixture is stirred well. The sample is then titrated with 0.1 mol/L sodium hydroxide standard titration solution until a pink color is observed. The volume of the sodium hydroxide standard titration solution consumed is recorded. Subsequently, 25 mL of 0.1 mol/L sodium hydroxide standard titration solution is accurately added to the pink-colored mixture, and the mixture is shaken well. Two boiling chips are added, a condenser is attached, and then the mixture is refluxed in a boiling water bath for 30 min. Afterward, the flask is removed and cooled to room temperature. The reacted sample is titrated with 0.1 mol/L sulfuric acid standard solution. The titration continues until the red color completely disappears, indicating the end of the titration. The volume of sulfuric acid consumed is then recorded. Concurrently, 50 mL of 40% volume fraction ethanol solution is aspirated, and a blank experiment is performed according to the above method, recording the volume of sulfuric acid solution consumed. The total ester content is calculated using the following formula:

$$X_2 = \frac{c \times (V_0 - V_1) \times 88}{50.0} \tag{2}$$

X_2 is the mass concentration of total ester (ethyl acetate), in g/L; c is the actual concentration of sulfuric acid standard titration solution, in mol/L; V_0 is the titrated volume of the sulfuric acid standard solution consumed by the blank test sample, in mL; V_1 is the volume of sulfuric acid standard solution consumed by the sample, in mL; 88 is the numerical value of the molar mass of ethyl acetate, the unit is g/mol; and 50 is the volume of the sample drawn, in ml.

2.3. Electronic nose and sensory evaluation

The PEN3 electronic nose from Germany's AIRSENSE is used in the experiment. The electronic nose consists of 10 metal oxide sensors, and the sensor performance is described in Table 1. Each sample is accurately weighed at 2.000 g and placed into a headspace bottle. It is also sealed at 25 °C for 20 min to ensure adequate volatilization. Before detection, the sensors are balanced in dry air for 180 s to establish a baseline. The probe of the electronic nose is then inserted into the vial to capture the headspace air, with a total sampling duration of 60 s. For analytical accuracy, sensor responses are recorded at the 52-s mark, which is considered to be the most stable. This process is repeated five times for each sample to ensure the reliability and reproducibility of the results [24]. Then, the sensory characteristics of the Baijiu before and after aging are described using the "flavor wheel" evaluation method, and a 10-point scale is used to describe the perceived intensity. The scores for newly produced Baijiu taste, sauce flavor, "aging" aroma, mellow degree, and refreshing were 0 for none, 1–3 for low, 4–6 for medium, and 7–10 for high. The sensory evaluators repeat the evaluation three times for each sample, and the final evaluation for each sample is the average of the results of the three tastings by each sensory evaluator [9].

Table 1
PEN electronic nose sensor sensitive substances

Serial number	Transducers	Sensitive materials
S1	W1C	Sensitive to aromatic compounds
S2	W5S	Sensitive to nitrogen oxides
S3	W3C	Sensitive to ammonia, aromatic compounds
S4	W6S	Sensitive to hydrides
S5	W5C	Sensitive to olefins, aromatic compounds
S6	W1S	Sensitive to alkanes
S7	W1W	Sensitive to inorganic sulphones
S8	W2S	Sensitive to some aromatic compounds and alcohols
S9	W2W	Sensitive to organic sulphones, aromatic compounds
S10	W3S	Sensitive to alkanes and fats

3. Results and Discussion

3.1. Comparative analysis of the three light sources

From Figure 2, it can be seen that the 365 nm light source is located in the UV region. A distinct sharp peak is observed at 365 nm, where the spectral intensity drops rapidly on both sides. Its spectrum is relatively narrow, with a full width at half maximum (FWHM) of 10 nm, indicating that the emitted photon energy is concentrated within the UV range and the light source has high monochromaticity [25].

The 395 nm light source is located at the boundary between the UV and visible light regions and represents the intermediate wavelength among the three light sources. Similar to the 365 nm light source, its spectrum is relatively narrow, with a FWHM of approximately 12 nm, indicating good monochromaticity. A distinct peak is observed at 395 nm. Compared to the 365 nm light source, its spectrum exhibits a slight tailing toward the visible light region, with the intensity gradually decreasing near the UV-visible boundary.

The 455 nm light source is situated in the blue light region and has the longest wavelength among the three sources. Its spectral width is slightly broader, with a FWHM of approximately 20 nm, but it maintains relatively good monochromaticity overall. A distinct peak is observed at 455 nm. Unlike the previous two sources, it exhibits more pronounced spectral tailing toward longer wavelengths, and the spectral intensity extends to the range of 500–600 nm to a certain extent. This indicates that, in addition to its dominant blue light emission, the light source also contains minor contributions from other visible light components.

The comparative analysis of the characteristics of the three light sources is presented in Table 2. All three sources exhibit high emission intensities at their respective peak wavelengths, indicating strong emission energy at their intended spectral positions. This high intensity ensures sufficient photon flux under illumination, thereby effectively initiating the esterification reaction.

3.2. Fluorescence spectroscopy analysis

To assess the degree of aging of sauce-flavored Baijiu, fluorescence spectroscopy tests are conducted. Figure 3 shows the fluorescence spectra of Dong Zhi Jia samples before and after

Figure 2
Spectrogram of the light source

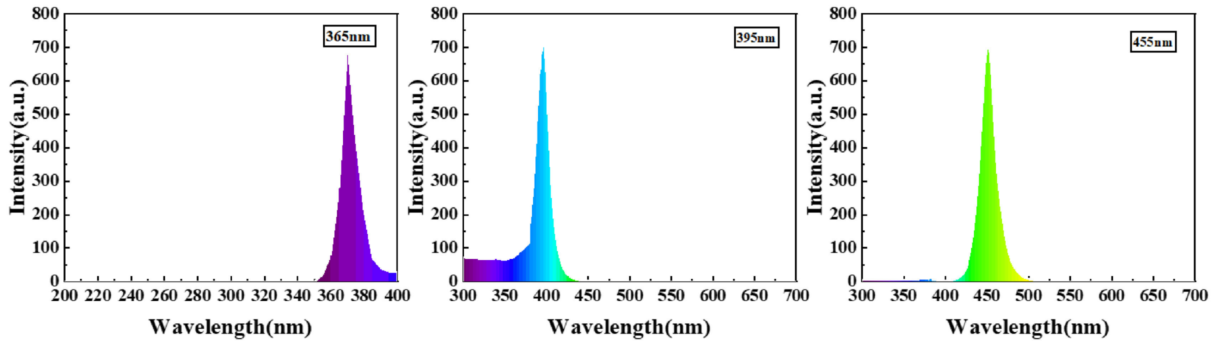


Table 2
Comparative analysis of the characteristics of the three light sources

Parameter	365 nm	395 nm	455 nm
Spectral range	Ultraviolet (UV-A)	UV-A/visible boundary	Visible (blue)
Peak wavelength	365 ± 2 nm	395 ± 2 nm	455 ± 3 nm
FWHM (nm)	10	12	20
Photon energy	~3.4 eV	~3.1 eV	~2.7 eV
Spectral purity	High (sharp peak, low tailing)	Moderate (minor visible tailing)	Lower (broad emission)
Penetration depth	Moderate (UV absorption)	High (transition zone)	Highest (visible range)

aging. Figure 3(a) is the excitation spectrum. It can be seen from Figure 3(a) that, compared with the original Baijiu, the half peak width of the excitation spectrum of the aged sample has increased. The largest increase in half peak width is observed for the sample numbered 3 illuminated by a light source with a wavelength of 395 nm. The overall shape of the peak in the excitation spectra remains unchanged. Figure 3(b) shows the emission spectra. It can be seen from Figure 3(b) that the optimal excitation wavelength for the samples is 330 nm. The position of the optimum emission peak for each sample exhibits a blue shift to a different extent compared with that of sample 1. The relative fluorescence intensity of the best emission peaks increased by about 28%, 161%, and 344%, respectively. Samples 2 and 3 show a larger increase in fluorescence intensity at the maximum emission wavelength and a higher degree of blue shift, with peak wavelengths centered around 380 nm. It is shown that ethyl butyrate, ethyl hexanoate, ethyl acetate, and ethyl valerate could produce fluorescence peaks around 380 nm after irradiation with 330 nm light, while phenethyl acetate and ethyl lactate could produce fluorescence peaks around 430 nm after irradiation with 330 nm light [26]. Baijiu is a complex compound system; the overall fluorescence spectrum of Baijiu is formed by the superposition of fluorescence produced by a variety of monomer fluorescent substances [27]. Most ester compounds have electronic transition types of $\pi^*\to\pi$ or $\pi^*\to n$, which have the highest fluorescence efficiency, accompanying the formation of esters. Although the content of other substances in the Baijiu, such as alcohols and aldehydes, may increase and produce fluorescence, the fluorescence intensity of esters is comparatively strong, leading to a certain degree of blue shift in the peak wavelength of the overall fluorescence emission spectrum. It can be inferred that after irradiation, there is a certain degree of increase in the content of esters in the Baijiu. When Baijiu is irradiated with a 455 nm light source, insufficient excited-state oxygen is produced to accelerate the oxidation reaction, resulting in a weaker enhancement of fluorescence intensity. The highest fluorescence intensity at 395 nm may be attributed to the abundance of substances in the Baijiu capable of absorbing the energy from light sources around 395 nm, leading to more efficient energy conversion. Ester substances are the main components in the formation of Baijiu's flavor, and the increase of ester substances is more conducive to the improvement of Baijiu quality [28].

3.3. Total acids and total esters analysis

To further investigate the aging effect of each aging light source under different aging time conditions, we examine the total acid and ester content variations for each sample over 4 weeks, starting from week 0. The test results are shown in Figure 4.

All the samples irradiated with the 365 nm light source show different decreases in total acid content compared to the original Baijiu samples. The observed reduction rates in total acid for the samples are 4.59%, 5.50%, 30.28%, and 11.93%, respectively. The most significant decrease in total acid content occurred during the 3 weeks. The total acid content of the samples shows a decreasing trend in the first 3 weeks of aging and starts to increase in the fourth week. The total ester content of the samples shows an increasing and then decreasing trend under a 365 nm light source. The total ester content of the samples increased by 5.56%, 6.57%, and 4.04% in the first 3 weeks of total ester content testing. In the second week of total ester testing, the samples reach a maximum total ester content of 2.11 g/L. After the fourth week of irradiation, the total ester content of the sample decreased by about 7.07% from the original Baijiu sample.

The total acid content of the samples irradiated with a 395 nm light source shows different degrees of decrease than the original samples. They decreased by 3.67%, 4.59%, 11.93%, and 10.09%, respectively. The total acid content decreases in the first 3 weeks

Figure 3

Fluorescence spectra of Dong Zhi Jia samples before and after aging (1, 2, 3, and 4 represent the original liquor not irradiated and the samples irradiated with light sources of 365 nm, 395 nm, and 455 nm, respectively). (a) Excitation spectra of Dong Zhi Jia at 430 nm emission wavelength; (b) emission spectra of Dong Zhi Jia at 330 nm excitation wavelength

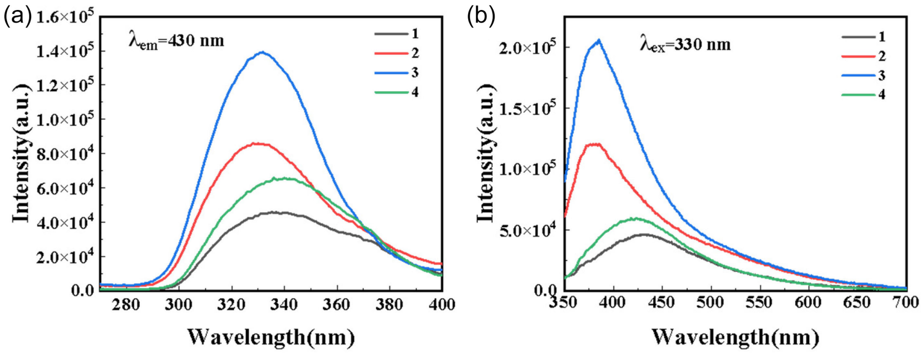
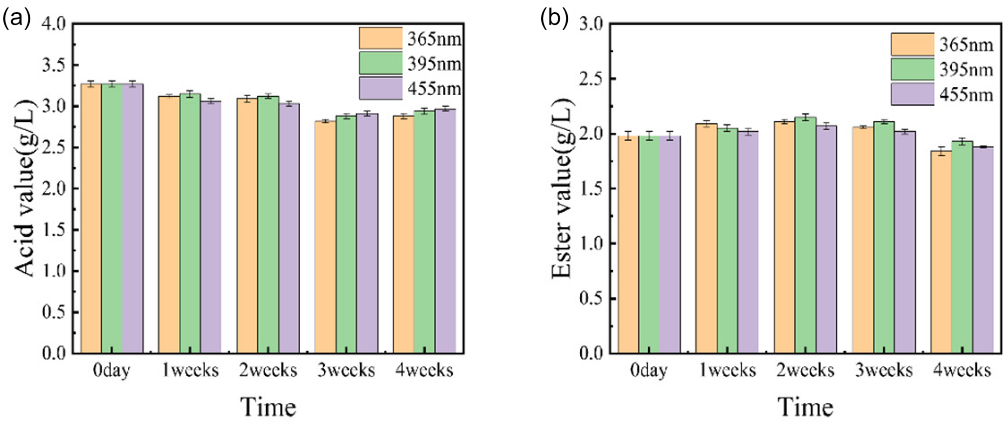


Figure 4

Changes in total acid and total ester of each sample of Dong Zhi Jia aged under different wavelengths of light source for 0~4 weeks. (a) The variation of total acid content; (b) the variation of total ester content



and then increases gradually. The total ester content varied similarly to the irradiation with a 365 nm light source. The total ester content increased by 3.53%, 8.59%, and 6.57% during the first 3 weeks of irradiation. The maximum total ester content reached 2.15 g/L in week 2. In week 4, the total ester content decreased by 2.53% to reach the lowest value.

All samples irradiated with the 455 nm light source show different decreases in total acid content compared to the original Baijiu samples. They decreased by 6.42%, 7.34%, 11.01%, and 9.17%, respectively. The overall trend is consistent when compared to the results of irradiation at 365 and 395 nm. The total acid content started to show an increasing trend in the fourth week. In the first 3 weeks, the total ester content increased by 2.02%, 4.55%, and 2.02%, respectively. In the fourth week, the total ester content decreased significantly, with the lowest value being 1.58 g/L. The decrease is about 5.05%.

When the samples are irradiated with the higher energy of UV light, the redox reaction in Baijiu is accelerated. Most of the esterification reactions between acids and alcohols occurred in the first 3 weeks. At this stage, the alcohols and acids in the Baijiu react to form esters, which are the main elements in the formation of flavor substances. The content of esters reaches a maximum in the third week. In the fourth week, the reaction starts to shift toward the hydrolysis of esters. An increase followed the hydrolysis of esters in the content of acids [29]. This is consistent with the natural aging pattern of Baijiu. In addition, irradiation with 395 nm light sources significantly influences the Baijiu's total acid and ester content. In the second week of irradiation, the total ester content experienced a greater increase than that of the original Baijiu. It can be obtained that 395 nm is the better aging band among the three light sources, and the optimal aging period is 2 weeks. From the perspective of current national standards, the total acid and total ester content of the Baijiu after 2 weeks of aging has reached the level of first-class Baijiu. The total ester content is very close to the standard of 2.20g/L for premium-grade Baijiu.

3.4. Electronic nose test analysis

To further illustrate the aging effect of the optimally aged samples, an electronic nose test was conducted on samples aged for 2 weeks using a 395 nm light source. This test targets the volatile compounds that significantly contribute to the aroma of Baijiu, including aromatic compounds, alkanes, fatty acids, nitrogen oxides, hydrides, and 10 other major categories of sensitive substances. Each sample was tested four times, and the results of the PCA are presented in Figure 5. In Figure 5(a), the contribution rate of the first principal component is 99.7%, while

Figure 5
Results of PCA for e-nose test

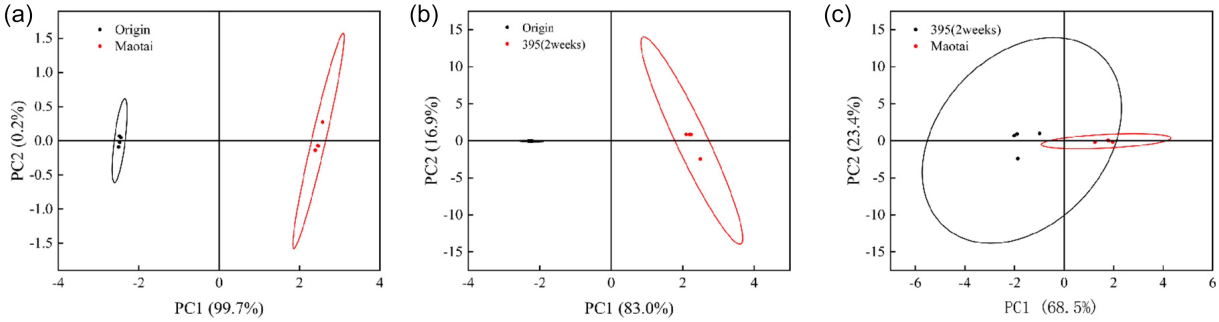
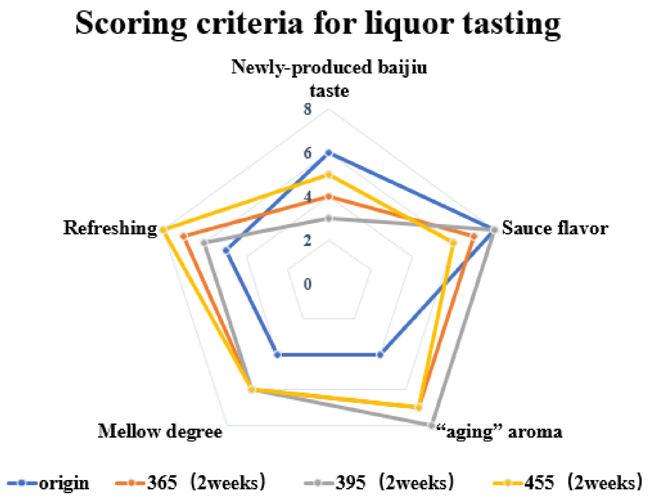


Figure 6
Radar chart of sensory evaluation



that of the second principal component is 0.2%. PCA effectively distinguishes the aromas of the original Baijiu and Maotai [23, 30]. In Figure 5(b), the contribution rate of the first principal component is 83.0%, and that of the second principal component is 16.9%. PCA also demonstrates a clear distinction between the original Baijiu and the light-irradiated Baijiu samples. In Figure 5(c), the contribution rate of the first principal component is 68.5%, and the contribution rate of the second principal component is 23.4%. Notably, the aged sample overlaps with Moutai. According to the PCA results, the aroma components of the aged samples are closer to those of Moutai compared to the original Baijiu. This further supports the conclusion that irradiation with a 395 nm light source for 2 weeks can enhance the flavor profile, making it more akin to that of high-quality Baijiu.

3.5. Sensory evaluation analysis

Ten practitioners of Baijiu conducted sensory evaluations, and the final scores were plotted on a radar chart. As illustrated in Figure 6, the overall aroma of the samples shows a notable improvement following light irradiation. The newly produced Baijiu taste in the three groups of samples exhibits a greater reduction post-photoirradiation, with the samples irradiated at 455 nm demonstrating the most significant decrease in the newly produced Baijiu taste. Furthermore, with the exception of the samples irradiated at 455 nm and the original Chinese Baijiu sample—which received identical scores for sauce flavor—the other two samples experienced a decline in this attribute. The irradiated samples received higher scores for aged and freshness attributes compared to the original samples, with freshness scores reaching approximately 7 and agedness scores around 7.5. The cellar aroma of the irradiated samples achieved a score of 6, representing a substantial improvement over the original Baijiu's score of 2. Overall, photoirradiation exerts a positive influence on the Baijiu samples across all evaluated aspects. The aroma of the irradiated Baijiu is distinctly purer, and the irritation associated with the newly produced Baijiu taste has been significantly mitigated. Additionally, attributes such as freshness, aged aroma, and cellar aroma have all experienced certain enhancements, indicating a more stable Baijiu body and the gradual development of a distinctive aroma composition. Conversely, there is a slight reduction in the sauce aroma, which enhances the harmony of the overall aroma and suggests that photoirradiation has achieved a certain aging effect [9].

3.6. Reliability analysis of light-irradiation aging method

The experiments employed narrow-bandwidth LEDs to ensure spectral precision and minimize side reactions. The exclusion of deep-UV light eliminated any risk of DNA damage. In the determination of total acids and esters, triplicate assays demonstrated coefficients of variation below 5%, confirming excellent reproducibility. Under 395 nm irradiation, total esters steadily increased to 2.15 g L^{-1}, while total acids declined in parallel, mirroring the trend of natural aging. PCA of electronic nose data revealed that the light-aged samples closely resembled Maotai in key aroma markers, such as aromatic compounds and pyrazines. No oxidants or catalyst residues were detected, thereby meeting food safety standards. Sensory evaluation conducted by trained Baijiu panelists confirmed a significant reduction in "new-spirit" notes and a marked enhancement of aged aroma, validating the flavor improvement. Although further optimization is required for large-scale efficiency and long-term stability, this approach provides a novel pathway for the rapid aging of Baijiu.

4. Conclusion

This paper presents a light-based aging method for sauce-flavored Baijiu. LED lights with central wavelengths of 365, 395, and 455 nm were employed to irradiate the sauce-flavored Baijiu "Dong Zhi Jia" to expedite the aging process. Various tests, including fluorescence spectroscopy, total acid and ester assays, electronic nose PCA, and sensory evaluation, were conducted on the aged samples. The results indicated that 2 weeks of irradiation with the 395 nm LED light significantly enhanced the liquor quality by rapidly increasing the ester content. Both sensory and electronic nose analyses revealed that the aged samples exhibited reduced pungency and richer aromas, closely resembling high-quality Baijiu such as Maotai. This method provides a practical and efficient alternative to traditional aging techniques.

Funding Support

This work was supported by the "Pioneer" and "Leading Goose" R&D Program of Zhejiang Province (No. 2024C01193), Shanghai Science and Technology Committee (STCSM) Science and Technology Innovation Program (No. 22N21900400, No. 23N21900100), and Key R&D Program of Jiangsu Province (No. BE2023048).

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Xiang Gao: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Visualization. **Ri Zeng Tao:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Visualization. **Chun Feng Guo:** Validation, Resources, Writing – review & editing, Supervision. **Qi Fei Zhu:** Software, Formal analysis, Investigation, Visualization. **Bobo Yang:** Resources, Writing – review & editing, Supervision. **Jun Zou:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

References

[1] Li, W., Zhang, H., Wang, R., Zhang, C., & Li, X. (2024). Temporal profile of the microbial community and volatile compounds in the third-round fermentation of sauce-flavor *baijiu* in the Beijing region. *Foods*, *13*(5), 670. https://doi.org/10.3390/foods13050670

[2] Wang, Z., Xiong, A., Yu, Y., & Zheng, Q. (2022). Electrochemical esterification in distilled liquor via gold catalysis and its application for enhancing ester aroma of low-alcohol liquor. *Current Research in Food Science*, *5*, 1769–1776. https://doi.org/10.1016/j.crfs.2022.10.003

[3] Wang, C., Wegeberg, C., & Wenger, O. S. (2023). First-row d^6 metal complex enables photon upconversion and initiates blue light-dependent polymerization with red light. *Angewandte Chemie*, *135*(43), e202311470. https://doi.org/10.1002/ange.202311470

[4] Huang, H., Gao, Y., Wang, L., Yu, X., Chen, S., & Xu, Y. (2024). Maillard reaction intermediates in Chinese Baijiu and their effects on Maillard reaction related flavor compounds during aging. *Food Chemistry: X*, *22*, 101356. https://doi.org/10.1016/j.fochx.2024.101356

[5] Du, J., Xu, Z., Sun, H., Zhu, Y., Zhang, J., Huang, M., . . . , & Wu, J. (2025). Effect of a new sea-aging method on the flavor of Baijiu. *Food Research International*, *212*, 116442. https://doi.org/10.1016/j.foodres.2025.116442

[6] Xiong, A., Zhao, K., Hu, Y., Yang, G., Kuang, B., Xiong, X., . . . , & Zheng, Q. (2020). Influence of electrochemical oxidation on the maturation process of the distilled spirit. *ACS Omega*, *5*(29), 18349–18355. https://doi.org/10.1021/acsomega.0c02090

[7] Chen, Z., Xie, H.-Y., Chen, G.-E., Xu, S.-J., Xu, Z.-L., Li, Y.-J., & Mao, H.-F. (2021). Self-adhesive PMIA membranes with virus-like silica immobilized lipase for efficient biological aging of Chinese liquor. *Journal of Membrane Science*, *621*, 118990. https://doi.org/10.1016/j.memsci.2020.118990

[8] Zeng, Y., Wang, Y., Chen, Q., Xia, X., Liu, Q., Chen, X., . . . , & Zhu, B. (2022). Dynamics of microbial community structure and enzyme activities during the solid-state fermentation of Forgood Daqu: A starter of Chinese strong flavour Baijiu. *Archives of Microbiology*, *204*(9), 577. https://doi.org/10.1007/s00203-022-03198-w

[9] Wei, L., Hu, J., Pan, C., Cheng, P., Zhang, J., Xi, D., . . . , & Hu, F. (2023). Effects of different storage containers on the flavor characteristics of Jiangxiangxing Baijiu. *Food Research International*, *172*, 113196. https://doi.org/10.1016/j.foodres.2023.113196

[10] Kang, J.-E., Kim, C.-W., Yeo, S.-H., Jeong, S.-T., Kim, Y.-S., & Choi, H.-S. (2018). Effect of heat-treated *Nuruk* on the quality characteristics of aged *Yakju*. *Food Science and Biotechnology*, *27*(3), 715–724. https://doi.org/10.1007/s10068-018-0306-4

[11] Xu, M., Zhu, S., Ramaswamy, H. S., & Yu, Y. (2017). Effect of high pressure treatment and short term storage on changes in main volatile compounds of Chinese liquor. *Scientific Reports*, *7*(1), 17228. https://doi.org/10.1038/s41598-017-17549-x

[12] Gavahian, M., Manyatsi, T. S., Morata, A., & Tiwari, B. K. (2022). Ultrasound-assisted production of alcoholic beverages: From fermentation and sterilization to extraction and aging. *Comprehensive Reviews in Food Science and Food Safety*, *21*(6), 5243–5271. https://doi.org/10.1111/1541-4337.13043

[13] Acquaviva, V., D'Auria, M., & Racioppi, R. (2014). Changes in aliphatic ester composition of white wines during exposition to light. An HS-SPME-GC-MS study. *Journal of Wine Research*, *25*(2), 63–74. https://doi.org/10.1080/09571264.2014.888648

[14] Falguera, V., Forns, M., & Ibarz, A. (2013). UV–vis irradiation: An alternative to reduce SO_2 in white wines? *LWT – Food Science and Technology*, *51*(1), 59–64. https://doi.org/10.1016/j.lwt.2012.11.006

[15] Niu, J., Li, W., Du, B., Wu, Y., Lang, Y., Sun, B., . . . , & Li, X. (2025). Temporal heterogeneity of microbial communities and flavor metabolism during storage of high-temperature *Daqu*. *Food Chemistry*, *464*, 141577. https://doi.org/10.1016/j.foodchem.2024.141577

[16] Kim, S. H., Jung, H. J., & Lee, J. H. (2021). Changes in the levels of headspace volatiles, including acetaldehyde and formaldehyde, in red and white wine following light

irradiation. *Journal of Food Science*, *86*(3), 834–841. https://doi.org/10.1111/1750-3841.15642

[17] Kvam, E., & Benner, K. (2020). Mechanistic insights into UV-A mediated bacterial disinfection via endogenous photosensitizers. *Journal of Photochemistry and Photobiology B: Biology*, *209*, 111899. https://doi.org/10.1016/j.jphotobiol.2020.111899

[18] Whalen, M. J., Aizenberg, A. M., Shirazi, F. M., Berrigan, J. J., & Walter, F. G. (2024). Skin decontamination with and without water irrigation. *Disaster Medicine and Public Health Preparedness*, *18*, e220. https://doi.org/10.1017/dmp.2024.118

[19] Boreddy, S. K. R., Hegde, P., Arun, B. S., Aswini, A. R., & Babu, S. S. (2022). Molecular composition and light-absorbing properties of organic aerosols from west-coast of tropical India. *Science of the Total Environment*, *845*, 157163. https://doi.org/10.1016/j.scitotenv.2022.157163

[20] Harte, A., Cassella, J. P., & McCullagh, N. A. (2020). Recovery of trace evidence in forensic archaeology and the use of alternate light sources (ALS). *Forensic Science International*, *316*, 110475. https://doi.org/10.1016/j.forsciint.2020.110475

[21] Valanciute, A., Ross, C. A., Burden, A., Mohanan, S. M. P. C., Sabbah, M., Ghobrial, J. M. W., . . . , & Dhaliwal, K. (2025). Far-ultraviolet light causes direct DNA damage in human lung cells and tissues. *Scientific Reports*, *15*(1), 18055. https://doi.org/10.1038/s41598-025-02869-0

[22] Tao, R., Liu, H., Guo, C., Zou, J., Zhu, Q., Yang, Y., . . . , & Chen, L. (2023). Vintage identification of sauce-flavor liquor based on fluorescence spectroscopy. *Quality Assurance and Safety of Crops & Foods*, *15*(4), 125–132. https://doi.org/10.15586/qas.v15i4.1371

[23] Zhang, W., Xiao, Y., Deng, R., Wang, Y., Qiu, Y., Sun, Q., & Luo, A. (2023). An electric-field instrument for accelerated aging to improve flavor of Chinese Baijiu. *Food Science and Technology*, *174*, 114446. https://doi.org/10.1016/j.lwt.2023.114446

[24] Xu, M., Wang, J., & Zhu, L. (2019). The qualitative and quantitative assessment of tea quality based on E-nose, E-tongue and E-eye combined with chemometrics. *Food Chemistry*, *289*, 482–489. https://doi.org/10.1016/j.foodchem.2019.03.080

[25] Lee, H. L., Chung, W. J., & Lee, J. Y. (2020). Narrowband and pure violet organic emitter with a full width at half maximum of 14 nm and *y* color coordinate of below 0.02. *Small*, *16*(14), 1907569. https://doi.org/10.1002/smll.201907569

[26] Yang, J.-L., Zhu, T., Xu, Y., Fan, W.-L., Chen, G.-Q., & Wu, H. (2009). Báijiǔ dān tǐ wùzhí zǐwài yíngguāng guāngpǔ yánjiū [Study on ultraviolet fluorescence spectra of monomers of distilled spirits]. *Spectroscopy and Spectral Analysis*, *29*(12), 3339–3343. https://doi.org/10.3964/j.issn.1000-0593(2009)12-3339-05

[27] Liu, X., Wang, X., Cheng, Y., Wu, Y., Yan, Y., & Li, Z. (2023). Variations in volatile organic compounds in Zhenyuan Daocai samples at different storage durations evaluated using E-nose, E-tongue, gas chromatography, and spectrometry. *Food Science and Technology*, *173*, 114186. https://doi.org/10.1016/j.lwt.2022.114186

[28] Wei, Y., Zou, W., Shen, C., & Yang, J. (2020). Basic flavor types and component characteristics of Chinese traditional liquors: A review. *Journal of Food Science*, *85*(12), 4096–4107. https://doi.org/10.1111/1750-3841.15536

[29] Xie, Z., Zhang, K., Zhao, J., & Yang, J. (2021). Jiàng xiāng xíng báijiǔ chénniàng yánjiū jìnzhǎn [Research progress of Moutai-flavor Baijiu aging]. *China Brewing*, *40*(3), 1–5. https://doi.org/10.11882/j.issn.0254-5071.2021.03.001

[30] Zhang, J., Yin, B., Lian, Z., Sun, H., Zhang, G., Li, Z., . . . , & Shi, G. (2024). A practical method based on gas chromatography–mass spectrometry combined with chemometrics for the identification of Moutai liquor. *International Journal of Food Science and Technology*, *59*(10), 8027–8036. https://doi.org/10.1111/ijfs.17145

How to Cite: Gao, X., Tao, R. Z., Guo, C. F., Zhu, Q. F., Yang, B., & Zou, J. (2025). Study on the Aging of Sauce-Flavored Baijiu Based on Light Irradiation. *Journal of Optics and Photonics Research*. https://doi.org/10.47852/bonviewJOPR52025878