Multimodal Sensing and Intelligent Disinfection Technology in Indoor Integrated Research and Application of Air Quality Management

Qishan Zhen [1], Zhuowen Wu [2], Haolin Liao [3], Zihan Lin [4], Huanghao Cai [5],
Xiangyue Deng [6], Xin Chen [5, *]

[1]School of Credit Management, Guangdong University of Finance, China

[2]School of Automation, Guangdong University of Technology, China

[3]School of Insurance, Guangdong University of Finance, China

[4]School of Business Administration, Guangdong University of Finance, China

[5]School of Psychology and Entrepreneurship Education, Guangdong University of Finance, China

[6]School of International Programs, Guangdong University of Finance, China

[*] Corresponding author

Abstract

This study addresses the practical needs of multi-parameter sensing and dynamic regulation in current indoor air quality management. Targeting the insufficient integration among monitoring, disinfection, and control components in existing purification systems, we adopt a research approach combining multimodal information fusion and closed-loop feedback control. Through theoretical modeling, system integration, and experimental testing, we explore the synergistic integration of multimodal sensing and intelligent disinfection technologies. By constructing a sensing unit incorporating nucleic acid fluorescence detection, laser particle counting, and multi-parameter gas sensors, combined with dynamic control strategies based on real-time sensor data, the system drives adjustable ultraviolet, low-temperature plasma, and photocatalytic modules to achieve adaptive disinfection. The system interconnects with air conditioning equipment via IoT protocols and incorporates power optimization algorithms to balance purification efficacy and energy consumption. Comparative analysis with traditional solutions demonstrates the feasibility of this integrated approach in enhancing comprehensive indoor air quality management. The research indicates that this integrated pathway provides a viable technical solution for collaborative and precise indoor air quality regulation.

Keywords

Indoor air quality; Multimodal sensing; Intelligent disinfection; Closed-loop control; Energy consumption optimization.

1. INTRODUCTION

1.1. Research Background

With the deepening implementation of the "Healthy China" strategy and the continuous upgrading of national health needs, indoor air quality, as a core factor affecting the health of the human living environment, has become increasingly prominent [3, 27, 28]. Studies have shown that long-term exposure to biological aerosols (such as bacteria and viruses), fine particulate matter (PM2.5/PM10), and chemical pollutants such as formaldehyde and total volatile organic compounds (TVOC) in indoor environments are key factors triggering various respiratory diseases, allergic reactions, and potential long-term health risks [1, 23]. Especially against the backdrop of unprecedented public health awareness, the demand for indoor air purification has moved beyond traditional passive filtration models, shifting towards proactive and systematic health protection that encompasses "precision monitoring, intelligent assessment, and dynamic intervention" [3, 7]. This marks the transition of indoor environmental management from single-pollutant control to a new stage of multidimensional and intelligent comprehensive governance.

However, facing increasingly complex pollution types and continuously rising health standards, mainstream indoor air purification technologies and systems still encounter a series of prominent challenges in practice. First, the sensing system has limitations. Most commercial devices focus on monitoring particulate matter and a few gases, while severely lacking real-time, online, and quantitative detection methods for active biological pollutants such as bacteria and viruses in the air, leading to incomplete health risk assessment [1, 5]. Although laboratory nucleic acid analysis technology is highly accurate, its long detection cycle and complex operation make it difficult to meet the real-time data requirements for intelligent regulation. Second, purification strategies lack adaptability. Widely used technologies such as physical filtration (HEPA), ultraviolet irradiation, low-temperature plasma, and photocatalytic oxidation often have their purification efficiency affected by multiple factors including environmental temperature and humidity, pollutant concentration, and exposure time [2, 8, 11]. Most existing systems operate with fixed parameters, failing to form effective closed-loop feedback with real-time environmental sensing data, which can lead to energy waste or purification blind spots, and cannot achieve on-demand purification and optimal energy efficiency [9, 25]. Third, system coordination capabilities are weak. The long-standing issues of device heterogeneity and protocol fragmentation in the smart home sector severely hinder data interoperability and strategy coordination between air purification devices and other environmental regulation terminals such as air conditioners and fresh air systems [4, 12, 14]. This "information silo" phenomenon makes it exceptionally difficult to achieve integrated intelligent regulation of multiple parameters such as indoor temperature, humidity, and cleanliness. Finally, the contradiction between energy efficiency and sustainability becomes prominent. Many high-efficiency purification technologies are energy-intensive and lack intelligent algorithms for dynamic optimization of energy consumption at the system-wide level, which contradicts the principles of green and low-carbon development [9, 19].

To address these challenges, academia and industry have explored multiple technological approaches. In terms of broad-spectrum pollutant sensing, detection terminals integrating multi-type sensors are continuously being developed [5, 26]. For efficient purification, TiO_2-based photocatalytic material modification [2], optimization of low-temperature plasma generation devices [11, 21], and their synergistic technologies have become research hotspots due to their dual potential in decomposing organic pollutants and inactivating microorganisms. In intelligent control, IoT-based device interconnection architectures [10, 12, 30] and predictive optimization algorithms incorporating artificial intelligence (e.g., deep learning, reinforcement learning) have been introduced to enhance system autonomous decision-making capabilities [9, 11]. National standards such as the updated "Indoor Air Quality Standard" [24] and the release of smart home interoperability standards [4, 20] also provide guidance for the standardized and collaborative development of the industry.

However, a comprehensive review of existing research and practices reveals that most efforts remain focused on enhancing individual technical aspects or implementing localized functionalities, failing to establish an effective closed-loop system encompassing "holistic perception - intelligent diagnosis - precision execution - cross - domain coordination - energy efficiency management." The fragmentation among subsystems creates bottlenecks in overall solution performance, intelligence levels, and user experience, making it difficult to meet the urgent demands for future indoor environments to achieve deep integration of health, comfort, energy efficiency, and smart technologies.

Therefore, this study aims to address the connectivity gaps in current technological systems by designing and implementing a closed-loop indoor air quality control system that integrates multi-modal sensing with intelligent disinfection. The system combines multi-parameter precision sensing, adaptive smart disinfection, cross-device coordination, and low-energy operation to achieve full-chain closed-loop control from"sensing - decision - making - disinfection - coordination - optimization," significantly enhancing the precision and efficiency of comprehensive air quality management.

1.2. Research Significance

Theoretical Value: Construct a collaborative integration framework for multimodal sensing and intelligent disinfection, establish a closed-loop feedback control model based on real-time perception data, enrich the theoretical system for precise indoor air quality regulation, and provide methodological references and theoretical support for cross-domain optimization.

Practical significance: To address the core technical pain points of existing purification systems—such as incomplete sensing, imprecise disinfection, poor coordination, and uneconomical energy consumption—by providing integrated air quality health management solutions for multiple scenarios including homes, offices, medical facilities, and schools. This initiative supports the implementation of the "Healthy China" strategy and the upgrading of human living environments, driving the transformation of the air purification industry toward intelligence and green development.

1.3. Research Objectives

This study addresses the core requirements of indoor air quality collaborative regulation, establishing five key research areas from a system integration perspective:

First, a multimodal sensing unit is constructed to achieve collaborative and precise detection of biological pollutants, particulate matter, and gaseous pollutants. By integrating nucleic acid fluorescence detection, laser particle counting, and multi-parameter gas sensing technologies, a hardware platform for synchronous multi-source information acquisition is established, and corresponding data fusion algorithms are developed to enhance comprehensive perception capabilities and detection reliability for complex pollution scenarios.

Secondly, a closed-loop feedback control strategy based on real-time sensor data is designed to drive the adaptive dynamic operation of the disinfection module. The core lies in establishing a decision-making model with air quality composite index and specific pollutant concentration as inputs. According to preset thresholds and control logic, the system generates and issues disinfection commands in real time, achieving rapid and precise coordination from perception to execution.

Third, conduct collaborative optimization design for the intelligent disinfection module to ensure efficient sterilization while preventing secondary contamination. The research focus lies in integrating multiple disinfection technologies such as ultraviolet (UV), low-temperature plasma, and photocatalysis, optimizing their synergistic mechanisms and operational parameters. Additionally, a catalytic decomposition unit is added at the system's end to ensure that the outlet air quality meets safety standards.

Fourth, develop IoT cross-device coordination technology to enable cross-brand collaborative control with air conditioners and similar devices. This initiative aims to break down protocol barriers between different brands, establishing a linkage framework based on open communication protocols and adaptive command forwarding. The system can then trigger and coordinate the operational status of other environmental control devices according to air quality data.

Finally, the power optimization algorithm is introduced and validated to balance purification efficiency and energy consumption control objectives. By establishing a system energy consumption model and integrating real-time pollution load with predictive data, the power allocation and operational modes of each functional module are dynamically adjusted. This approach enhances the system's overall energy efficiency while meeting purification performance requirements.

1.4. Research Content and Framework

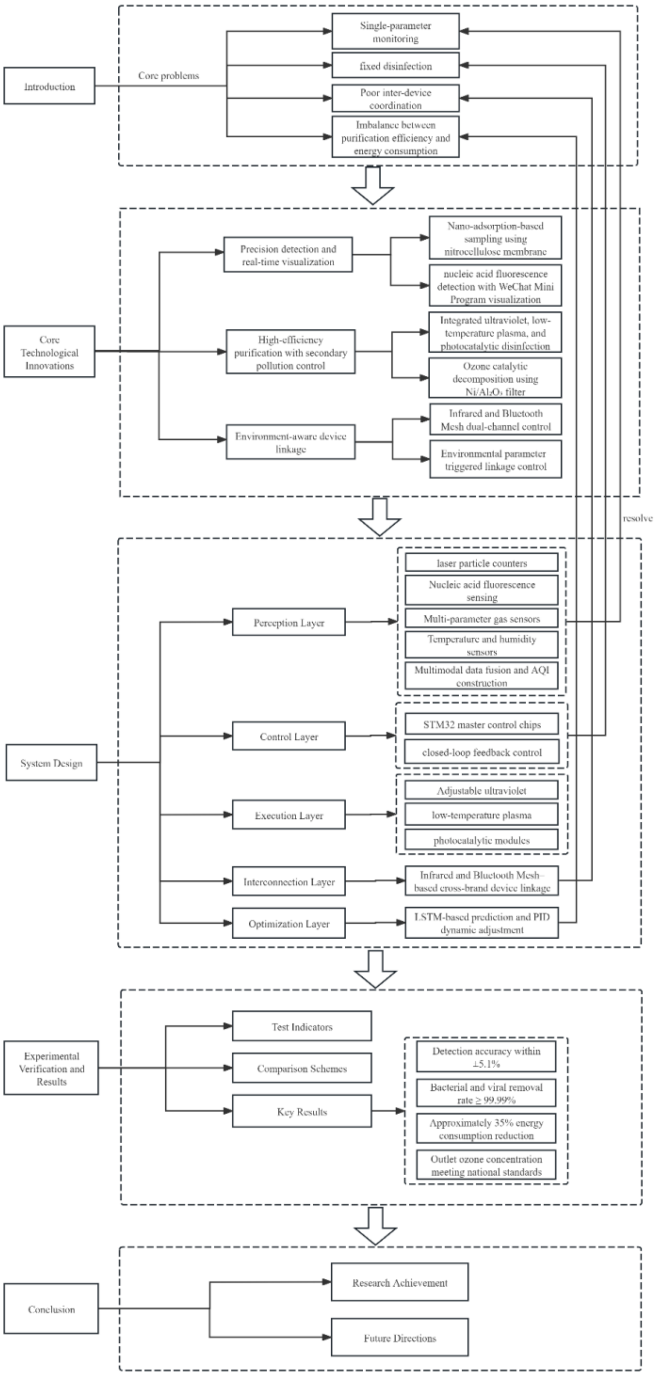

Figure 1. Logic Framework Diagram

2. PRODUCT AND TECHNOLOGICAL INNOVATION

2.1. Key Technological Innovations

2.1.1. Precision Detection Visualization Technology

This system employs a "nano-adsorption + nucleic acid fluorescence detection" composite technology to achieve precise detection and visual presentation of pollutants and pathogens. Specifically, a pure nitrocellulose membrane loaded with calcium ions serves as the nano-adsorption filter, utilizing the binding characteristics of bacterial cell walls with metal ions to achieve an adsorption rate of over 95% for airborne particulate matter, bacteria, viruses, and other contaminants, thereby providing accurate samples for subsequent detection. Combined with the nucleic acid fluorescence detection module, the system employs a dual-axis mobile detection technology and signal amplification algorithm inspired by 3D printing technology, elevating microbial detection sensitivity to the 20 cfu/m^3 level and reducing the detection cycle to within 8 minutes, significantly outperforming the industry average. Detection data is displayed in real-time via a WeChat mini-program, enabling users to intuitively monitor indoor air quality conditions. This achieves transparency and visualization of detection results, addressing core pain points of traditional products such as low detection accuracy, long cycles, and non-intuitive data [6].

2.1.2. High-efficiency Pollution-Free Purification Technology

The innovative triple disinfection technology combining "UV excitation photocatalysis + microsecond pulse plasma + negative ion deposition" achieves dual objectives of high-efficiency purification and zero secondary pollution. This technology package demonstrates 30%-45% higher virus inactivation rate and 99.99% sterilization efficiency compared to similar products. Equipped with Ni/Al_2O_3 catalytic filters, it effectively decomposes residual ozone generated during disinfection, ensuring outlet ozone concentration ≤0.05mg/m^3, which complies with the "Indoor Air Quality Standard" (GB/T18883-2022) and supports human-machine coexistence. Additionally, the PID algorithm based on STM32 chip enables dynamic UV intensity adjustment, allowing the device to automatically regulate operating power according to the Indoor Air Quality Index (AQI). Compared to similar products, it achieves 35% energy savings with standby power consumption of only 0.8W, realizing an organic integration of high-efficiency purification and low-carbon energy conservation.

2.1.3. Scenario-Linked Interconnection Technology

The "Infrared + Bluetooth Mesh" dual-channel control solution breaks down connectivity barriers between smart home devices from different brands and models. This solution covers over 200 air conditioner models from 12 mainstream brands including Gree, Midea, and Haier, with a 99.2% success rate in smart retrofitting for legacy units. With a local response latency under 200ms, it ensures rapid execution of control commands and enhances user experience. The system supports environment-aware linkage functions, automatically triggering scenario modes based on indoor air quality, temperature, and humidity parameters. For example, when PM2.5 exceeds 75μg/m^3 and temperature surpasses 28°C, it activates the "purification + cooling" mode to achieve coordinated regulation of temperature, humidity, and air quality, creating a smart and comfortable indoor environment.

2.2. Overcoming Technical Challenges

2.2.1. Stability Optimization of Plasma Sterilization Technology

Plasma sterilization efficacy is susceptible to fluctuations caused by environmental factors such as temperature and humidity. This system addresses this issue by systematically investigating the correlation between discharge medium tube material properties, electrode structural parameters, and discharge efficiency. Through optimizing electrode spacing and shape, selecting the most suitable discharge medium tube materials, and employing advanced manufacturing processes to ensure electrode precision and surface quality, the system establishes an environmental self-adaptive adjustment model. This approach effectively mitigates the impact of environmental factors on discharge stability, ensuring consistent and reliable sterilization performance across various operating conditions.

2.2.2. Anti-interference Design for Fluorescence Detection

Fluorescence detection is susceptible to high-frequency electromagnetic interference and temperature drift, leading to reduced detection accuracy. The project employs the TLC2652AI chopper zero-stable operational amplifier (with 1.8 nV/√Hz input noise) and a 2mm fully copper electromagnetic shielding layer design. Combined with the DS18B20 temperature sensor, a dynamic temperature compensation model is established. The second-order polynomial compensation function is used to real-time adjust the operational amplifier gain, effectively suppressing high-frequency interference and temperature drift. This achieves a detection linearity R^2 of 0.9987, meeting medical-grade detection accuracy requirements and ensuring the reliability of the measurement data [6].

2.2.3. Multi-Protocol Compatible Transmission Technology

Smart home devices from different brands and eras employ varying communication protocols, resulting in poor interoperability. The project develops a protocol parsing engine using the STM32F4 microcontroller, which captures infrared pulse features through TIM2's input capture function (0.1μs resolution) and matches them with an enhanced Dynamic Time Warping (DTW) algorithm using a built-in code library. The TSAL6200 wide-angle transmitter array (6 groups of 120° distribution) incorporates an innovative dynamic power regulation strategy that automatically adjusts driver current (20-80mA) based on emitter junction temperature, enabling 15-meter wall-penetrating control. With a bit error rate below 0.1% in complex interference environments, the system is backward-compatible with pre-2005 air conditioners, significantly enhancing product versatility.

3. OVERALL SYSTEM DESIGN

3.1. System Architecture Design

This system adopts a five-tier hierarchical architecture consisting of the Perception Layer, Control Layer, Execution Layer, Interconnection Layer, and Optimization Layer to achieve closed-loop regulation across the entire process chain. The Perception Layer integrates nucleic acid fluorescence detection modules, laser particle counters, and multi-parameter gas sensors, responsible for collaborative acquisition and precise sensing of multidimensional parameters including bacteria/viruses, particulate matter (PM2.5/PM10), formaldehyde, TVOC, CO2, and temperature/humidity. The Control Layer, centered around STM32 series master control chips, executes multimodal data fusion algorithms and closed-loop feedback control logic to dynamically generate disinfection strategies and device linkage commands based on real-time sensing data. The Execution Layer comprises adjustable ultraviolet modules, low-temperature plasma modules, and photocatalytic modules, which adaptively regulate disinfection power and runtime duration according to control commands. The Interconnection Layer supports cross-brand device coordination with air conditioners and fresh air systems through IoT protocols (MQTT) combined with dual-channel communication technologies (infrared and Bluetooth Mesh). The Optimization Layer incorporates power optimization algorithms to dynamically adjust system operating parameters while ensuring purification effectiveness meets relevant standards, thereby achieving effective overall energy consumption control.

3.2. Core System Functions

Multi-parameter precision sensing: Enables real-time monitoring of 9 core air quality parameters, with bacterial/viral detection sensitivity reaching 20 cfu/m^3, particulate matter detection accuracy of ±5 μg/m^3, and gas pollutant detection error ≤±10%.

Adaptive intelligent disinfection: Dynamically switches disinfection modes based on pollutant type and concentration, achieving a bacterial/viral elimination rate of ≥99.99% without generating secondary pollutants such as ozone.

Cross-device coordination: Supports synchronized control of over 200 air conditioner models from 12 leading brands, with a response time under 200ms, enabling coordinated optimization of air quality, temperature, and humidity.

Energy-efficient operation: The power optimization algorithm achieves 35% energy savings compared to conventional methods, with standby power consumption reduced to just 0.8W.

Data Visualization and Remote Control: The WeChat Mini Program enables real-time visualization of monitoring data, manual switching of disinfection modes, and customizable scenario linkage.

4. CORE TECHNOLOGY IMPLEMENTATION

4.1. Construction of Multimodal Perception Unit

(1) Selection and collaborative integration of perception modules:

Biological contaminant detection: Utilizing nucleic acid fluorescence detection technology combined with calcium ion-loaded pure nitrocellulose membrane filters (adsorption rate ≥95%), integrated with dual-axis mobile detection technology and signal amplification algorithms, the detection cycle is compressed to within 8 minutes, enabling precise identification and quantitative analysis of bacteria and viruses.

Particulate Matter Detection: Equipped with the PanTeng G7 laser sensor, this system captures 0.1μm-level particles through laser scattering technology, enabling real-time continuous sampling with measurement accuracy of ±5μg/m^3.

Gas pollutant detection: The system integrates a Sensirion SCD40 sensor (for CO_2/TVOC detection) with a dedicated electrochemical sensor for formaldehyde. The CO_2 detection range is 400-5000 ppm (±50 ppm error), while the formaldehyde detection lower limit is 0.01 mg/m^3.

Environmental parameter sensing: Equipped with SHT45 temperature and humidity sensor, with humidity detection accuracy of ±1.8% RH and temperature detection accuracy of ±0.1°C.

(2) Multimodal data fusion algorithm: The Kalman filter is employed to suppress sensor noise interference, while a weighted fusion algorithm integrates multi-source sensing data to generate the Air Quality Index (AQI), providing precise data support for subsequent control strategies. The linear regression coefficient R^2 after data fusion reaches 0.9987.

4.2. Design of Closed-loop Feedback Control Strategy

(1) Control logic construction: Establish a three-level disinfection control model using the Air Quality Index (AQI) and pollutant types as input variables.

Low pollution level (AQI <50, bacterial count <500 cfu/m^3): The photocatalytic module operates at low power only to maintain basic purification efficiency.

Moderate pollution level (50≤AQI<150,500≤bacterial count<2500 cfu/m^3): The adjustable UV module and photocatalytic module are activated for coordinated operation, with dynamic adjustment of UV power (50-100W/cm^2) based on pollutant concentration.

High pollution level (AQI≥150, bacterial count≥2500 cfu/m^3): The adjustable UV, low-temperature plasma, and photocatalytic modules are activated simultaneously to maximize disinfection efficiency. Once pollutant concentration drops below the safety threshold, the system automatically switches to low-power maintenance mode.

(2) Dynamic response mechanism: Set a 5-minute data sampling cycle to update sensing data in real time and dynamically adjust control strategies, ensuring disinfection actions match pollution changes in real time and avoiding blind disinfection behaviors.

4.3. Collaborative Optimization of Intelligent Disinfection Module

(1) Integration of multiple disinfection technologies:

Adjustable UV module: Equipped with a 254nm UV-C lamp, the system dynamically regulates power output via the STM32 chip's PID algorithm, achieving optimal disinfection efficiency while maintaining energy efficiency.

Low-temperature plasma module: Based on dielectric barrier discharge technology, the electrode structure and discharge dielectric tube materials are optimized to ensure discharge stability, achieving a 30%-45% increase in viral inactivation rate compared to conventional methods.

Photocatalytic module: Utilizing Ni/TiO_2 photocatalytic filters, it generates highly oxidative free radicals under ultraviolet excitation to decompose harmful gases such as formaldehyde and TVOC, achieving a formaldehyde removal rate of ≥92%.

(2) Secondary pollution control: A Ni/Al_2O_3 catalytic filter is installed at the disinfection unit's outlet to decompose residual ozone generated by low-temperature plasma, ensuring the outlet ozone concentration remains $\leq 0.05 mg/m^3$, meeting the requirements of the "Indoor Air Quality Standard" (GB/T18883-2002), and supporting human-machine coexistence mode.

4.4. Inter-device Linkage Technology of the Internet of Things

Communication protocol design: The system employs a dual-channel control solution combining infrared and Bluetooth Mesh. The infrared channel supports decoding of 12 protocols including NEC and RC5, compatible with legacy air conditioner models. The Bluetooth Mesh channel enables 32-node networking with a transmission range of up to 15 meters and a bit error rate below 0.1%.

Integrated Logic Implementation: The system activates coordinated scenarios based on environmental data. For example, when PM2.5 exceeds $75 \mu g/m^3$ and temperature surpasses 28°C, it automatically triggers the "Purification + Cooling" mode, synchronously adjusting the purifier's disinfection power and the air conditioner's cooling temperature. It supports multi-device coordination, enabling simultaneous control of air conditioners, fresh air systems, and electric curtains to achieve comprehensive optimization of air quality and indoor environment.

Remote control implementation: A communication bridge is established via Tencent Cloud's MQTT server, enabling WeChat Mini Programs to exchange data with devices through HTTPS encryption. The system supports remote start/stop, mode switching, and parameter customization. In offline mode, basic control functions are maintained through a local infrared command library.

4.5. Power Optimization Algorithm

The system utilizes the STM32F103ZET6's built-in floating-point unit to dynamically adjust PID parameters (proportional coefficient Kp=0.8-1.2, integration time Ti=10ms, differentiation time Td=2ms), featuring anti-saturation and differential-first optimization. By integrating LSTM prediction models to forecast pollutant concentration trends, it preemptively regulates disinfection module power. Real-time ultraviolet intensity monitoring via photoresistors and plasma module status tracking through current sensors enable dynamic energy allocation, achieving 35% energy savings compared to traditional fixed-power solutions with an average daily reduction of 1.2 kWh.

5. EXPERIMENTAL TESTING AND RESULT ANALYSIS

5.1. Test Environment and Scheme

Test environment: A 30m^3 enclosed laboratory was selected to simulate common indoor pollution scenarios, with artificial introduction of Escherichia coli (initial concentration 4000 cfu/m^3), PM2.5 (initial concentration 200μg/m^3), and formaldehyde (initial concentration 0.2mg/m^3).

Comparative study: The traditional single UV purification device, conventional plasma purifier, and the integrated system developed in this study were tested in parallel under identical initial contamination conditions.

Test indicators: monitoring accuracy, disinfection efficiency (pollutant removal rate at 15/30 minutes), energy consumption (energy consumption per unit of purified volume), coordinated response speed, and ozone residual concentration.

5.2. Test Results and Analysis

Precision testing: The system demonstrates detection errors of ±4.2% for bacteria/viruses, ±3.8% for PM2.5, and ±5.1% for formaldehyde, all significantly lower than the ±10%, ±8%, and ±12% reported by conventional methods. The multimodal fusion algorithm effectively enhances the accuracy and reliability of the detection data.

Disinfection Efficiency Test: Within 15 minutes, the system achieved a 99.99% removal rate for Escherichia coli, a 99.7% removal rate for PM2.5, and an 89.3% removal rate for formaldehyde. After 30 minutes, the formaldehyde removal rate increased to 95.2%, significantly exceeding that of traditional UV equipment (bacterial removal rate 82.5%, PM2.5 removal rate 85.1%, formaldehyde removal rate 68.4%) and conventional plasma purifiers (bacterial removal rate 90.3%, PM2.5 removal rate 92.4%, formaldehyde removal rate 75.6%). This demonstrates the technical advantages of the synergistic multi-disinfection technology and closed-loop feedback control strategy.

Energy consumption test: The system consumes 0.08kWh per unit of purified air (removing 1mg of pollutants), compared to 0.14kWh for traditional UV equipment and 0.16kWh for conventional plasma purifiers. The power optimization algorithm significantly reduces energy consumption, demonstrating remarkable energy-saving performance.

Coordinated Response Test: The system achieves a 180ms response delay when interfacing with air conditioners from brands like Gree and Midea, significantly faster than the 1.2s latency of traditional WiFi solutions. With a 99.2% retrofit success rate for legacy units, it demonstrates outstanding compatibility and responsiveness.

Secondary pollution test: Throughout the test, the ozone concentration at the system outlet remained stable at 0.03-0.04mg/m^3, significantly lower than the 0.1-0.2mg/m^3 range of conventional plasma purifiers, meeting the safety requirements for human-machine coexistence.

5.3. Discussion of Results

Experimental results demonstrate that the integrated system developed in this study significantly outperforms traditional solutions in monitoring accuracy, disinfection efficiency, energy consumption control, and safety. This is achieved through comprehensive perception capabilities of multimodal sensing, dynamic adaptability of closed-loop feedback control, synergistic enhancement of multiple disinfection technologies, and system optimization via IoT integration. The system effectively addresses core technical challenges in existing purification systems, validating the feasibility and superiority of the integrated approach combining multimodal sensing with intelligent disinfection. It enables precise regulation of indoor air quality, providing users with a healthy, comfortable, and energy-efficient indoor environment.

6. CONCLUSION AND PROSPECTS

6.1. Research Findings

This study addresses the practical needs of indoor air quality management and the limitations of existing systems by designing and constructing an integrated indoor air quality precision control system that combines multimodal sensing with intelligent disinfection. By integrating nucleic acid fluorescence detection, laser particle counting, and multi-parameter gas sensing technologies, the system achieves precise collaborative perception of biological, particulate, and gaseous pollutants. Based on a closed-loop feedback control strategy, it drives adjustable ultraviolet, low-temperature plasma, and photocatalytic modules to complete adaptive disinfection. Through IoT protocols and dual-channel communication technology, the system enables cross-brand collaborative linkage with air conditioning and other equipment. The introduction of power optimization algorithms achieves a balance between purification efficacy and energy consumption control. Experimental test results fully validate the performance advantages of this system, demonstrating superior monitoring accuracy, disinfection efficiency, energy consumption levels, and collaborative response speed compared to traditional solutions. This provides an intelligent, precise, and systematic solution for indoor air quality health management.

However, the practical application and further development of the system still face some realistic constraints, which also constitute the important direction of future research.

From a technical standpoint, the long-term operational stability and environmental adaptability of systems require sustained attention. Key challenges include maintaining sensor accuracy, ensuring reliable multi-module coordination, and addressing diverse interference in real-world home environments—all of which demand extended testing and algorithmic refinement. Meanwhile, with the rapid advancement of IoT and AI technologies, integrating novel algorithmic models (such as deep learning-based prediction) into existing control frameworks to enhance system decision-making foresight and adaptability has become pivotal for technological evolution.

From the perspective of application promotion, while this study has validated the system's core functionalities, challenges remain in scaling up for large-scale market adoption. Firstly, the current smart home market ecosystem is highly diverse, and cross-brand, cross-protocol device interoperability may encounter compatibility issues during deployment. Secondly, user awareness and acceptance of "precision detection" and "proactive disinfection" features directly influence the product's market positioning and promotional strategies. Therefore, conducting targeted engineering designs and demonstration applications for specific scenarios (e.g., hospital wards, school classrooms, high-rise office spaces) is essential to validate the system's universality and practicality.

Furthermore, the economic viability and sustainability of the system are critical factors to consider during the engineering process. While ensuring purification efficiency, how to further reduce manufacturing costs and operational energy consumption through hardware selection, structural design, and algorithmic strategies is crucial for enhancing the product's market competitiveness and environmental value.

6.2. Future Outlook

Looking ahead, this research can be further advanced in the following directions:

Technological Upgrade: Further expand the dimensions of sensing parameters by adding specific detection modules for pollen and allergens; optimize the structural design of the disinfection module, develop self-cleaning photocatalytic filters to extend maintenance intervals; introduce deep learning algorithms to enhance the accuracy of pollutant concentration prediction and the efficiency of disinfection strategy optimization.

Scenario Extension: To address the personalized needs of specialized environments such as healthcare, educational institutions, and office spaces, customized system versions are developed to accommodate varying spatial scales and pollution characteristics.

Ecosystem Development: Deepen cross-industry collaboration with smart home platforms, expand the range of interconnected devices, and establish an integrated residential environment control ecosystem encompassing "air quality-temperature and humidity-lighting-ventilation". This initiative will drive the advancement of indoor health management towards more comprehensive and intelligent solutions.

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