Literature Review on Automated Monitoring and Fermentation Turning Control Systems for Solid-State Fermentation of Mature Vinegar

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Abstract: Solid-state layered fermentation is the core process for forming the unique flavor of mature vinegar. However, its traditional production mode relying on manual experience faces bottlenecks such as low efficiency and large quality fluctuations, making intelligent upgrading an inevitable demand for industrial development. This paper systematically combs the research literature on automated technologies for solid-state fermentation of mature vinegar, and conducts analysis from three dimensions: the evolution of monitoring technologies, the upgrading of fermentation turning control, and system integration practices. Research shows that monitoring technologies have developed from single-point temperature measurement to multi-parameter online sensing, and near-infrared spectroscopy (NIRS) combined with LoRa wireless transmission technology has realized the synchronous monitoring of flavor substances and environmental parameters; fermentation turning control has experienced a three-stage leap from mechanization, automation to intelligence, and the combination of fuzzy PID and fermentation kinetic models has significantly improved acid production efficiency; however, existing systems still have problems such as difficulty in multi-parameter coupled control and poor adaptability between flavor stability and digitization. In the future, it is necessary to build an integrated intelligent system of "perception-modeling-control-optimization" through multi-sensor fusion, digital twin modeling, and industry-university-research collaboration.

Keywords: Solid-state fermentation of mature vinegar; Automated monitoring; Intelligent fermentation turning; Fermentation kinetics

1. Introduction

1.1. Research Background and Significance

China has a vinegar brewing history of more than 3,000 years. Taking Huguo Mature Vinegar as an example, since its creation in 1889, it has formed a typical flavor with rich sour and aromatic notes relying on the unique solid-state layered fermentation process. Its products cover multiple categories and are representative of characteristic fermented foods in southern Sichuan. As the core technology of traditional brewing, solid-state fermentation promotes microbial metabolism through a gas-solid-liquid three-phase coexistence system, which has the advantages of low energy consumption and rich product flavors. However, uneven heat and mass transfer require frequent fermentation turning regulation, and the traditional manual operation mode restricts industrial upgrading.

According to industry data, China's vinegar production capacity reached 1.8 million tons in 2023, but less than 20% of enterprises adopted automated production lines. The temperature error of manual monitoring can reach ±2℃, leading to fluctuations in total acid content between batches exceeding 15%. With the proposal of requirements for the intelligent and digital transformation of traditional foods in the "Implementation Plan for the Digital Transformation of the Food Industry", the development of automated systems adapted to the mature vinegar process has become the key to breaking through industrial bottlenecks. This paper provides theoretical reference and technical paths for the intelligent transformation of solid-state fermentation brewing through a systematic review of relevant research.

1.2. Literature Retrieval and Screening

Taking "solid-state fermentation", "vinegar", "automated monitoring", "fermentation turning machine", and "fermentation kinetics" as core keywords, this paper retrieved literature from databases such as Web of Science, CNKI, and PubMed from 2010 to 2025, supplemented by the patent database of the State Intellectual Property Office and industry reports. The retrieval followed the standards of "theme relevance-technical innovation-application feasibility". After three stages of preliminary screening (excluding duplicate literature), secondary screening (reading abstracts to exclude irrelevant research), and precise screening (reading full texts to evaluate quality), 62 core literatures were finally included, including 38 journal papers, 17 patent literatures, 5 academic dissertations, and 2 industry reports, covering research results from major vinegar-producing countries such as China, Japan, and South Korea, to ensure the comprehensiveness and authority of the review.

1.3. Framework of the Review

This paper first defines core concepts and theoretical foundations, clarifies the technical connotation of solid-state fermentation monitoring and control; secondly, sorts out the research status from two dimensions: the evolution of monitoring technologies and the upgrading of fermentation turning control, and analyzes system integration modes combined with enterprise practice cases; then analyzes the technical bottlenecks and application obstacles faced by current research; finally, proposes future development directions, forming a logical system of "theory-current status-problems-prospects".

2. Definition of Core Concepts and Theoretical Foundations

2.1. Definition of Core Concepts

2.1.1. Solid-State fermentation process of mature vinegar

This process uses high-quality wheat bran, rice, glutinous rice, and wheat flour as main raw materials, supplemented by vinegar koji, edible salt, and nearly 100 kinds of Chinese herbal medicines. After saccharification and alcohol fermentation, it enters the acetic acid fermentation stage. Using small vats as fermentation carriers, it adopts the traditional method of natural sun exposure during the day and dew exposure at night, with a total fermentation and aging cycle of up to three years. The moisture content of vinegar grains is maintained at 60%-64%, and the pH value is 4.0-4.4[1]. The synergistic metabolism of Acetobacter pasteurianus and Lactobacillus helveticus forms characteristic flavor substances such as acetic acid and lactic acid. As a key operation, fermentation turning achieves temperature reduction (temperature difference up to 8.5℃) and oxygen supplementation through mechanical turning, directly affecting microbial activity and product formation [2].

2.1.2. Automated monitoring and fermentation turning control system

It refers to a closed-loop system integrating sensor perception, data transmission, intelligent decision-making, and executive mechanisms. Its core functions include: real-time collection of parameters such as temperature, moisture, and dissolved oxygen of vinegar grains, generation of fermentation turning instructions based on preset models or algorithms, completion of turning operations through motor-driven mechanisms, and support for remote data monitoring and process optimization. It is the core carrier for realizing "knowable, controllable, and optimizable" solid-state fermentation [3,4].

2.2. Theoretical Foundations

2.2.1. Solid-State fermentation kinetics theory

It reveals the dynamic relationship between microbial growth, substrate consumption, and product formation. Core models include: Monod equation describing the relationship between acetic acid bacteria growth and ethanol concentration, Han-Levenspiel equation quantifying product inhibition effect, and Boltzmann equation fitting the generation curve of flavor substances such as lactic acid. Research by the team of Jiangnan University shows that this theory can invert the microbial metabolic state through starch hydrolysis rate, providing a quantitative basis for the decision-making of fermentation turning timing [5].

2.2.2. Mass and heat transfer theory in multiphase systems

The pore structure of solid-state fermentation substrates determines oxygen transfer efficiency and thermal diffusion characteristics. The mass transfer area is optimal when the particle size is 425-500μm. Digital twin technology can construct a substrate-environment coupled heat transfer model, controlling temperature fluctuations within ±0.8℃, providing theoretical support for sensor layout and fermentation turning parameter optimization [5].

2.2.3. Internet of things and intelligent control theory

Wireless data transmission is realized based on protocols such as LoRa and ModBus, and a closed-loop control system is constructed combined with fuzzy PID algorithm. Practice by Jiangsu Hengshun shows that this theory can dynamically adjust fermentation turning frequency according to temperature changes, increasing acetic acid yield by 12% in summer.

3. Research Progress on Solid-State Fermentation Monitoring Technologies

3.1 Evolution of Monitoring Technologies

3.1.1. Manual sampling and detection stage (Before 2010)

Glass thermometers were used for single-point temperature measurement and titration for acid measurement, which had three limitations: first, destroying the integrity of the fermentation environment, with the local microbial community change rate reaching 18% after sampling; second, detection delay exceeding 2 hours, unable to respond to metabolic fluctuations in real time[6]; third, poor data representativeness, with the temperature gradient between the surface and deep layers of vinegar grains reaching 8.5℃. At this stage, the fermentation state could only be judged through experience, and this mode was adopted by all traditional vinegar enterprises.

3.1.2. Single-Point sensor online monitoring stage (2010-2020)

Contact sensors realized real-time collection of temperature and moisture. Representative technologies include: a portable thermometer dedicated for vinegar grains developed by Jiangsu Hengshun, which solved the problem of traditional instruments being easily adhered to by vinegar grains [7]; Sichuan Baoning Vinegar adopted a slide-type temperature measurement device to meet the monitoring needs of different tank types [8]. However, this stage still had problems such as single parameters and response lag. For example, the average error of DS18B20 temperature sensor was ±0.5℃, which could not meet the needs of multi-factor regulation.

3.1.3. Multi-Parameter fusion sensing stage (Since 2020)

Near-infrared spectroscopy, electrochemical, and gas sensors are integrated to realize synchronous monitoring of physical and chemical parameters and flavor substances. Near-infrared spectroscopy (NIRS) combined with BP-Adaboost algorithm has a root mean square error of only 0.0726 for predicting pH value and a correlation coefficient of 0.9811, which can simultaneously detect 8 key indicators such as glucose and acetic acid [9]. The application of LoRa wireless transmission technology solves the wiring problem in industrial environments. For example, the monitoring system for strong-flavor liquor cellars realizes wireless transmission of temperature and moisture data through SX1278 radio frequency chips, reducing the average errors to 0.23℃ and 0.65% respectively [10].

3.2 Application Status of Key Monitoring Technologies

At present, the key monitoring technologies for the solid-state fermentation of mature vinegar have formed a collaborative application pattern of contact and non-contact types, covering the core detection requirements such as physicochemical parameters and flavor substances. See Table 1 for details on the specific detection parameters, core advantages, practical application cases and accuracy performance of various technologies, which provide diversified technical support for the real-time and accurate perception of the fermentation process [7-8,11].

Table 1. Application status of key monitoring technologies

Monitoring Technology	Detection Parameters	Technical Advantages	Application Cases	Accuracy Indicators
Contact Sensor Array	Temperature, Moisture, pH Value	Low Cost, Easy Integration	Slide-type Temperature Measurement Device of Sichuan Baoning Vinegar	Temperature Error ±0.3℃
Near-Infrared Spectroscopy (NIRS)	Acetic Acid, Lactic Acid, Reducing Sugar	Non-Destructive, Multi-Parameter Synchronization	Online Monitoring System for Flavor Substances of Jiangsu Hengshun	Correlation Coefficient ≥0.95
Non-Contact Infrared Temperature Measurement	Surface Temperature Distribution	No Interference with Fermentation Environment	Cellar Monitoring System of Luzhou Laojiao	Response Time < 1 Second
Gas Sensor	Oxygen, Carbon Dioxide	Real-Time Reflection of Microbial Metabolism	Dissolved Oxygen Monitoring of Zhenjiang Xiangcu Fermentation Tanks	Measurement Error < 5%

4. Research and Development of Fermentation Turning Control Technologies

4.1. Evolution of Fermentation Turning Equipment Technology

The development of fermentation turning technology can be divided into four stages, realizing a leap from manual to intelligent:

4.1.1. Traditional manual stage (Before 1990)

Vinegar grains were turned manually with shovels, and the frequency was controlled by experience (usually once every 24 hours). The labor intensity was high (per capita daily processing of 5 tons of vinegar grains), and uneven fermentation turning led to a local spoilage rate of 3%-5%.

4.1.2. Initial mechanization stage (1990-2010)

5. Chain-driven fermentation turning machines realized mechanical replacement of manual labor. For example, the FP-150 fermentation turning machine filled the industrial gap, but its turning depth was fixed (only 20cm), and the vinegar grains at the edges were not fully turned. The ZNF rotary arm type fermentation turning machine reduced costs through structural optimization, adapting to the needs of small and medium-sized vinegar enterprises.

4.1.3. Automated upgrading stage (2010-2020)

An adjustable depth fermentation turning mechanism was developed (such as Patent CN201610226388.6), and the turning depth could be adjusted within the range of 15-40cm to meet the needs of different fermentation stages. The spiral fence crushing mechanism (CN201310608056.0) solved the problem of vinegar grain caking, and the fermentation turning uniformity was increased to 92%.

4.1.4. Intelligent control stage (Since 2020)

Servo motors, PLC controllers, and multi-spectral sensors (CN202322139301.X) are integrated to dynamically adjust fermentation turning parameters through real-time monitoring data. Research shows that intelligent fermentation turning based on the ADH gene expression law of acetic acid bacteria can increase acetic acid yield by 18%.

4.2. Optimization of Fermentation Turning Control Strategies

4.2.1. Control based on single-parameter threshold

Early automated systems took temperature as the core control index, triggering fermentation turning when the temperature of vinegar grains exceeded 38℃. Relevant research shows that this strategy can increase acetic acid yield by 10%, but it does not consider differences in microbial communities, and is prone to insufficient lactic acid production in the middle and late stages of fermentation.

4.2.2. Multi-parameter coupled control

A control model was constructed by combining temperature, dissolved oxygen, and acid production rate. Jiangsu Hengshun adopted a fuzzy PID algorithm to adjust fermentation turning frequency according to the coupled signals of temperature change rate (>0.8℃/minute) and oxygen concentration (<5%), increasing acid production rate by 15% in summer and extending the active time of acetic acid bacteria by 3 days.

4.2.3. Predictive control based on kinetic models

The team of Jiangnan University established a microbial growth prediction model based on the Monod equation, predicted the heat production peak through starch consumption rate, and triggered fermentation turning 2 hours in advance, controlling temperature fluctuations within ±1℃ and reducing the coefficient of variation of total acid content between batches to less than 8%. The application of this strategy in Zhenjiang Xiangcu shows that it can simultaneously meet the metabolic needs of acetic acid bacteria and lactic acid bacteria, realizing the synergistic generation of flavor substances.

5. System Integration and Intelligent Practice Cases

5.1. Typical Enterprise Technical Solutions

Leading domestic vinegar enterprises and technology companies have carried out extensive practices focusing on the intellectualization of solid-state fermentation, forming technical schemes adapted to different production scenarios. The system architecture, core technology selection and application effects of each enterprise have been compiled and summarized in Table 2. These practical cases provide referenceable practical experience for the overall intelligent transformation of the industry [7-8,11-12].

Table 2. Typical Enterprise Technical Solutions

Enterprise Name	System Architecture	Core Technologies	Application Effects	Literature Source
Jiangsu Hengshun	Distributed Intelligent Fermentation System	Near-Infrared Spectroscopy + Federated Learning	Flavor Substance Detection Delay < 5 Minutes, Data Security and Compliance	Enterprise Technical Report, 2024
Sichuan Baoning Vinegar	Slide-Type Monitoring-Fermentation Turning Linkage System	Modular Sensors + PLC Control	Fermentation Turning Uniformity Up to 95%, Labor Cost Reduced by 60%	Patent CN20232139301.X
Luzhou Laojiao	Non-Contact Monitoring System	Infrared Temperature Measurement + LoRa Transmission	Monitoring Coverage 100%, Response Time < 1 Second	Patent CN202421628489.2
Baixiang Technology	3D Vision Intelligent Control System	Machine Vision + Motion Control Algorithm	Fermentation Turning Positioning Accuracy ±5mm, Equipment Utilization Rate Increased by 20%	Software Copyright 2024SR0276334

5.2. Technological Exploration for Mature Vinegar

Aiming at the characteristics of layered fermentation of mature vinegar, preliminary technical explorations have been carried out: a three-layer monitoring architecture (bottom sensor array, middle data transmission, top upper computer analysis) is adopted, temperature data at different depths are collected through 8-channel DS18B20 sensors, and the load of the fermentation turning motor is monitored by Hall current sensors to realize overload protection. However, the system has not yet integrated the monitoring of flavor substances, and still adopts fixed threshold control for fermentation turning, which needs further optimization to meet industrial needs.

6. Research Gaps and Existing Problems

6.1. Technical Bottlenecks

6.1.1. Insufficient multi-parameter perception accuracy

Existing systems mainly focus on temperature monitoring, and the real-time detection coverage of flavor substances such as lactic acid and acetic acid is less than 30%. Sensors are easily affected by the high humidity and high acidity of vinegar grains. The response error of gas sensors increases by 37% after 72 hours of continuous operation, and the fitting degree between MEMS sensors and microbial growth curves is only 0.72, making it difficult to accurately reflect the fermentation state.

6.1.2. Poor adaptability of control models

Traditional PID control is difficult to cope with the nonlinear and time-varying characteristics of solid-state fermentation. Existing kinetic models are mostly constructed based on laboratory conditions, and their generalization ability in industrial scenarios is insufficient. The micro-environmental differences in layered fermentation of mature vinegar (the porosity difference between the surface and deep layers is 22%) lead to the inability of a single model to adapt to the whole domain, and the parameter regulation lag is significant.

6.1.3. Weak synergy of system integration

There are data silos between monitoring-control-management systems, and 80% of small and medium-sized vinegar enterprises' automated equipment cannot be connected to ERP systems. Fermentation turning equipment is powered by 220V AC, and cable dragging leads to increased failure rates. The equipment stability score is only 6.2/10 (full score 10 points).

6.2. Application Obstacles

6.2.1. Contradiction between flavor stability and digitization

Excessive automated regulation may damage the synergistic metabolism of microorganisms. A pilot test by a vinegar enterprise shows that fully automated production leads to a 12% decrease in lactic acid content and a reduction in flavor richness [13]. The adaptability between digital models and traditional process experience is insufficient, and it is difficult to quantitatively integrate the experience of senior craftsmen into control algorithms.

6.2.2. Imbalance between cost and benefit

The initial investment of intelligent systems is about 2 million yuan per production line, and the investment recovery period of small and medium-sized vinegar enterprises exceeds 5 years, restricting technology promotion. The maintenance cost of sensors is high, and the annual calibration cost of near-infrared spectroscopy probes reaches 80,000 yuan, which is difficult for enterprises to bear.

6.2.3. Lack of technical standardization

There are no automated technical standards for mature vinegar. Key indicators such as sensor layout and fermentation turning parameters have no unified specifications. The compatibility of systems from different enterprises is poor, making it difficult to form industrial synergy.

7. Future Research Directions and Prospects

7.1. Directions of Technological Innovation

7.1.1. Construction of multi-dimensional monitoring system

Develop special sensors resistant to acid, alkali, and adhesion. Based on near-infrared-Raman spectroscopy combined technology, realize synchronous monitoring of 10 parameters such as temperature, dissolved oxygen, and organic acids. Miniaturize detection modules combined with microfluidic chip technology, reducing equipment costs by more than 30%. Construct an optimized model of sensor array, and realize precise layout of monitoring points based on CFD simulation, increasing coverage to 90%.

7.1.2. Optimization of intelligent control models

Integrate fermentation kinetics and digital twin technology to establish a multi-scale coupled model of "microorganism-substrate-environment". Introduce reinforcement learning algorithms to train adaptive control models through massive production data, realizing predictive regulation of fermentation turning parameters. Aiming at the characteristics of layered fermentation, develop a zonal control strategy to control temperature fluctuations at different depths within ±0.5℃.

7.1.3. System integration and safety upgrade

Adopt industrial internet platforms to realize interconnection of monitoring-control-management data, develop low-power wireless sensor nodes, and solve cable safety hazards based on lithium battery power supply. Establish a data security system to protect enterprise process privacy through federated learning, adapting to the needs of informatization transformation.

7.2. Industrial Implementation Paths

7.2.1. Industry-university-research collaborative innovation

Cooperate with universities to build an exclusive fermentation database for mature vinegar, quantify traditional process experience (such as "determining fermentation turning by observing the color of vinegar grains"), and transform it into algorithm rules integrated into control models.

7.2.2. Gradient technology promotion

Develop economical systems for small and medium-sized enterprises (investment controlled within 500,000 yuan), first realize key parameter monitoring, and then gradually upgrade intelligent control functions.

7.2.3. Construction of standard system

Formulate "Technical Specifications for Automated Solid-State Fermentation of Vinegar", clarify key indicators such as sensor accuracy and fermentation turning uniformity, and promote the technical standardization of the industry.

8. Conclusions

This paper systematically combs the research progress of automated monitoring and fermentation turning control technologies for solid-state fermentation of mature vinegar, and clarifies the development context from manual experience to intelligent systems: monitoring technologies have achieved a leap from single-point to multi-parameter, fermentation turning control has completed the upgrading from mechanization to intelligence, and the feasibility of technologies has been verified by the practices of multiple enterprises. However, existing research still faces bottlenecks such as insufficient perception accuracy, poor model adaptability, and weak system synergy, especially the shortcoming in the balance between flavor stability and digitization.

Future research should focus on the process characteristics of layered fermentation of mature vinegar, and build an integrated intelligent system of "perception-modeling-control-optimization" through multi-sensor fusion, digital twin modeling, and reinforcement learning algorithms. At the same time, it is necessary to strengthen industry-university-research collaboration, realize the in-depth integration of traditional process experience and modern technologies, formulate technical standards adapting to industrial needs, promote the transformation of the mature vinegar industry towards efficient, high-quality, and stable intelligent production, and provide a demonstration path for the modernization development of traditional fermented foods.

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