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# Design and Implementation of Intelligent Pet Anti-Barking Collar Control System Based on Multi-Sensor Fusion

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**Abstract**

Traditional single-microphone anti-bark collars suffer high false alarms, poor multi-dog adaptability, missing safety safeguards and failure to pass overseas EMC certifications. This paper develops an embedded control system based on decision-level multi-sensor fusion, using STM32L4 low-power MCU integrated with MEMS audio, capacitive wearing detection and NTC temperature sensors to form a perception-decision-execution closed loop. It supports two spray volumes (0.25 mL / 0.5 mL), ±30% adaptive recognition thresholds and a 12-hour continuous-use safety lock. Verified by third-party FCC Part 15 and CE-EMC labs, the system is mass-produced for TA.TIAOM products sold on Amazon UK. Real household tests deliver an 89.3% effective correction rate, and multi-sensor joint judgment drastically reduces noise-induced misfires, providing a viable engineering solution for pet wearable behavior collars.

**Keywords:** multi-sensor fusion, pet smart wearables, anti-barking control, STM32L4, FCC/CE EMC, low-power embedded, adaptive threshold, safety lock, cross-border electronics

## 1. Introduction

### *1.1 Research Background*

Europe owned 85 million pet dogs in 2024, bringing widespread noise disputes. Conventional single-acoustic collars reach a 22.7% false trigger rate, with severe sensor drift between −10 ℃ and +55 ℃, fixed correction levels and no overload protection, unable to meet U.S. and EU EMC market entry rules. Decision-level multi-sensor fusion features low power draw and strong anti-interference, making it ideal for battery-powered pet wearables. This work targets both theoretical optimization and commercial compliance.

### *1.2 Research Status*

Spray correction outperforms ultrasonic and shock modes, yet relevant embedded multi-sensor control research is scarce. Data/feature fusion demands excessive computing resources, while most existing prototypes lack EMC optimization and real-environment validation, leading to low manufacturability. Current products face high false triggers, weak environmental adaptability and incomplete safety mechanisms, which this system addresses.

### *1.3 Three Core Innovations*

1) Architecture: Triple-sensor fusion (sound + fit detection + temperature) blocks false triggers from the judgment source.
2) Mechanism: ±30% adaptive sensitivity plus 12-hour automatic lock accommodates diverse breeds and prevents pet overstimulation.
3) Engineering: Full hardware & software EMC optimization passes FCC and CE tests; the design is commercialized with quantified real-scene performance metrics.

## 2. Relevant Theoretical and Key Technical Fundamentals

### *2.1 Basic Theory of Multi-Sensor Fusion*

Multi-sensor fusion hierarchical model: Data-level fusion conducts preprocessing and fusion operations directly on original sampling sequences, retaining complete raw information but bringing large data throughput, which imposes high requirements on MCU storage and computing resources and is unsuitable for the resource constraints of this system.

1) Feature-level fusion: Extract feature parameters of each sensor signal and build feature vectors for fusion operations, consuming considerable computing resources.
2) Decision-level fusion: Each sensor independently outputs local judgment results, followed by logical fusion of multi-channel judgment results to output the final system decision. This paradigm features low computing load and strong fault tolerance, fitting low-power microcontrollers such as STM32L4, so the system adopts a decision-level fusion architecture.

Define the local judgment output of each sensor: as $S_1$ (effective audio event judgment), $S_2$ (wearing state judgment), $S_3$ (temperature working condition judgment), where $S_i in 0,1$, with 1 representing the corresponding condition is satisfied and 0 representing the opposite. The judgment output $Y$ allowing the system to trigger correction actions satisfies the logical expression:

The system only permits spray correction actions when all three conditions are met: valid barking audio, normal wearing state of the device, and environmental temperature within the allowable operating range.

Basics of multi-source sensing data preprocessing: The embedded sampling link inevitably introduces high-frequency noise, temperature drift and signal jitter. This paper adopts moving average filtering to smooth original sampling sequences. Let the original sampling sequence be $x(k)$ and the sliding window length be $N$; the filtered output $x_f(k)$:

A fixed-length sliding window suppresses random pulse interference and realizes time sequence alignment of multi-channel sensor sampling simultaneously, eliminating logical offset caused by sampling time differences of different peripherals.

### *2.2 Core Sensing Detection Mechanism*

1) MEMS Audio Sensor Bark Signal Identification Mechanism: Effective signals of canine barking are mainly distributed in the 250–3500 Hz frequency band, with distinguishable spectrum characteristics from low-frequency environmental background noise and human voices (Liu Y & Wang Z, 2024). The MEMS microphone converts sound pressure signals into analog voltage quantities, which are sent to ADC for digital sampling after signal amplification and band-pass filtering. The system takes signal amplitude as the main discrimination feature, superimposed with frequency band constraints to filter interference signals outside the characteristic frequency band of dog barking.
2) Capacitive Wearing Detection Mechanism: The capacitive induction sensor continuously detects the equivalent capacitance between electrodes and ground. When the device is stably worn on the pet's neck fur surface, the equivalent capacitance shifts significantly; when the device falls off and hangs in the air, the capacitance returns to the reference baseline. The MCU continuously collects the output of the capacitive induction channel and distinguishes wearing/falling-off states through threshold comparison, so as to intercept actions under no-load conditions. Ambient humidity causes baseline drift of capacitance, and the system periodically completes baseline compensation during operation to reduce detection deviation induced by environmental humidity.
3) NTC Temperature Sensor Detection Mechanism: The resistance value of NTC thermistor decreases exponentially with temperature rise, converted into voltage signals through a voltage divider circuit and sent to ADC. The resistance-temperature relationship is described by the B-value equation:

Where: $R_{25}$ denotes the nominal resistance at 25 ℃ (Li M & Zhang H, 2023); $B$ is the NTC material B constant; $T$ is thermodynamic temperature. The MCU reversely solves real-time ambient temperature through ADC collected divided voltage for system working condition verification, avoiding abnormal operation risks under extreme temperature conditions.

### *2.3 STM32L4 Low-Power Embedded Control Technology*

The STM32L4 series adopts Cortex-M4 core, supporting multi-level low-power modes including Stop1, Stop2 and Standby. It can turn off peripheral clocks and put the core into sleep, waking up relying on external interrupts or ADC events, fitting the power consumption constraints of battery-powered wearable devices. The overall machine current can drop to microampere level under system sleep mode; when sensors capture potential effective events, wake-up is triggered to enter working mode for sampling, judgment and output control.

The system adopts a closed-loop control paradigm: sensor signal collection → signal preprocessing → multi-source fusion judgment → actuator output → status feedback. After a single control cycle ends, the system enters sleep or continues cyclic sampling according to event status.

*2.4 Basic Theory of Electromagnetic Compatibility*

FCC Part 15 and CE-EMC stipulate mandatory test items for consumer electronic equipment such as radiated disturbance, conducted disturbance, electrostatic discharge (ESD) and electrical fast transient pulse (EFT). Radiated disturbance restricts the intensity of electromagnetic waves radiated outward by equipment; conducted disturbance restricts conducted interference at power ports; electrostatic discharge simulates electrostatic impact on human bodies during daily use. On the hardware level, PCB partition layout, ground segmentation, configuration of filter capacitors and minimization of signal loops are adopted to control electromagnetic disturbance within standard limits, which is a necessary prerequisite for equipment to realize cross-border market access.

## 3. Overall System Scheme and Demand Analysis

*3.1 System Functional and Performance Demand Analysis*

Functional Demands

1) Multi-sensor signal collection: Periodically collect acoustic signals, capacitive wearing signals and NTC temperature signals.
2) Bark event judgment: Realize effective identification of bark events based on the multi-sensor fusion framework.
3) Dual-gear spray output: Support controllable output of small dose (0.25 mL) and large dose (0.5 mL) sprays.
4) Adaptive sensitivity adjustment: Dynamic compensation of identification thresholds within ±30% of the reference value.
5) Safety locking protection: Automatically lock the spray output channel when cumulative continuous operation time reaches 12 hours.
6) Battery power detection and low-power alarm: Real-time battery level monitoring and low-voltage reminder function.
7) Man-machine interaction visualization: through red-green dual LED indicators reflecting system status.
8) Abnormal working condition protection: Forbid correction action output under extreme temperature and sensor abnormal conditions.

Performance Demands

Table 1. Core System Performance Indicators

| **Parameter Item** | **Design Index** |
|---|---|
| Bark identification response delay | ≤220 ms |
| Sensitivity adjustment range | ±30% of reference threshold |
| Spray gear output | 0.25 mL, 0.5 mL |
| Continuous safety locking duration | 12 h |
| Operating temperature range | -10 ℃ ~ +55 ℃ |
| Sleep overall machine current | ≤12 μA |
| Single-battery endurance | ≥14 h |
| Electromagnetic compatibility | Meet FCC Part 15, CE-EMC standards |

Engineering Demands

Miniaturized hardware to fit pet collar mounting; lithium battery power supply; mass production feasibility; compliance with mandatory certification constraints for overseas markets.

Table 2. Comprehensive Comparison of Different Technical Schemes

| Technical Scheme | Perception Mode | Safety Protection Mechanism | Adaptive Capacity | Pass EMC Certification? | Typical False Trigger Rate |
|---|---|---|---|---|---|
| Traditional single-audio anti-barking collar | Single MEMS microphone | No overload locking | Fixed threshold | Most fail to meet standards | 22.7% |
| Commercial high-end single-sensor products | Single MEMS microphone | Simple timeout protection | A small number of manual gears | Partially meet standards | 14.3% |
| Multi-sensor fusion scheme proposed in this paper | Audio + capacitive wearing detection + temperature | 12-hour cumulative locking + working condition interception | ±30% dynamic self-adaptation | Fully compliant | 4.1% |

*3.2 Overall System Architecture*

The system adopts a five-layer hierarchical architecture: perception layer, fusion decision layer, execution control layer, man-machine interaction layer and power guarantee layer.

- Execution Control Layer: Spray drive circuit, outputting sprays of corresponding gears according to judgment results, integrated with hardware overcurrent and overvoltage protection.
- Perception Layer: MEMS audio sensor, capacitive wearing detection sensor and NTC temperature sensor, converting physical quantities into analog electrical signals and outputting to the main controller ADC channel.
- Fusion Decision Layer: STM32L4 main controller unit, undertaking ADC sampling, signal preprocessing, multi-sensor fusion judgment and control algorithm operation.
- Execution Control Layer: Spray drive circuit, outputting sprays of corresponding gears according to judgment results, integrated with hardware overcurrent and overvoltage protection.
- Man-Machine Interaction Layer: Red-green dual LED indicators, reflecting working status, trigger alarm, low power and locking protection status.
- Power Guarantee Layer: Lithium battery power supply loop, LDO voltage regulation and power detection circuit, providing stable power supply for the whole system.

Complete system working logic: After power-on, the equipment completes peripheral initialization and sensor baseline calibration; periodically collect raw data of multi-channel sensors; execute moving average filtering preprocessing; carry out decision-level fusion judgment; output corresponding gear sprays only when all constraint conditions are satisfied; the cumulative timing module judges whether to trigger 12-hour safety locking; LEDs refresh equipment status synchronously; enter low-power sleep mode without valid events, waiting for the next event wake-up sampling.

*3.3 Core Technical Difficulties and Corresponding Solutions*

Difficulty 1: False triggers induced by complex environmental noise; single audio sensing cannot distinguish dog barks from environmental clutter.

Solution: Introduce dual constraints of wearing state and temperature working conditions to filter invalid trigger scenarios relying on decision-level fusion.

Difficulty 2: Significant differences in bark amplitude among dogs of different sizes; fixed thresholds fail to adapt to multiple dog breeds.

Solution: Design an adaptive threshold compensation algorithm within ±30% to dynamically adjust identification gates following environmental baselines.

Difficulty 3: Pet stress risks caused by long-term continuous operation.

Solution: Introduce a 12-hour cumulative timing automatic locking protection mechanism.

Difficulty 4: Judgment deviation induced by unsynchronized sampling time sequences of multi-channel sensors.

Solution: Unify sampling cycles to complete time sequence alignment and moving filtering processing.

Difficulty 5: Electromagnetic interference of miniaturized wearable equipment hardly meets certification

standards.

Solution: PCB analog-digital partition layout, optimized grounding topology and multi-stage filter network addition.

## 4. Modular Design of System Hardware Circuit

The hardware is wholly divided into STM32L4 minimum system module, multi-sensor collection module, spray drive module, man-machine interaction module and power management module. PCB design strictly separates analog signal domains and digital signal domains; analog ground and digital ground are interconnected through magnetic beads at a single point to suppress coupling interference of digital circuits on weak analog sensing links.

### *4.1 Main Controller Minimum System Circuit*

The main controller unit selects the STM32L431 low-power microcontroller. The minimum system includes external high-speed/low-speed clocks, reset circuit and debugging download circuit. Complete GPIO and ADC channel resource allocation: ADC1 is used for audio signal collection, ADC2 for NTC temperature voltage division sampling; GPIO ports realize capacitive induction detection, spray drive control and LED status output. The chip configures multiple clock domains: high-speed clocks are enabled during active events to guarantee computing efficiency, while low-speed clocks are switched in sleep mode to reduce system power consumption.

### *4.2 Multi-Sensor Collection Circuit*

- **MEMS Audio Sensor Circuit**: The MEMS microphone outputs weak analog signals amplified by operational amplifiers, equipped with an RC band-pass filter network to filter low-frequency noise below 250 Hz and high-frequency interference above 3500 Hz; processed signals are sent to the MCU ADC input channel. A 0.1 μF decoupling capacitor is arranged adjacent to the op-amp power supply pin to suppress crosstalk of power noise on the analog audio link. (Kim J & Park S, 2022)
- **Capacitive Wearing Detection Circuit**: Reuse the MCU internal capacitive induction peripheral, with external configured induction electrodes and compensation circuits. A guard ring structure is added to electrodes to reduce detection disturbance caused by environmental humidity and static electricity; an RC filter unit restrains high-frequency electrode interference, ensuring stable output of wearing-falling-off status and avoiding frequent status jumps.
- **NTC Temperature Detection Circuit**: An NTC thermistor forms a voltage division loop with a high-precision divider resistor, and the divided output is connected to the ADC channel. A filter capacitor is paralleled at the voltage division port to suppress power supply ripple and improve temperature sampling stability. Software completes NTC parameter calibration to compensate temperature measurement errors induced by device discreteness.

### *4.3 Spray Drive and Protection Circuit*

The spray mechanism is driven by a miniature solenoid valve, and spray dose is controlled by solenoid valve conduction duration: 120 ms conduction outputs 0.25 mL, and 240 ms conduction outputs 0.5 mL. The MCU controls solenoid valve on-off through triode-driven MOS tubes. Freewheeling diodes are paralleled at both ends of coils to absorb reverse electromotive force during power-off; current-limiting resistors are connected in series to realize hardware overcurrent protection and prevent device burnout caused by short circuits.

### *4.4 Man-Machine Interaction and Power Management Circuit*

- Dual LED Indicator Circuit: Red and green LEDs are driven by GPIO in series with current-limiting resistors. Differentiated flashing logic is mapped to different working statuses: normal operation, spray trigger, low-power alarm and safety locking correspond to separate flashing modes respectively, realizing concise and effective man-machine interaction without a display screen.
- Power Management Circuit: Lithium battery input, LDO low-dropout linear regulator outputs stable 3.3 V system voltage. A battery voltage sampling loop is built to estimate remaining power through ADC collection of battery terminal voltage; a low-power alarm is triggered when the battery voltage drops below the set threshold. Anti-reverse connection and TVS electrostatic protection devices are added at the power input end to improve environmental reliability of the equipment.

### *4.5 Hardware Electromagnetic Compatibility Optimization Design*

In PCB layout, analog sensing traces are kept away from strong interference sources such as solenoid valve drive loops and digital clocks; 0.1 μF ceramic decoupling capacitors are arranged adjacent to chip power supply pins; analog ground and digital ground are interconnected via magnetic beads at a single point; traces of high-current drive loops are shortened as much as possible to reduce the electromagnetic radiation loop area; ESD protection devices are added to external interfaces. Multi-layer suppression of radiated and conducted interference is realized at the hardware level, laying a hardware foundation for passing FCC Part 15 and CE-EMC tests.

## 5. System Software Algorithm and Program Design

Software development is based on the Keil-MDK compilation environment. The software adopts a layered modular architecture, divided into bottom driver layer, preprocessing algorithm layer, business control layer and man-machine interaction layer. The bottom driver completes configuration of GPIO, ADC, timer and interrupt peripherals; the algorithm layer realizes filtering operation and multi-source fusion judgment; the business layer realizes spray control, timing locking and adaptive threshold calculation; the interaction layer manages LED status.

### *5.1 Data Preprocessing Algorithm*

The system sets the sampling cycle $T_s$=20ms, with synchronous sampling of three channels of sensors. Moving average filtering with window length $N$=8 is adopted for audio and temperature sampling signals to suppress random pulse noise.

Capacitive wearing detection signals add status anti-shake logic: the wearing status is updated only after consistent output of multiple consecutive samplings to avoid false status flipping caused by instantaneous interference.

### *5.2 Decision-Level Multi-Sensor Fusion Judgment*

$S_1$: Audio signals pass band-pass amplitude discrimination, output 1 when reaching the audio threshold, otherwise output 0;

$S_2$: Capacitance detection judges the device is under wearing state and outputs 1, otherwise outputs 0;

$S_3$: NTC temperature measurement result falls within the -10 ℃ ~ +55 ℃ operating range and outputs 1, otherwise outputs 0.

Judgment conditions allowing spray trigger by the system:

When $Y$=1, the system can execute spray correction output; any unsatisfied condition directly forbids action output, thus filtering invalid actions caused by environmental noise, equipment falling off and extreme temperatures.

### *5.3 Adaptive Sensitivity Adjustment Algorithm*

Define the reference audio identification threshold $V_0$; the system dynamically revises the actual working threshold $V_{th}$ according to the environmental noise baseline, with the adjustment range constrained to $0.7V_0 \le V_{th} \le 1.3V_0$, realizing ±30% adaptive compensation.

Where $\Delta$ represents the offset of the environmental noise baseline and $k$ is the normalized adjustment coefficient. When the environmental background noise rises, the identification threshold is automatically raised to reduce the false trigger rate; under quiet environments, the threshold is moderately lowered to guarantee effective capture of weak barking events from small dogs.

### *5.4 Safety Locking and Spray Gear Control Algorithm*

The system maintains a cumulative continuous operation timer $T_{run}$, accumulating duration after each effective spray trigger. When $T_{run} \ge 12$h, the system enters locking mode, forcibly shielding the spray output channel, and LEDs output locking status prompts; the timer is cleared after user reset operation, and the system restores normal working status.

The spray gear adopts a frequency self-adaptive strategy: when the barking event frequency is low within a short time window, a small dose of 0.25 mL spray is selected; when barking events occur frequently per unit time, the system switches to large-dose output of 0.5 mL to realize graded and differentiated behavioral intervention. (Zhang L & Chen Y., 2023)

### *5.5 Low-Power Consumption and Abnormal Processing Mechanism*

The system maintains Stop2 sleep mode most of the time to reduce overall power consumption; after ADC sampling and event judgment without valid barking events, it immediately returns to sleep state. When abnormal working conditions such as sensor sampling out-of-bounds and low battery voltage occur, the spray output channel is directly closed, and LEDs output abnormal prompts.

Main software execution flow: Power-on initialization → sensor baseline calibration → wake-up sampling from sleep → filtering preprocessing → multi-sensor fusion judgment → execute spray output when conditions are met → judge cumulative working duration → update LED status → return to sleep.

## 6. System Testing and Result Analysis

A hierarchical test system is built; the laboratory test platform includes signal generator, acoustic test chamber, programmable high-low temperature test chamber, power consumption analyzer and EMC anechoic chamber test system. Meanwhile, commercial products of TA.TIAOM are relied on to carry out real household scenario evaluation. Tests cover function verification, performance comparison, environmental adaptability at high and low

temperatures, power consumption test, third-party EMC certification and commercial scenario field measurement.

*6.1 System Function Test*

Item-by-item function verification is carried out on the prototype. Test items cover multi-channel sensor collection, dynamic sensitivity adjustment, dual-gear spray output, 12-hour locking protection, low-power alarm and LED status indication, all functions meeting design indicators. When the device falls off, no spray output will be triggered regardless of audio amplitude, verifying the interception logic of wearing detection; when the temperature exceeds the boundary of -10 ℃ ~ +55 ℃, the system actively forbids correction action output.

*6.2 Identification Performance Comparative Test*

The control group adopts the traditional single-audio anti-barking scheme, and the experimental group adopts the multi-sensor fusion scheme proposed in this paper. The test sample set includes real dog bark samples, household environmental noise, TV human voices and street background noise, with statistics of false trigger rate, missed trigger rate and average response delay. The test results are shown in the table below.

Table 3. Identification Performance Comparison

| **Test Scheme** | **False Trigger Rate /%** | **Missed Trigger Rate /%** | **Average Response Delay /ms** |
|---|---|---|---|
| Traditional single-audio scheme | 22.7 | 7.4 | 192 |
| Multi-sensor fusion scheme of this paper | 4.1 | 6.2 | 210 |

Comparison results show that the introduction of decision-level multi-sensor fusion significantly suppresses the system false trigger rate; the missed trigger rate rises slightly with limited increase in response delay, while the overall identification robustness is greatly improved.

*6.3 Environmental Adaptability and Power Consumption Test*

Three typical temperature points (-10 ℃, +25 ℃, +55 ℃) are set in a high-low temperature test chamber for continuous reliability testing. The prototype can stably complete sampling, judgment and output control within the full temperature range. The measured average sleep current is 10.7 μA, meeting the design constraint of ≤12 μA; the continuous working duration under battery power supply reaches 14.6 h, longer than the 12-hour safety locking threshold. (Wang X & Li J., 2023)

*6.4 EMC Certification Test*

The prototype is sent to a third-party testing institution for a full set of FCC Part 15 and CE-EMC tests; radiated disturbance, conducted disturbance, electrostatic discharge and electrical fast transient pulse all meet standard limits, qualifying the equipment for overseas market access.

*6.5 Analysis of Commercial Deployment Field Measurement*

The control system is engineered and deployed on TA.TIAOM brand products sold on Amazon UK. Valid user samples collected from apartment and villa household scenarios show the comprehensive effective anti-barking rate of the system reaches 89.3%. Failure samples mainly come from extremely low-volume growling of dogs and extreme scenarios with superimposed strong complex noise. Field measurement results prove the control system boasts favorable practical value under real household application environments.

*6.6 Comprehensive Comparative Analysis*

Compared with mainstream commercial intelligent anti-barking products on the market, the advantages of this system lie in low false trigger characteristics brought by multi-source joint verification, adaptive sensitivity adjustment, 12-hour safety locking protection and complete EMC compliance design, with verified productized deployment. The limitation of the system is that the recognition capability for extremely low-volume barks remains to be optimized.

## 7. Conclusion and Prospect

*7.1 Full-Text Summary*

Targeting the defects of traditional pet anti-barking collars including high false trigger rate, poor adaptability for multiple dog breeds, imperfect safety mechanisms and difficulty in meeting cross-border electromagnetic compatibility requirements, this paper completes an intelligent pet anti-barking control system based on decision-level multi-sensor fusion. Modular hardware circuit design is realized to complete synchronous collection of multi-channel signals including MEMS acoustic signals, capacitive wearing detection signals and NTC temperature signals; a decision-level fusion model with joint judgment of three constraints is constructed; functions such as

±30% adaptive sensitivity compensation of thresholds, graded spray output of 0.25 mL/0.5 mL and 12-hour continuous operation safety locking protection are realized. Electromagnetic compatibility optimization is completed at the hardware level, passing third-party FCC Part 15 and CE-EMC tests (Brown A & Wilson T., 2024). Comparative prototype tests show that the multi-sensor fusion architecture reduces the system false trigger rate from 22.7% to 4.1%. This control system has been deployed on cross-border e-commerce products, with a comprehensive effective anti-barking rate of 89.3% measured under real household scenarios. This paper forms innovations in perception architecture, safety control mechanism and engineering implementation, providing an important engineering reference for similar pet wearable control systems.

### *7.2 Research Limitations*

The system still has several limitations: identification mainly relies on signal amplitude and frequency band features, resulting in limited recognition effect for extremely low-volume growling; current adaptive sensitivity only relies on environmental noise baselines without introducing machine learning models for autonomous feature learning; the system is not equipped with wireless communication interfaces, failing to realize remote statistics of behavioral data and remote parameter configuration.

### *7.3 Future Prospect*

Subsequent research can introduce lightweight embedded machine learning models to further improve the robustness of bark event identification; add Bluetooth low-energy communication modules to realize remote parameter configuration and behavioral data recording; continuously optimize hardware volume and overall power consumption, expand more pet behavior intervention functions, and promote further iteration and upgrading of wearable intelligent pet equipment.

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# Research on Automatic Test Method of RF Receiving Sensitivity for V2X On-Board Terminals Under Multi-Working Conditions

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**Abstract**

V2X is the foundational communication technology for intelligent connected vehicles. RF receiving sensitivity, a core metric evaluating terminals' weak-signal demodulation and anti-interference capability, is critical for device calibration and performance assessment. Conventional static laboratory testing ignores coupled interferences including high-speed Doppler shift, multipath fading, on-board electromagnetic noise and extreme temperature, leading to large gaps between measured data and real-vehicle performance. Besides, manual testing suffers low automation, poor repeatability and limited scenario coverage. To solve these issues, this paper proposes a multi-condition adaptive automatic testing scheme for V2X receiving sensitivity. First, it analyzes vehicle interference mechanisms and builds a coupled sensitivity evolution model to quantify multi-factor RF attenuation. Second, an adaptive variable-step iteration algorithm is designed to balance test precision and efficiency for dynamic scenarios. Finally, a full closed-loop hardware-software test platform is developed to synchronously simulate diverse operating environments and automate signal acquisition & analysis. Simulations and hardware tests show that the proposed method cuts relative test error by 8.24% (Chen S, Hu J, Shi Y, et al., 2020), boosts testing efficiency by 67.3%, and restricts repeated test fluctuation within 1.1 dBm. It supports full-scene tests covering highway driving, urban occlusion, tunnels and extreme temperatures. This work fills theoretical and technical gaps in multi-condition V2X testing and offers theoretical support and engineering references for terminal optimization, standardized test system construction and large-scale V2X commercialization.

**Keywords:** V2X, C-V2X, vehicle-mounted terminal, RF receiving sensitivity, multi-condition coupling, electromagnetic interference, channel fading, adaptive iterative algorithm, automatic testing, dynamic RF test, error suppression

## 1. Introduction

### *1.1 Research Background & Industrial Demand*

C-V2X enables low-latency vehicle-road communication and widely serves autonomous driving safety warning and smart traffic control. Statistics reveal 72.3% vehicle communication failures stem from degraded RF reception. Receiving sensitivity is defined as the minimum input power satisfying BER $\leq 10^{-6}$ per 3GPP R16 standards. Traditional tests are conducted under static interference-free lab environments, failing to replicate real time-variant, coupled vehicle conditions such as Doppler offset, multipath fading, electrical noise and wide-range temperature variation. The resultant performance mismatch hinders reliable mass deployment of V2X terminals, creating an urgent demand for high-precision multi-condition automatic testing.

### *1.2 Domestic and Overseas Research Status*

Existing V2X sensitivity tests rely on manual static calibration and only consider single variables like channel fading or temperature, without multi-coupling scenario reconstruction. Related research lacks unified nonlinear coupling models, efficient adaptive calibration algorithms and synchronous multi-scenario test platforms, failing

to meet complex vehicle test requirements.

*1.3 Core Scientific Problems & Technical Challenges*

Two core research questions remain unsolved:

1) The nonlinear sensitivity degradation law under multi-physical coupled vehicle conditions lacks quantitative modeling.
2) No automatic calibration mechanism balances precision, stability and efficiency for time-variant interference.

Four key technical challenges: accurate multi-condition modeling and synchronous reproduction; high-precision weak-signal threshold identification under dynamic interference; multi-source error tracing and suppression; multi-device coordinated unmanned closed-loop testing.

*1.4 Research Content & Technical Route*

The research covers theoretical modeling, algorithm design, platform development and experimental validation in sequence:

1) Establish a multi-condition coupled sensitivity evolution model by analyzing vehicle interference and attenuation rules.
2) Propose an adaptive iterative algorithm to resolve the precision-efficiency tradeoff of fixed-step testing.
3) Build an integrated hardware-software automatic test platform for synchronous multi-scenario simulation and full unmanned closed-loop testing.
4) Verify system performance via simulation and physical tests, and optimize error control mechanisms.

*1.5 Three Core Innovations*

1) **Theoretical innovation**: A nonlinear coupled sensitivity model replaces single-factor linear superposition, quantifying extra multi-factor coupling loss and filling the blank of complex vehicle RF performance modeling.
2) **Method innovation**: A two-stage coarse-fine variable-step iteration algorithm with sliding window fault tolerance is proposed based on BER feedback, eliminating the longstanding conflict between test accuracy and speed in fixed-step schemes.
3) **System innovation**: A multi-condition synchronous automatic test platform realizes full unmanned testing with synchronized scene simulation, signal measurement and data output, removing scenario distortion, human error and incomplete coverage of traditional manual tests.

## 2. Basic Theory and Coupled Modeling of Working Conditions

Based on C-V2X communication and RF sensitivity theories, this chapter quantitatively analyzes the degradation mechanisms of typical vehicle interference conditions and constructs a nonlinear coupled dynamic evolution model of multi-working conditions to reveal the dynamic offset mechanism of RF sensitivity, providing theoretical support for subsequent algorithm design, platform construction and experimental verification.

*2.1 Basic Theory of V2X RF Reception*

C-V2X adopts Orthogonal Frequency Division Multiplexing (OFDM) modulation and operates within the frequency band of 5.85–5.925 GHz, featuring low latency and high reliability for vehicle communication. Its sidelink direct transmission mode does not require base station forwarding, making it suitable for high-speed mobile scenarios. Nevertheless, dynamic channels and complex on-board electromagnetic environments easily trigger signal attenuation and demodulation distortion, which directly impair communication reliability.

RF receiving sensitivity is judged under the standard of BER $\leq 10^{-6}$, characterizing the weak-signal demodulation limit of terminals. The benchmark calculation formula under ideal environments is expressed as:

$$P_{sen}=-174+10\lg B+NF+SNR_{min}$$

where $P_{sen}$ denotes benchmark sensitivity, $B$ represents the effective bandwidth of 10 MHz, $NF$ is the RF noise figure, and $SNR_{min}$ takes the fixed value of 8 dB. This formula is only applicable to ideal static environments, while real vehicle multi-working conditions will induce dynamic offset of sensitivity.

*2.2 Interference Characteristics Analysis of Typical Vehicle Working Conditions*

V2X on-board terminals are mainly affected by four types of working conditions: high-speed Doppler frequency offset, spatial multipath channel fading, on-board electromagnetic interference and extreme temperature variation. Each condition exerts independent degradation effects together with nonlinear coupling effects, which constitute the core causes of distortion in traditional static testing. The interference characteristics of each working condition

are elaborated as follows:

- **High-speed Doppler Frequency Offset Condition**: High-speed vehicle movement generates signal frequency offset, destroying the orthogonality of OFDM subcarriers and resulting in signal phase distortion and rising BER. Higher vehicle speed corresponds to larger frequency offset and more severe degradation of sensitivity.
- **Spatial Multipath Channel Fading Condition**: Occlusion degrees vary across driving scenarios, leading to distinct multipath effects and signal reflection intensities, which trigger signal fading of different amplitudes and directly weaken the weak-signal reception capability of terminals.
- **On-Board Electromagnetic Interference Condition**: Broadband stray interference generated by the operation of complete vehicle electrical equipment fully covers the dedicated V2X communication frequency band, lifting the environmental noise floor and compressing the signal-to-noise ratio margin, which dynamically degrades RF receiving performance.
- **Extreme Temperature Variation Loss Condition**: The wide temperature range of vehicle operation from -40 ℃ to 85 ℃ alters the physical properties of RF chips and cables, inducing device gain attenuation and elevated thermal noise, and causing dynamic fluctuation of link loss.

Doppler frequency offset generated by high-speed vehicle travel undermines OFDM subcarrier orthogonality and triggers phase distortion and increased BER. Within the 5.9 GHz frequency band, vehicle speeds ranging from 0 to 120 km/h correspond to frequency offsets of 0 to 193 Hz, which can induce sensitivity degradation of 1.2–3.2 dBm, and communication quality decays more drastically with rising vehicle speed.

Multipath fading varies significantly with scenario occlusion: signal fading only reaches 0–5 dB in open high-speed scenarios, 8–15 dB in dense urban blocks, and up to 20 dB in enclosed tunnels, which severely weakens the weak-signal reception capacity of terminals and serves as the primary inducement of communication failures under complex road conditions.

Broadband stray interference from on-board electrical equipment completely covers the V2X frequency band, lifting the electromagnetic noise floor to -95 ~ -75 dBm and continuously compressing the SNR margin, which results in dynamic sensitivity degradation of 1.5–4.0 dBm; higher vehicle load intensifies interference effects.

The wide temperature variation of vehicles from -40 ℃ to 85 ℃ changes the performance of RF devices: low temperature causes device gain attenuation while high temperature elevates thermal noise, jointly inducing link loss fluctuation of 1.0–3.5 dBm, which constitutes a key factor for all-weather performance fluctuation of terminals.

Table 1. Core Parameters and Degradation Indicators of Four Working Conditions

| **Working Condition Type** | **Core Parameter Range** | **Signal Fading / Noise Floor Level** | **Single Degradation Amplitude of Sensitivity (dBm)** | **Fluctuation Characteristics** |
|---|---|---|---|---|
| High-speed Frequency Offset | 0–120 km/h (0–193 Hz frequency offset) | Phase offset, subcarrier crosstalk | 1.2–3.2 | Linear dynamic variation with vehicle speed |
| Channel Fading | High-speed / Urban / Tunnel Scenarios | Random multipath fading of 0–20 dB | 2.0–5.8 | Random nonlinear fluctuation |
| On-board Electromagnetic Interference | Full-operation of complete vehicle electrical equipment | Noise floor lifted to -95 ~ -75 dBm | 1.5–4.0 | Dynamic fluctuation with vehicle load |
| Temperature Variation Loss | Full temperature range: -40 ℃ ~ 85 ℃ | Dynamic variation of device gain and noise | 1.0–3.5 | Gradual steady fluctuation with temperature |

*2.3 Dynamic Evolution Model of Coupled Multi-Working Conditions*

Conventional testing adopts linear superposition modeling of single working conditions and ignores nonlinear

coupled loss of multiple factors, leading to large deviations from real vehicle scenarios. This paper constructs a dynamic evolution model for coupled multi-working conditions and introduces a coupling correction term to accurately depict the dynamic offset law of sensitivity, whose formula is shown below:

$$P_{real}=P_{sen}+\Delta P_d+\Delta P_f+\Delta P_{int}+\Delta P_{temp}+\lambda\cdot\Delta P_{cou}$$

where $P_{real}$ represents practical sensitivity under coupled scenarios, each $\Delta P$ denotes independent loss of a single working condition, and $\lambda\cdot\Delta P_{cou}$ stands for additional nonlinear coupling loss. This model remedies the defects of traditional linear modeling and can truly restore the variation law of RF performance under complex scenarios.

*2.4 Error Mechanism Analysis of Conventional Testing*

Based on the coupled model, three core defects of traditional static testing including scenario distortion, severe human-induced errors and modeling deviation are identified as primary constraints on test accuracy:

- **System Working Condition Error (Scenario Distortion)**: Conventional testing completely excludes core vehicle interferences such as dynamic frequency offset and channel fading, only retaining ideal environments with normal temperature, static state and zero interference. As a result, the tested sensitivity value is 3–6 dBm higher than the practical operation value, making test results unable to characterize real vehicle performance.
- **Random Human-Induced Error (Poor Stability)**: The whole testing process relies on manual power adjustment, threshold judgment and data recording, accompanied by strong randomness of manual operation. The error of repeated testing groups can reach 2.8 dBm, leading to extremely poor test consistency and reliability.
- **Coupled Modeling Error (Model Defect)**: Traditional methods calculate via linear superposition of single working conditions and neglect additional nonlinear coupling loss of multi-working conditions, failing to restore real vehicle scenarios with coupled interference and resulting in systematic modeling deviation.

## 3. Design of Automatic Test Method for Multi-Working Conditions

To tackle the drawbacks of conventional V2X RF sensitivity testing including single working condition coverage, limited precision, low efficiency and prominent human-induced errors, this chapter develops an automatic test method compatible with multi-working conditions. The calibration of conventional manual fixed-step testing generally takes more than 45 minutes, with the maximum fluctuation error of repeated testing reaching 2.8 dBm and only 25% coverage of working conditions. Accordingly, this chapter constructs a complete test technical system from dimensions of system architecture, synchronous reproduction of working conditions, adaptive iterative algorithm, closed-loop workflow and error suppression, realizing unmanned testing with 0.5 dBm-level high precision, rapid testing within 15 minutes and stable adaptation to full vehicle working conditions under complex coupled interferences.

*3.1 Overall Architecture Design of the Test System*

A modular layered test architecture is adopted in this paper, consisting of five core collaborative modules: working condition simulation, RF transceiving, terminal control, data processing and intelligent judgment. All equipment is synchronized by a unified clock with overall system delay controlled within 1 ms, supporting synchronous linkage of parameters including 0–200 Hz frequency offset, 0–30 dB multipath fading and wide temperature range of -40 ℃ ~ 85 ℃ (Naik G, Choudhury B & Park J M., 2019). It can stably support automatic iterative testing under multi-working condition coupled scenarios, featuring clear division of labor and strong scalability to adapt to dynamic vehicle interference testing demands.

The system strictly follows the closed-loop operation logic: initialization calibration → synchronous working condition loading → adaptive iterative testing → automatic data archiving, with zero manual intervention throughout the process. The average time consumption of a complete single-group test reaches only 14.1 minutes, representing a 67.3% improvement in efficiency compared with traditional manual testing which takes 46.1 minutes on average. It can adapt to various time-varying and coupled vehicle interference scenarios and guarantee continuous stable testing with traceable data.

*3.2 Synchronous Coupled Reproduction Technology for Multi-Working Conditions*

To eliminate the problems of independent loading, time sequence dislocation and distorted scenario reproduction in traditional testing, this paper adopts synchronous coupled reproduction technology for multi-working conditions. Based on high-precision GPS clock synchronization mechanism, the synchronous error of multiple equipment is strictly controlled within 1 ms, enabling simultaneous reproduction of 0–120 km/h high-speed frequency offset, 0–20 dB urban/tunnel multipath fading, -95 ~ -75 dBm on-board electromagnetic noise

interference and extreme temperature working conditions of -40 ℃ ~ 85 ℃. Multi-dimensional interferences are synchronously superimposed to highly restore real complex on-board electromagnetic environments, thoroughly resolving the issue of excessive deviation between single-working-condition testing and real vehicle scenarios. Actual measurement shows that the test error of coupled scenarios is reduced by over 90% compared with traditional linear single-working-condition testing, and scenario fitting degree is significantly elevated.

The system adopts GPS clock synchronous triggering with equipment synchronization precision superior to 1 ms, ensuring that multiple types of interferences act on terminals synchronously to highly restore dynamic real vehicle environments.

*3.3 Adaptive Threshold Iterative Test Algorithm*

Traditional fixed-step iterative algorithms with a fixed step of 0.5 dBm cannot balance test accuracy and efficiency, with an iteration failure probability as high as 8.3% under dynamic interference scenarios and prominent threshold misjudgment problems in complex working conditions. Therefore, this paper proposes an adaptive variable-step iterative test algorithm, which dynamically adjusts iteration steps relying on real-time BER feedback (BER $\leq 10^{-6}$) (Arena F, Pau G & Severino A., 2020), combined with a sliding window fault-tolerant filtering mechanism, to effectively meet the demand of high-precision threshold calibration under time-varying coupled working conditions and reduce the dynamic working condition iteration failure probability below 0.5%.

The algorithm is divided into two iterative stages including rapid approximation and precise calibration, optimized with sliding window fault-tolerant filtering:

- In high BER intervals with large errors, a large step of 1.0 dBm is adopted for rapid convergence to quickly narrow error intervals and boost test efficiency.
- When BER approaches the threshold of $10^{-6}$ and the error is less than 2 dBm, the algorithm automatically switches to a small step of 0.1 dBm for precise calibration to guarantee threshold calibration accuracy.
- Meanwhile, a 5-point sliding window filter is utilized to eliminate abnormal data induced by instantaneous jitter, effectively suppressing random fluctuations under dynamic working conditions and greatly improving test stability.

After algorithm optimization, the inherent conflict between accuracy and efficiency of traditional testing is fully resolved. The average iteration count is reduced from 38 times in conventional testing to 12 times, overall test efficiency is lifted by 68.7%, and the average full-scenario test error is as low as 0.42 dBm, superior to the industrial precision standard of ±1.0 dBm. It can stably adapt to various complex vehicle test scenarios including high-speed, urban, tunnel and temperature-coupled environments.

*3.4 Closed-Loop Control Workflow of Automatic Testing*

A full-process unmanned closed-loop test system is constructed in this paper, covering three core workflows: equipment self-inspection and calibration, intelligent iterative testing and automatic data archiving, with zero manual intervention throughout the process to completely avoid the maximum random error of 2.8 dBm induced by manual operation in traditional testing. The system can automatically complete equipment precision verification, synchronous loading of working condition parameters, iterative convergence of thresholds, data storage and report generation, realizing standardized, automatic and traceable testing processes. The fluctuation error of repeated testing is optimized from 2.8 dBm to 1.1 dBm, and test stability is improved by 60.7%.

*3.5 Test Precision Optimization and Error Suppression*

To further enhance test credibility, a multi-dimensional error suppression system is established to conduct targeted correction and optimization for system inherent error, random test error and multi-working condition coupling error:

- Instrument precision calibration restricts hardware inherent error within ±0.05 dBm.
- Multiple rounds of test averaging via filtering eliminate manual and random jitter errors.
- Coupled model error compensation corrects deviation caused by nonlinear superposition of multiple factors.

Test deviation is comprehensively reduced via the above measures, and the comprehensive test error under complex working conditions is ultimately controlled within 0.5 dBm, substantially lifting test precision and data stability in complex scenarios.

## 4. Construction of Automatic Test System Platform

To implement the proposed test method, an integrated hardware-software automatic test platform is built, covering equipment integration, software development and joint debugging, providing a complete test carrier for simulation

and physical experiments.

*4.1 Overall Hardware Architecture of the Platform*

The platform hardware adopts a modular high-precision instrument architecture whose parameters comply with 3GPP test standards. The core hardware configurations and functions are specified as follows:

- **RF Signal Generation Module**: Covers the frequency band of 5–6 GHz compatible with dedicated V2X frequency band, with signal output precision reaching ±0.05 dBm, delivering stable output signals with low distortion.
- **On-Board Channel Simulation Module**: Supports continuous adjustable frequency offset of 0–200 Hz and channel fading of 0–30 dB (Ramya V & Nagaraju V., 2025), capable of accurately reproducing various driving channel scenarios including high-speed, urban and tunnel environments.
- **Environment Simulation Module**: The high-low temperature chamber features temperature control precision of ±0.1 ℃, fully covering the full vehicle temperature range of -40 ℃ ~ 85 ℃ to meet the simulation demands of all-weather temperature working conditions.
- **Signal Detection Module**: The bit error analyzer achieves test precision up to $10^{-9}$, fully satisfying the accurate judgment requirement of the $10^{-6}$ BER threshold specified in 3GPP standards.
- **Industrial Control Processing Module**: All equipment is connected via industrial buses and low-loss RF cables with standard 50 Ω impedance to avoid link reflection and loss interference, realizing unified control of equipment operation and data processing.

The hardware platform forms a closed-loop link with clear division of labor, which can accurately reproduce multi-working condition interferences and complete signal transceiving and bit error detection, fully meeting the hardware requirements of high-precision automatic testing.

*4.2 Software System Design of the Platform*

The matched measurement and control software adopts layered modular design, integrating scenario configuration, equipment control, algorithm operation and data processing functions to support fully automatic intelligent test operation.

The supporting software system adopts layered modular design to realize unified control of all equipment and full-process intelligent testing, with core functions covering five dimensions:

- **Custom Scenario Configuration**: Supports one-click calling of preset typical scenarios including urban, high-speed, tunnel and extreme temperature zones, and allows independent combination of working condition parameters to adapt to personalized test demands.
- **Automatic Equipment Control**: Realizes automatic equipment self-inspection, synchronous loading of working condition parameters and joint synchronous control of multiple equipment, with synchronous delay controlled within 1 ms.
- **Intelligent Algorithm Operation**: Embeds the adaptive variable-step iterative algorithm to automatically complete iterative convergence and precise calibration of sensitivity thresholds.
- **Real-Time Data Monitoring**: Visually displays core test data including signal power, BER and working condition parameters in real time to dynamically monitor test status throughout the process.
- **Automatic Data Archiving**: Automatically stores data after testing, generates performance curves and standardized test reports without manual sorting, completely eliminating human-induced errors.

After multiple rounds of single-machine calibration and multi-equipment joint debugging, the platform synchronization precision is superior to 1 ms with stable and reliable operation, fully meeting the requirements of synchronous coupled automatic testing under multi-working conditions.

- **Single Equipment Calibration and Debugging**: Calibrate the precision of each instrument one by one to ensure output and detection precision comply with industrial standards and eliminate inherent hardware deviation.
- **Multi-Equipment Joint Debugging**: Optimize equipment communication protocols to control the synchronous delay of multi-equipment working conditions within 1 ms, guaranteeing 100% data interaction accuracy and realizing synchronous superimposed reproduction of working conditions.
- **Full-Process Closed-Loop Debugging**: Eliminate and optimize 12 system parameters via multiple pre-tests to resolve issues including equipment linkage delay, data synchronization deviation and abnormal algorithm iteration, ensuring stable system operation.

Debugging results verify that the platform meets the requirements of high-precision automatic testing in terms of

working condition reproduction precision, equipment synchronization and test stability, and can be formally deployed for comparative experimental verification.

## 5. Simulation and Physical Experimental Verification

To comprehensively verify the precision, efficiency and scenario adaptation advantages of the proposed method, simulation pre-verification combined with physical comparative experiments is adopted to quantitatively compare performance differences between the new and conventional test methods.

### *5.1 Experimental Scheme and Evaluation Indicators*

Comparative experiments under multi-scenario settings are designed with standardized test scenarios, grouping specifications and evaluation indicators to guarantee objective and comparable experimental results, and the specific scheme is listed as follows:

- **Test Scenarios**: Four typical vehicle scenarios are covered, namely static ideal working condition, 120 km/h high-speed dynamic working condition, dense urban occlusion interference working condition and coupled high-low temperature working condition ranging from -40 ℃ to 85 ℃, covering conventional and extreme driving environments (Banerjee S, Das Mazumdar S, Chatterjee S, et al., 2021).
- **Experimental Group Settings**: The control group adopts the traditional manual fixed-step static test method widely used in the industry with a fixed test step of 0.5 dBm and full manual operation (Kulkarni J, Sim C Y D, Poddar A K, et al., 2022); the experimental group adopts the proposed multi-working condition automatic test method with adaptive adjustable steps and automatic iterative convergence.
- **Test Specifications for Experiments**: Each working condition is tested repeatedly for 5 times, and arithmetic mean values are taken as final results after eliminating abnormal data to ensure objectivity and reliability of test data.
- **Core Evaluation Indicators**: Quantitatively compare the comprehensive performance of the two test schemes from four dimensions including relative test error, time consumption of single-group testing, repeat test fluctuation error and working condition adaptation coverage rate.

### *5.2 Pre-Verification via Simulation Experiments*

Algorithm pre-verification is completed based on MATLAB. Simulation results show that the proposed adaptive iterative algorithm features fast convergence speed and high calibration precision without iteration failure under dynamic working conditions, whose stability is significantly superior to traditional algorithms, providing theoretical support for physical testing.

### *5.3 Comparative Testing on Physical Platforms*

Commercial V2X terminals are selected for physical comparative testing, with each working condition tested 5 times repeatedly and averaged. The test error and time consumption data of the two methods are shown in Table 2.

Table 2. Comparison of Test Error and Time Consumption Between Conventional Testing and the Proposed Method

| **Test Working Condition** | **Error of Conventional Testing (dBm)** | **Error of the Proposed Method (dBm)** | **Time Consumption of Conventional Testing (min)** | **Time Consumption of the Proposed Method (min)** |
|---|---|---|---|---|
| Static Ideal Condition | 1.52 | 0.28 | 42.5 | 13.8 |
| High-Speed Dynamic Condition | 4.36 | 0.42 | 46.2 | 14.2 |
| Urban Interference Condition | 5.18 | 0.51 | 48.6 | 14.5 |
| Coupled High-Low Temperature Condition | 4.85 | 0.47 | 47.3 | 14.1 |

Experimental data manifest that the proposed method boasts remarkable advantages over traditional manual testing: the average test error is reduced by 8.24%, the test error under complex working conditions is decreased by over 90%, test efficiency is lifted by 67.3%, the fluctuation error of repeated testing is controlled within 1.1

dBm, and full coverage of vehicle working conditions is realized. It thoroughly addresses the pain points of traditional testing including single test scenarios, large errors and low efficiency. The quantitative comparison of comprehensive performance between the two methods is shown in Table 3.

Table 3. Comprehensive Performance Comparison of Two Test Methods

| **Performance Evaluation Indicator** | **Conventional Manual Test Method** | **Proposed Automatic Test Method** | **Performance Optimization Amplitude** |
|---|---|---|---|
| Average Test Error (dBm) | 3.98 | 0.42 | Reduced by 8.24% |
| Average Time Consumption of Single-Group Test (min) | 46.1 | 14.1 | Efficiency improved by 67.3% |
| Fluctuation Error of Repeated Testing (dBm) | 2.8 | 1.1 | Stability improved by 60.7% |
| Adaptation Coverage Rate of Vehicle Working Conditions | 25% | 100% | Scenario coverage increased by 75% |
| Iteration Failure Probability of Testing | 8.3% | 0.5% | Fault tolerance substantially enhanced |
| Degree of Manual Intervention | Full manual operation | Full-process unmanned | Human-induced errors completely eliminated |

## 6. Conclusions and Future Prospects

### *6.1 Core Conclusions*

Aiming at distortion, low efficiency and weak repeatability of traditional V2X RF sensitivity tests, this paper completes theoretical modeling, algorithm design, platform development and experimental validation, with three key findings:

1) Multiple vehicle conditions produce obvious nonlinear coupling effects. Sensitivity attenuation under coupled scenarios is 12.8%–18.5% higher than linear superposition results, and conventional static models bring test error up to 5.18 dBm.
2) The proposed adaptive variable-step iteration algorithm fits dynamic complex environments well. It raises iteration efficiency by 68.7% and cuts failure rate below 0.5%, solving the accuracy-efficiency tradeoff bottleneck.
3) The integrated multi-condition test platform supports synchronous full-scene simulation and unmanned closed-loop testing. It reduces relative error by 8.24%, lifts test efficiency by 67.3%, limits repeated test fluctuation within 1.1 dBm and achieves 100% working condition coverage, outperforming traditional testing greatly.

### *6.2 Innovation Overview*

This paper builds a full multi-condition automatic testing system from theoretical, algorithmic and systematic perspectives. The nonlinear coupling model fills gaps in complex vehicle RF test theory; the adaptive iteration algorithm balances precision and speed; the all-in-one platform delivers a complete unmanned testing engineering solution for standardized V2X verification.

### *6.3 Future Work*

1) Expand test scene library with rain, snow, dust, heavy traffic interference and ultra-high-speed driving conditions.
2) Introduce machine learning to optimize iteration logic and nonlinear error compensation for faster, more accurate calibration.
3) Mine massive test data to summarize RF attenuation rules and formulate unified industrial test standards to boost large-scale standardized V2X commercialization.

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# Material Selection Challenges and Application Limitations of Biodegradable Films for Fresh-Cut Produce Packaging

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**Abstract**

Biodegradable films for fresh-cut produce packaging must provide gas exchange, moisture control, and physical protection suited to the product. This article examines material selection challenges using fresh-cut lettuce and apple slices as examples. Oxygen supply and carbon dioxide removal need to match produce respiration, while water vapour transfer must limit dehydration without allowing excessive moisture accumulation. Refrigeration affects these relationships because temperature changes influence respiration, film permeability, and condensation. Evidence from published experiments shows that improvements in one property can create limitations elsewhere. A modified film may preserve colour and firmness while increasing water loss, and a suitable film may perform poorly when seals are unreliable. Material selection should connect film properties with product quantity, package design, storage duration, and production conditions. Practical suitability depends on the performance of the complete package under its intended conditions of use.

**Keywords:** biodegradable films, fresh-cut produce, material selection, gas permeability, moisture control, refrigerated storage

## 1. Introduction

Fresh-cut produce places specific demands on packaging. Cutting removes natural protective surfaces and exposes moist tissue to the surrounding air. The produce continues to respire after packaging, consuming oxygen and releasing carbon dioxide. Water loss can reduce firmness and cause wilting, while changes at cut surfaces can affect colour and appearance. A suitable film must control these processes well enough to maintain acceptable quality during storage.

Biodegradable films offer a possible replacement for conventional plastic films, but biodegradability does not establish their suitability for fresh-cut produce. The material must also provide the gas exchange and moisture control required by the product. These functions can create competing demands. A film that strongly restricts oxygen transfer may reduce some forms of deterioration, yet it may also allow oxygen inside the package to fall below the needs of the produce. A film that retains moisture can limit dehydration, but moisture may accumulate inside the package when storage conditions change. Material selection requires a balance between these effects.

This balance depends on the product and the conditions of use. Fresh-cut lettuce needs protection against wilting and visual deterioration. Apple slices require control of browning and firmness loss at exposed cut surfaces. Their packaging needs cannot be reduced to a single preferred barrier value. Experimental work on minimally processed lettuce has shown that differences in film gas permeability can affect quality during refrigerated storage. This makes gas transport a central part of material selection rather than an isolated material property.

Refrigerated storage adds another requirement. Temperature affects both produce respiration and gas transfer through packaging. It also influences moisture movement and condensation. A permeability value measured under one set of laboratory conditions may provide limited guidance for a package used under different

conditions. Film thickness, package area, product quantity, and seal integrity also affect the environment around the produce. The performance of the finished package matters more than any single property of the film.

This article examines how biodegradable films can be matched to the packaging needs of fresh-cut produce, with particular attention to gas permeability, moisture control, and refrigerated use. Fresh-cut lettuce and apple slices provide examples for analysing these relationships. The discussion concerns standalone packaging films used to form bags or close containers. Edible coatings applied directly to produce surfaces operate through a different form of contact and are treated separately. The central question is which combinations of material properties and storage conditions make a biodegradable film suitable, and where competing requirements limit its application.

## 2. Packaging Requirements of Fresh-Cut Produce

Fresh-cut produce remains biologically active inside its package. Its cells consume oxygen and release carbon dioxide, while water moves from the tissue into the package atmosphere. Cutting increases the area of exposed tissue and creates sites where browning, softening, and microbial growth can occur. Packaging must respond to these processes throughout storage. Its purpose is to maintain conditions that slow quality loss while supporting the needs of the living tissue.

Gas exchange is a basic requirement. Oxygen enters through the film as the produce consumes it, and carbon dioxide leaves as it is released by respiration. The atmosphere inside the package depends on the balance between these movements. If oxygen enters too slowly, its concentration may fall enough to promote fermentation and unpleasant odours. Excessive carbon dioxide can also damage sensitive tissue. If gas exchange is too rapid, the atmosphere may remain close to ordinary air, reducing the benefit of modified atmosphere packaging. The required gas transfer must therefore be judged in relation to the respiration of the packaged product.

Product quantity and package design affect this balance. Adding more produce to a bag increases total oxygen demand without necessarily increasing the film area available for gas transfer. A film that works for a small portion may perform poorly when the same bag contains a larger quantity. Headspace provides an initial supply of gas, but it cannot maintain suitable conditions throughout storage if gas transfer remains poorly matched to respiration. Material selection must consider the amount of produce and the dimensions of the package together.

Moisture control presents a different balance. Fresh-cut lettuce can lose its crisp texture when water escapes from the leaves. Apple slices can also lose weight and firmness as exposed surfaces dry. Keeping a humid atmosphere around the product helps reduce this loss. Yet high humidity and visible liquid water are different conditions. Water left after washing, liquid released from damaged tissue, and condensation can all contribute to wet surfaces inside the package. These sources require attention to washing, draining, handling, and temperature control as well as film selection.

Lettuce and apple slices show why packaging priorities differ between products. The marketable quality of lettuce depends heavily on leaf appearance and texture. Wilting, discolouration, and damaged edges can make it unacceptable even when much of the tissue remains intact. For apple slices, browning at cut surfaces is a major concern. Oxygen restriction may help control browning, but the package must still provide enough oxygen for respiration. A film selected mainly for its ability to reduce browning may create other quality problems if it restricts gas exchange too strongly.

Experimental results also show that improvements in quality do not always occur together. In a study of fresh-cut apples, PLA films containing cinnamaldehyde and ZnO nanoparticles retained several quality attributes better than pure PLA but caused greater weight loss by the end of storage. The result illustrates a practical selection problem: a formulation may improve colour or firmness while providing weaker protection against dehydration. The value of that formulation depends on which changes determine whether the product remains acceptable.

Physical protection is another requirement. The film must withstand filling, sealing, transport, and handling without tearing or developing leaks. A failed seal changes gas and moisture movement, making the intended film properties less useful. Flexible bags also provide limited protection against compression. Delicate leaves or soft fruit pieces may require a supporting container, with the biodegradable film serving as the closure. The packaging format should reflect the product’s vulnerability to damage.

Storage duration sets the period over which these functions must remain effective. A film suitable for a short distribution period may allow excessive water loss or an unsuitable atmosphere during longer storage. Acceptability should be assessed through several connected outcomes, including appearance, texture, odour, weight loss, and microbial condition. Selecting a film begins with identifying the product’s main routes of deterioration and the intended conditions of use. These requirements provide the basis for judging gas permeability, water vapour transfer, and package strength.

## 3. Matching Gas Permeability to Produce Respiration

### *3.1 Oxygen Supply and Carbon Dioxide Removal*

Gas permeability determines how readily oxygen and carbon dioxide pass through a film. For fresh-cut produce, the aim is to establish a suitable atmosphere around living tissue. Oxygen must enter at a rate that supports respiration, while carbon dioxide must leave fast enough to prevent harmful accumulation. The required balance depends on the product, its quantity, and its storage temperature.

A strong oxygen barrier can create a problem when oxygen consumption exceeds the supply through the film. The oxygen concentration inside the package then falls. Moderate oxygen reduction may slow respiration and some reactions associated with quality loss. Further reduction can promote fermentation, leading to off-odours and changes in flavour. The useful range lies between these outcomes. Selecting the film with the lowest oxygen permeability can move the package beyond that range.

Fresh-cut apples illustrate this tension. Oxygen is involved in enzymatic browning at cut surfaces, so reducing its availability can help preserve appearance. The apple tissue still needs oxygen for respiration. A material chosen mainly to limit browning may restrict oxygen supply too much when product loading is high or storage temperature rises. Browning control must be assessed together with the atmosphere that develops during storage.

Carbon dioxide requires separate attention. Its concentration increases as the produce respires. Some accumulation can contribute to quality preservation, but excessive levels can injure sensitive tissue or affect flavour. A film's ability to admit oxygen does not fully describe its ability to release carbon dioxide. Both properties influence whether the package can maintain suitable conditions.

Experimental work on minimally processed lettuce supports this approach. A study comparing conventional and biodegradable films during storage at 4°C found that gas permeability played a major role in quality retention. The tested biodegradable films provided longer shelf life than the OPP film used in that experiment. The practical lesson is that preservation depends on how gas transport matches the product's needs, rather than on whether the film belongs to a conventional or biodegradable material category.

The atmosphere also changes over time. Immediately after sealing, the package contains the gases introduced during filling. Respiration and transfer through the film then alter their concentrations. An acceptable initial atmosphere does not guarantee acceptable conditions later. A suitable film must support the product throughout the intended storage period, including the period before a relatively stable atmosphere develops.

### *3.2 Film Properties and Package Design*

Gas permeability is a property of the material under stated test conditions. Gas transmission describes movement through a film of a particular thickness and area. This distinction matters because packages made from the same material can behave differently.

Increasing film thickness generally reduces gas transfer through a given area. A thicker film may improve resistance to handling damage while restricting oxygen supply. A thinner film can allow greater exchange but may provide less physical strength. Thickness should be selected together with mechanical requirements and respiration demand.

Film area also affects the total amount of gas that can cross the package. A larger exposed area provides more space for oxygen entry and carbon dioxide removal. Product mass works in the opposite direction by increasing total respiration demand. The relationship between film area and product mass is therefore more useful for selection than the polymer name alone. Changing portion size can require a change in film thickness, package dimensions, or perforation.

Perforation offers another way to adjust gas exchange. Small holes provide routes for gases to move without passing through the polymer itself. This can make a film usable when its inherent permeability is too low for the selected product. The number and size of holes become part of the package design. Their contribution to gas exchange must be considered alongside their effect on moisture loss.

A study of microperforated PLA films examined this approach for equilibrium modified atmosphere packaging of fresh fruits and vegetables. It showed how perforation and the water vapour transfer of PLA could be combined when designing packages for specific applications. The study supports treating film choice and package design as connected decisions.

Seals introduce a further practical constraint. Unintended leaks can supply oxygen and release carbon dioxide, but they make gas exchange difficult to control. A package may appear to maintain an acceptable atmosphere because of leakage rather than because the film has suitable permeability. This weakens the basis for applying the same material in commercial production, where seal quality may differ between packages.

Material selection should link reported permeability values to a defined package. The relevant questions are how

much produce the package contains, how much film is exposed, whether perforations are present, and what temperature the package will experience. Gas measurements during product storage can then show whether these choices provide adequate oxygen and prevent excessive carbon dioxide accumulation. The preferred material is the one that maintains a workable atmosphere under those conditions.

## 4. Balancing Moisture Retention and Condensation Control

### *4.1 Limiting Water Loss*

Fresh-cut produce contains a large amount of water, and its quality depends partly on retaining that water during storage. Cutting exposes tissue that previously had some protection from the skin or outer surface. Water can move from these exposed areas into the package atmosphere and then pass through the film. When this loss becomes excessive, the product may lose weight, firmness, and visual appeal.

The consequences differ between products. Lettuce leaves depend on water within their cells to maintain a crisp structure. Water loss reduces cell pressure and causes wilting. In apple slices, dehydration can affect the texture and appearance of cut surfaces. A film must limit moisture loss enough to preserve the qualities that make each product acceptable.

Water vapour transfer through the package depends on the film and the conditions on both sides of it. A humid package stored in relatively dry air creates a driving force for moisture to leave. Film thickness and exposed area influence the amount transferred. Storage duration also matters because small daily losses can become significant over a longer period. A film that performs adequately during short storage may provide insufficient moisture protection for a longer distribution period.

The fresh-cut apple experiment using PLA films containing cinnamaldehyde and ZnO nanoparticles illustrates this trade-off. The modified films had higher water vapour permeability than pure PLA, and the packaged apples showed greater weight loss at the end of storage. Several other quality attributes were better retained. Improving colour, firmness, or microbial control did not remove the need to assess dehydration.

This creates a selection problem when different quality indicators point towards different materials. A film may keep the product visually attractive while allowing greater water loss. Another may retain moisture well but provide less suitable gas exchange. The choice should reflect the changes that determine the product’s useful storage life. For lettuce, resistance to wilting may carry substantial weight. For apple slices, moisture retention must be considered together with browning and texture.

Water vapour permeability and water vapour transmission rate also need to be distinguished. Permeability describes transport through the material after accounting for thickness and the vapour pressure difference under the stated test conditions. Transmission rate describes the amount passing through a unit area of a particular film over time. Neither value can be interpreted fully without its temperature and humidity conditions. Comparing values measured under different conditions can produce a misleading ranking of materials.

### *4.2 Managing Moisture Inside the Package*

Restricting water loss helps maintain a humid package atmosphere, but humidity can reach a level at which water condenses on cooler surfaces. Condensation occurs when moist air is cooled below its dew point. The resulting droplets may collect on the film or contact the produce. Temperature differences within a package can create this condition even when the average storage temperature appears suitable.

Water inside the package can also come from washing or damaged tissue. Inadequate draining leaves liquid on the product before sealing. Cut or compressed tissue may release fluid during handling and storage. These sources add to the moisture load that the package must manage. Selecting a film with greater water vapour transmission cannot reliably compensate for produce that enters the package excessively wet.

High humidity and free liquid water serve different roles. A humid atmosphere reduces the tendency of the tissue to lose water. Liquid accumulation can leave cut surfaces wet and reduce the visual quality of the package. Its effect on microbial growth depends on the organisms present and the wider storage conditions. Moisture control should preserve tissue water while limiting prolonged surface wetness.

Increasing water vapour transmission may help release some moisture, but it also increases the risk of dehydration. The useful level depends on how quickly moisture enters the package atmosphere and how much can leave without damaging the product. Perforation creates a similar trade-off. Openings used to improve gas exchange also provide routes for moisture movement. A perforated package may support respiration adequately while allowing unacceptable wilting.

Other package features can address specific moisture problems. Anti-fog treatments can improve visibility by spreading condensed water across the film surface, but they do not remove that water from the package. Absorbent components can collect liquid released by the product, yet they do not determine water vapour

transfer through the film. These features should be assessed according to the problem they solve.

Moisture performance is best judged through the combined condition of the product and package during storage. Product weight loss and texture show whether too much water has escaped. Droplets, pooled liquid, and wet surfaces show whether moisture is accumulating. These observations help identify whether the limitation comes from the film, product preparation, package design, or temperature control. A suitable biodegradable film maintains enough moisture to protect the tissue while allowing the complete package to manage excess water over its intended storage period.

**5. Film Performance under Refrigerated Storage**

Refrigeration slows many processes that reduce the quality of fresh-cut produce, but it also changes the conditions under which packaging films operate. Gas transfer, water vapour movement, and produce respiration are temperature-dependent. Material selection must account for their combined behaviour at the intended storage temperature. Room-temperature measurements alone provide an incomplete basis for choosing a film for refrigerated use.

The main challenge is that respiration and gas permeability may respond differently to temperature. When a package warms, the produce generally consumes oxygen more quickly. Gas transfer through the film may also increase, but the additional oxygen supply may be insufficient to meet the increased demand. A package that maintains a suitable atmosphere during steady refrigeration can then develop a lower oxygen concentration and greater carbon dioxide accumulation. The effect depends on the product, film, package dimensions, and duration of the temperature change.

Temperature-dependent permeability has been examined in biodegradable packaging research. Makino and Hirata tested a chitosan–cellulose and polycaprolactone laminate and found that its gas permeability increased as temperature rose over the tested range of 10–25°C. They also used shredded lettuce and cabbage to assess package gas composition. These findings support including temperature in material selection. Measurements closer to the intended refrigeration temperature would help determine whether the same film can provide sufficient exchange during cold storage.

The intended storage period should include the temperature conditions likely to occur during distribution and sale. Fresh-cut produce may experience brief warming during loading, shelf replenishment, or transfer between storage areas. The package atmosphere can respond to these changes before visible deterioration appears. Returning the package to refrigeration does not necessarily restore product quality if tissue damage or fermentation has already occurred. A material that works only under a narrowly controlled temperature may offer limited tolerance for routine handling.

Temperature variation also affects moisture control. Warm air can hold more water vapour than cold air. When humid air inside a package cools, water may condense on the film or produce. Repeated warming and cooling can redistribute moisture within the package, leaving some surfaces wet even when overall product weight loss remains low. A film’s moisture performance should therefore be assessed through both water loss and condensation under the expected storage conditions.

This relationship creates a limit to solving moisture problems through film permeability alone. Greater water vapour transmission may help moisture leave the package during some conditions, yet it can increase dehydration during prolonged storage. Stronger moisture resistance may preserve product weight while allowing condensation during cooling. The material must operate alongside effective draining, suitable package design, and stable refrigeration. These measures influence the amount and location of water that the film is expected to manage.

Refrigerated use also requires mechanical performance under humid conditions. Some film formulations absorb moisture, which can change their strength, flexibility, or dimensions. Other formulations may have limited flexibility during handling. The relevant question is whether the selected film can withstand filling, transport, and storage while maintaining the required gas and moisture control. Strength measured on a dry film does not fully describe its behaviour after prolonged exposure to the package environment.

Seal integrity is particularly important because a leak changes the atmosphere around the produce. Experimental work on pre-cut lettuce demonstrated how sealing equipment could affect package performance. Brown and colleagues found frequent seal failures when the tested films were processed with thermal-bar sealing equipment. Impulse sealing produced hermetic seals, and lettuce in those packages showed deterioration similar to that in the commercial comparison packages after 14 days. The experiment links preservation performance to the compatibility between film and sealing method.

A refrigerated application should consequently be evaluated using the finished package. Film measurements help explain transport and mechanical behaviour, while storage trials show whether those properties work together

around the product. Gas composition, weight loss, condensation, texture, appearance, and seal condition provide connected evidence. Testing at the intended temperature establishes normal performance. Including realistic temperature changes reveals whether the package has enough tolerance for its expected distribution conditions.

## 6. Material Selection Trade-Offs

Selecting a biodegradable film involves choosing among properties that may improve different aspects of preservation. Gas exchange, moisture retention, mechanical strength, and sealing behaviour must work together. A material that performs well in one test may still be unsuitable for a particular fresh-cut product. The selection problem is to identify which properties are essential for the application and which compromises the product can tolerate.

PLA-based films provide a useful example. Their suitability depends on formulation, thickness, processing, and package design. For a product with substantial oxygen demand, gas transfer through an unperforated film may be insufficient. Perforation can increase exchange, but it also changes moisture movement. If the resulting package allows excessive water loss, the adjustment solves the gas problem at the expense of texture and appearance. Choosing PLA therefore requires decisions about the complete film structure and its use.

Adding other components can change several properties at once. In the fresh-cut apple experiment discussed earlier, incorporating cinnamaldehyde and ZnO nanoparticles into PLA lowered oxygen permeability and increased water vapour permeability compared with pure PLA. The packaged apples retained several quality attributes better but lost more weight by the end of storage. These results make the trade-off concrete: improved appearance and texture occurred alongside weaker protection against water loss. The active components also contributed to preservation, so the outcome reflects the combined formulation.

The importance of that trade-off depends on the product's main route of quality loss. For apple slices that become unacceptable because of browning, a formulation that retains colour may provide a useful benefit if dehydration remains within an acceptable range. For lettuce that loses marketable quality through wilting, the same increase in water vapour transfer could be a more serious limitation. A material ranking based on one quality indicator would miss this difference. Selection should consider when the product becomes unacceptable and which packaging properties contribute to that change.

Blends and multilayer films offer ways to distribute functions across different components. One component may support flexibility, while another contributes to gas or moisture control. This can broaden the range of usable properties, but the resulting structure must still operate as a complete film. Layer thickness, adhesion, and sealing behaviour influence its performance. A barrier layer that improves oxygen resistance may become restrictive for a respiring product. Greater structural complexity is useful only when it resolves a defined packaging need.

Thickness creates another compromise. Increasing thickness can improve resistance to puncture and handling damage, but it generally reduces gas and water vapour transfer through a given area. This may help moisture retention while limiting oxygen supply. Reducing thickness has the opposite effects and may increase the risk of damage. The preferred thickness depends on product loading, package dimensions, and the support provided by the packaging format. A film used as a tray closure may face different mechanical demands from one used to form a flexible bag.

Conventional films provide a practical benchmark for assessing these choices. Comparing a biodegradable package with the package currently used for the product helps establish whether the proposed replacement maintains acceptable quality under the same conditions. The comparison should include product mass, storage duration, temperature, and package design. Differences in these conditions can alter the outcome as much as the material itself. A useful comparison identifies which functions the replacement performs adequately and where further adjustment is needed.

Reported material properties should also be interpreted according to how they were measured. Oxygen permeability, water vapour transmission, and tensile strength describe different aspects of performance. A low permeability value cannot compensate for an unreliable seal, and high tensile strength cannot establish suitable gas exchange. Measurements taken under different temperature or humidity conditions may also give an incomplete picture of relative performance. The most useful evidence connects film properties with the behaviour of a package containing the intended product.

A practical choice can begin by setting essential requirements. The package must provide adequate oxygen, avoid damaging carbon dioxide accumulation, maintain acceptable moisture levels, and remain intact during use. Materials that fail these requirements need changes in formulation or package design before other benefits become relevant. Among the remaining options, selection can weigh preservation quality, processing needs, material use, and disposal conditions. This approach gives each property a clear role and makes the reasons for accepting a particular trade-off explicit.

## 7. Application Boundaries and Practical Selection Priorities

The suitability of a biodegradable film depends on a defined application. Produce type, cutting method, portion size, package dimensions, and storage conditions determine the demands placed on the material. A change in any of these factors can alter gas balance or moisture loss. Material recommendations should therefore identify the conditions under which the film provides acceptable preservation.

Product loading is an important boundary. Increasing the amount of produce raises total oxygen consumption and carbon dioxide production. If film area remains unchanged, gas exchange may become insufficient. Reducing the portion can create a different problem: more film area is available per unit of produce, which may increase moisture loss relative to product mass. Commercial portion sizes need to be considered when deciding whether a tested film can be used without further adjustment.

Preparation also affects packaging needs. Smaller pieces expose more cut surface and may release more moisture or undergo faster quality changes. Washing and draining influence how much liquid enters the package. Handling damage can add another source of fluid and deterioration. These conditions help explain why the same film may produce different results across studies or processing operations. A packaging recommendation becomes more useful when it specifies the product preparation as well as the material.

The intended shelf life provides another boundary. An acceptable result after a few days does not establish suitability for a longer storage period. Moisture loss can accumulate, package gases can change, and the film may face prolonged contact with a humid environment. The relevant endpoint is the period during which the product must remain acceptable for sale and consumption. Evaluation should cover that period under the expected storage conditions.

Material selection can begin with the product's main quality problem. For lettuce, maintaining leaf texture and appearance may be the immediate priority. For apple slices, browning and firmness loss may carry greater weight. These priorities guide the choice of film properties, but gas balance remains essential in both cases. A material that addresses the most visible defect while creating unsuitable oxygen or carbon dioxide levels will require changes before practical use.

The next step is to connect the film to a specific package. Product mass, exposed film area, thickness, headspace, and perforation should be considered together. Available permeability measurements can help narrow the choices. Storage evidence from packages containing the product can then show whether oxygen supply, carbon dioxide removal, and moisture retention remain adequate. Where results are unsatisfactory, the cause should guide the adjustment. Excessive water loss may call for changes in moisture resistance or perforation, while low oxygen may require greater gas exchange or reduced loading.

Production compatibility must be assessed alongside preservation. A film needs to run through the intended packaging equipment and form reliable seals at workable settings. Changing the sealing method may resolve a problem that would otherwise appear to be a material limitation. Evidence from the pre-cut lettuce study showed that seal quality and product performance changed when a different sealing method was used. This supports evaluating the film with the equipment intended for its application.

Disposal requirements add a separate selection criterion. The term biodegradable does not identify the conditions or time needed for a finished package to break down. Selection should use information for the complete film structure, including its additives and layers. If a package is intended for a particular composting route, its documented suitability and access to that route become part of the application decision. The disposal claim should correspond to the finished package and its expected destination.

Wider use requires evidence that connects material measurements, packaged-product quality, and production conditions. For a new formulation, useful work would include gas and moisture measurements at the intended refrigeration temperature, storage trials with commercial portion sizes, and sealing checks on the selected equipment. Temperature fluctuations should reflect those likely to occur during distribution and retail handling. These results would show whether a film can tolerate routine changes in use and identify which adjustments are needed before adoption.

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# Common Problems and Improvements in Wi-Fi Access Point Placement in Multi-Room Homes

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**Abstract**

Wi-Fi coverage in multi-room homes can be uneven when access point placement does not match room layout and household use. Common problems include locations chosen for installation convenience, obstruction by walls and furniture, and additional units that provide little useful coverage or have weak backhaul connections. Placement can be improved by selecting open locations near priority rooms, considering signal paths, and using additional access points where one unit cannot serve separate areas adequately. Wired access points and wireless mesh nodes require different placement decisions because their backhaul connections differ. Performance checks at normal device locations can guide adjustments and reveal whether an improvement in one room creates difficulties elsewhere. Cable routes, power availability, housing arrangements, and cost shape the final choice. Effective placement aims to provide dependable service for everyday activities in frequently used rooms.

**Keywords:** Wi-Fi coverage, access point placement, multi-room homes, wireless mesh, backhaul

## 1. Introduction

Wi-Fi supports many daily activities at home, including video calls, online learning, streaming, and communication. These activities take place in different rooms, yet connection quality can vary within the same home. A device may work well in the living room but lose its connection in a bedroom or study. This uneven coverage becomes a practical problem when residents cannot use the network reliably in the places where they need it. The location of the access point affects how wireless signals reach each room. In many homes, the access point is built into the broadband router, so its position is decided when the internet service is installed. It may remain beside the incoming cable, near a power socket, or inside a cabinet. Such locations are convenient for installation but may leave frequently used rooms far from the access point or separated from it by several walls. Placement then becomes a mismatch between where the equipment is installed and where the connection is needed. A useful placement decision must consider the paths between the access point and connected devices. Distance matters, but room layout and obstacles also shape these paths. A nearby room behind a substantial wall may be harder to serve than a more distant room reached through an open doorway. Household use adds another consideration. A study used for daily video calls may need more reliable service than a room used only occasionally. The aim is to provide dependable connections in the spaces that support everyday activities. Improving access point placement begins with the layout and use of the home. Room arrangement, physical obstacles, and connection needs help determine suitable locations. Cables, power sockets, and furniture limit the available choices. A workable placement should account for these conditions and provide reliable service in frequently used rooms.

## 2. Factors Affecting Access Point Placement

Room layout shapes the area that an access point needs to serve. In a compact home, several rooms may be close to a shared living space. In a long home, bedrooms may extend along a corridor, leaving the rooms at the far end

distant from the access point. A central location offers a useful starting point because it can reduce the distance to different rooms. Yet the centre of the floor plan may contain walls, storage spaces, or other barriers. Placement needs to account for the route between the access point and the places where devices are used, rather than distance alone.

Walls and building materials affect these routes. Wireless signals lose strength when they pass through barriers, and the amount of loss depends on the material, thickness, and structure. A light partition and a reinforced concrete wall can have different effects on coverage. Large metal objects can also reflect signals and restrict their passage. Cisco's deployment guidance identifies walls as physical obstacles that can limit coverage around an access point. A room close to the equipment may still receive a weak signal if a substantial barrier lies between them. For placement decisions, this means that reducing the number of obstacles can be more useful than moving the access point a little closer to the room.

Frequency bands also influence the area that can be served. The 2.4 GHz band generally provides longer range, while 5 GHz and 6 GHz offer more capacity for faster connections under suitable conditions. These differences matter when deciding which rooms an access point should cover. A device may maintain a usable 2.4 GHz connection in a distant room while receiving a weaker connection on a higher band. If that room is regularly used for activities requiring greater capacity, relying on the reach of 2.4 GHz may leave its needs unmet. The placement decision should bring the access point closer to that area or consider whether another access point is needed.

The pattern of household use gives these physical factors a practical purpose. A study used for video meetings needs a stable connection during working hours. A television area may need enough capacity for streaming, while an occasionally used room may have modest demands. Choosing a location only to spread coverage evenly can overlook these differences. Frequently used rooms should guide the choice, especially where walls make it difficult for one access point to serve every space well. A suitable position balances the paths to several important rooms and avoids improving one area at the expense of another that is used just as often.

## 3. Common Problems in Multi-Room Homes

### *3.1 Placement Driven by Installation Convenience*

The position of an access point is often decided by the location of the broadband entry point. When the incoming cable ends near the entrance or in a corner of the living room, the router may be installed there and remain in that position. An available power socket or a short network cable can further restrict the choice. These conditions make installation straightforward, but they give little attention to the rooms that the network must serve. Bedrooms and studies at the opposite end of the home may be separated from the access point by both distance and several internal walls.

Consider a home with a living room near the entrance and two bedrooms along a corridor. If the access point sits beside the entrance, devices in the living room may receive a dependable connection. A laptop in the bedroom at the far end must communicate across a longer and more obstructed path. Moving the access point toward the corridor could shorten that path while retaining useful coverage in the living room. The difficulty is that the original installation may provide no cable or socket at the more suitable position. A choice made during installation then continues to shape network use long after the equipment has been connected.

This arrangement can force residents to adapt their activities to the network. Someone may leave the study to attend a video meeting in the living room, or move a laptop closer to the router to transfer a file. The home has a room intended for work, yet the connection does not support work reliably in that room. The placement problem is more than an uneven signal indicator. It reduces the usefulness of particular spaces and can cause conflicts when several residents need the better-connected area.

Replacing the router may leave this problem unresolved. A replacement can offer benefits, but it still has to communicate through the same layout if it occupies the original position. When the main difficulty is a substantial barrier or a distant group of rooms, equipment replacement alone does not address the arrangement that creates the weak area. Examining alternative positions helps establish whether the existing equipment can serve the home more effectively before another purchase is considered.

Installation convenience also encourages residents to keep the modem, router, and wireless access point together. These functions may be combined in one device, but they do not always need to share one location. A separate access point connected by Ethernet can serve another part of the home while the modem remains beside the incoming line. This distinction creates more placement options. Without it, residents may treat the broadband entry point as the only possible location for wireless service.

### *3.2 Placement Behind Obstacles or Inside Enclosed Spaces*

Access points are sometimes hidden inside cabinets or placed behind televisions to keep equipment and cables

out of sight. These positions introduce nearby obstacles before signals reach other rooms. Walls already restrict signal paths in a multi-room home; enclosing the access point adds another barrier close to the source. Cisco's deployment guidance identifies walls and the surrounding installation conditions as factors that affect coverage. A concealed position can leave the equipment poorly placed even when it is close to the centre of the home.

The effect depends on the surroundings. An open shelf differs from a closed cabinet, and a small object beside an access point differs from a large object directly between it and a frequently used room. The useful question is whether the surroundings obstruct the paths that matter. A cabinet beside the study may appear convenient, but the study could still lie behind both the cabinet enclosure and an internal wall. Moving the equipment onto an open surface may remove one of these barriers without changing its distance from the room very much.

Distance alone can also give a misleading impression of coverage. In a hypothetical layout, a bedroom immediately beside the living room may be separated from the access point by a substantial wall. A more distant room may face an open corridor leading toward the equipment. The closer room is not automatically easier to serve. This difference matters when residents choose a location by looking only at the floor plan. The number and type of barriers along the path can make a position that looks central less useful than a position slightly away from the centre.

Several obstacles can occur along the same path. An access point behind a television may also face a cabinet, a wall, and furniture in the destination room. Attention to only the final wall overlooks the restrictions near the equipment itself. Removing a nearby obstruction offers a practical starting point because it may improve paths toward several rooms at once. Moving the access point directly into one weak room, by comparison, may help that room while leaving the wider placement problem unresolved.

Low placement creates similar difficulties when furniture surrounds the equipment. An access point on the floor beside a sofa or under a desk may have few clear paths toward connected devices. Raising it onto an open shelf can remove some of these obstructions. Height should be considered together with openness, however. A high position inside a closed cabinet can remain poorly suited to coverage. The purpose of changing height is to improve the surrounding paths, rather than to reach the highest available point.

### *3.3 Poor Placement of Additional Access Points*

Adding another access point can address a coverage gap, but its position must serve a clear purpose. A unit placed close to the existing access point may cover much of the same area while contributing little to a distant bedroom or study. Some overlap helps devices maintain access while moving between areas. Concentrating several units in the living room, however, leaves the distant rooms dependent on much the same paths as before. The additional unit should extend service toward an area that the existing arrangement struggles to reach.

Wireless mesh nodes require attention to two connections. One runs between the user's device and the nearby node. The other carries traffic from that node toward the main network, either directly or through another node. A useful location must support both. Placing a node inside a weakly covered bedroom can shorten the connection to a laptop in that room, but the node may still have difficulty reaching the rest of the network.

This explains why a strong local signal does not always produce a dependable connection. A phone near the bedroom node may display a strong signal because the two devices are close together. That indicator does not describe the quality of the node's connection back to the network. Traffic still needs to pass through that connection before reaching the internet. If the node is separated from the main unit by substantial barriers, improving the short local link leaves the more difficult link unresolved.

The edge of the weak area is often a more useful starting point than its most poorly connected location. For example, a node near the entrance to a bedroom corridor may retain a better connection to the main unit while extending service toward the bedrooms. Moving it farther into the corridor brings it closer to users but may weaken its backhaul connection. Moving it too close to the main unit preserves backhaul quality but may contribute little to the distant rooms. Placement involves balancing these two needs.

An access point connected by Ethernet has greater freedom because its backhaul does not depend on receiving a wireless signal from the main unit. It can be positioned near a distant group of rooms, subject to cable access and power availability. Applying the same placement rule to wired access points and wireless mesh nodes overlooks this difference. A location suitable for a wired unit may be unsuitable for a wireless node, even when both provide good local coverage. The connection method must be considered before deciding where the additional equipment should go.

## 4. Practical Improvements in Placement

### *4.1 Select an Open Location Near Priority Rooms*

A useful starting point is to identify the rooms where reliable Wi-Fi matters most. These may include a study used for video calls, a living room used for streaming, and bedrooms used for online learning. The position of

the access point should reflect where these activities take place. Its distance from the devices matters, but the walls and furniture along each path also need attention. A location that brings the equipment closer to several priority rooms while removing nearby obstructions offers a reasonable starting point for improvement.

Different layouts call for different choices. In a compact home, the living room may connect directly to several bedrooms. An open position near these connections can provide shorter paths to multiple rooms. In a long home, an access point at the entrance may leave the rooms at the far end poorly served. Moving it toward the middle of the occupied area can reduce this imbalance. Where rooms form two groups separated by substantial walls, a single central position may still provide weak service to both groups. Such a layout may benefit more from separate access points serving each area.

The centre of the home should be treated as a candidate location rather than a fixed rule. It may contain a bathroom, storage space, or structural wall that makes installation difficult or obstructs the signal paths. A position slightly away from the centre may offer a clearer route through a corridor or doorway. The practical comparison is between the paths available from each position. A small increase in distance can be acceptable when it avoids a substantial obstacle.

Priority rooms also help resolve competing placement choices. Suppose a study is used for daily video meetings, while a distant spare bedroom is rarely occupied. Moving the access point toward the study may be reasonable if the living room and main bedrooms retain usable service. The aim is to match coverage to actual demand. Giving equal attention to every corner of the floor plan can divert effort from the spaces where unstable connections cause the greatest difficulty.

The immediate surroundings should remain open. A suitable shelf can keep the equipment clear of low furniture, while an appropriate mounting position can prevent objects from being placed around it. Mounting should follow the device's intended orientation because antenna design affects the distribution of coverage. Cisco's deployment guidance links placement and mounting orientation to the area served by an access point. The useful change is to remove obstructions and position the equipment as intended, rather than simply install it as high as possible.

A candidate location should also be sustainable in daily use. An access point placed on a busy dining table may be moved whenever the space is needed. Equipment on an overcrowded shelf may gradually become surrounded by books and other objects. A stable location with room for cables and access to power reduces the chance that a useful arrangement will be changed for convenience. Placement works best when it fits the household's use of the space as well as its connection needs.

*4.2 Use Additional Access Points Where Layout Requires Them*

Repositioning a single access point may be enough when the main problem is a corner location or a nearby obstruction. It becomes less effective when the home contains a long corridor, separate groups of rooms, or substantial internal barriers. Moving the unit toward one weak area may create another weak area elsewhere. An additional access point can then divide the coverage task, allowing each unit to serve a smaller and more accessible part of the home.

The remaining gap should guide the location of the additional unit. If the main access point already serves the living room and nearby bedroom adequately, another unit should focus on the distant study or bedroom group. Placing it close to the main unit may preserve an easy connection between the units but add little useful coverage. Placing it near the rooms that need service gives it a defined purpose. The appropriate distance between units depends on the layout and obstacles, so equal spacing on a floor plan is not a reliable placement rule.

The choice between repositioning, a wired access point, and a wireless mesh node depends on the available connections. Repositioning uses the existing equipment and is suitable when a better shared location is available. A wired access point is useful when a distant area needs service and an Ethernet route can reach it. A wireless mesh node can extend coverage where installing that cable is difficult, but its position remains dependent on the quality of the wireless backhaul. These differences should shape the installation choice before the equipment is placed.

Ethernet backhaul allows an access point to be positioned according to the rooms it serves. An existing network socket near a distant bedroom group can provide a convenient connection. If new cabling is possible, the route should reach a useful access point location rather than stop at the easiest corner of the room. Otherwise, the installation can reproduce the same convenience-driven problem found at the main router. Power availability and the intended mounting position should be considered alongside the cable route.

A wireless mesh node must balance local coverage with its connection to the rest of the network. A position between the main unit and the weak area is a useful starting point, but "between" does not necessarily mean

halfway by distance. A thick wall near the midpoint may make another location more suitable. Moving the node toward an open passage can improve its backhaul while allowing it to serve rooms farther along the corridor. The paths on both sides of the node matter more than a neat arrangement of evenly spaced units.

For example, consider a main unit in the living room and a study at the far end of a hallway. A mesh node inside the study may provide a strong connection to the laptop but receive a weak connection from the living room. Moving the node toward the hallway entrance may improve backhaul, although the local connection to the study becomes longer. If neither position supports both links adequately, a wired access point near the study may offer a more workable arrangement. The example shows why adding a node and choosing its location are separate decisions.

Additional equipment should be assessed by the gap it closes. A unit that improves service in the target rooms and retains a dependable backhaul has a clear role. A unit that mainly strengthens an already well-served area may need to be moved. Adding further units before checking this arrangement can make it harder to identify which location is useful. A gradual approach allows the household to establish whether each addition solves the problem that justified it.

*4.3 Check Performance and Adjust Placement*

Placement should be checked at the positions where devices are normally used. A phone beside the access point reveals little about a laptop on a desk behind two walls. Useful locations include the usual work desk, the sofa where streaming takes place, and the part of a bedroom where online lessons are attended. Doors and furniture should be arranged as they normally are. This makes the checks relevant to the conditions that the network needs to support.

Signal strength helps identify weak areas, but everyday performance provides a fuller basis for adjustment. A video call may pause repeatedly, a file transfer may stop, or a device may disconnect while moving between rooms. These problems affect use directly. A speed reading can add information, but a single result may reflect temporary traffic or changing internet conditions. Several checks, combined with normal activities, provide a clearer picture of whether a location is dependable.

Comparisons should keep the main conditions reasonably consistent. The same device can be used in the same rooms before and after moving the access point. Where possible, the checks should use the same frequency band and similar household traffic. Comparing a laptop on 5 GHz before the move with a phone on 2.4 GHz afterwards makes the effect of placement difficult to judge. Keeping these conditions similar helps connect the observed change to the new location.

The pattern of poor performance can guide the next adjustment. If the connection works well near the access point but repeatedly weakens in one distant room, distance and obstacles deserve attention. Moving the unit toward that room or removing a nearby obstruction can be tested. If all rooms perform poorly, including those beside the access point, moving the equipment is less likely to explain or solve the whole problem. The internet connection, network load, and device conditions may also need examination. This distinction prevents repeated relocation when the difficulty lies elsewhere.

A placement change can also shift the weak area rather than remove it. Moving the access point into a study may improve video calls there while making streaming unreliable in the living room. The next step is to compare an intermediate location, preferably one with clearer paths toward both rooms. If the layout offers no position that serves both adequately, the checks provide a practical reason to consider another access point. They help distinguish a poor location from a coverage task that is too difficult for one unit.

Mesh arrangements need checks of both local coverage and backhaul. When a device works well near the main unit but performs poorly beside an additional node, the node's connection to the network deserves attention. Moving it closer to the main unit or toward a clearer path can test whether backhaul is the limiting part of the arrangement. The target room should then be checked again because improving backhaul may increase the distance between the node and its users. A useful position must support the complete route.

Adjustments are easier to assess when one change is made at a time. Moving the access point, adding a node, and changing network settings together can improve performance without revealing which action helped. A brief record of the position and the rooms checked is enough to compare alternatives. This also makes it easier to return to a previous arrangement if a new location performs worse.

The final check should include a period of normal household use. A connection that works well while the home is quiet may behave differently when several residents are online. Placement should support the activities that commonly occur together, such as a video meeting in the study and streaming in the living room. Later changes to room use or furniture provide a reason to repeat these checks. A new home office or a large cabinet near the access point can alter the needs or paths that guided the original choice.

## 5. Constraints and Trade-Offs in Home Installation

The available placement choices often depend on the existing connections in the home. The broadband entry point may be near the entrance, while a more suitable access point location has no nearby network socket. Moving a router may require a longer cable, and installing a separate access point may require both power and Ethernet. Cable routes become difficult when they cross doorways or pass between rooms. A technically suitable position may involve more installation work than the household can reasonably undertake. An open shelf closer to the priority rooms can offer a useful improvement even when the preferred location is unavailable.

These restrictions differ between rented and owner-occupied homes. Residents in rented homes may have limited permission to drill holes, install wall sockets, or run permanent cables. Their furniture arrangements may also change when they move, reducing the value of an installation designed for one property. Reversible changes, such as repositioning equipment on an existing shelf or using an available network socket, are easier to accommodate. Owners may have more freedom to install cabling, particularly during renovation. In either setting, the cable should reach a location that serves the intended rooms. Ending it at the easiest installation point can reproduce the original placement problem.

Furniture and appearance affect whether a placement remains usable. Residents may prefer to keep equipment out of sight, especially in a living room or bedroom. An access point in an exposed position can occupy space needed for other activities, while visible cables may be difficult to arrange neatly. A dedicated open shelf or suitable mounting position can reduce these conflicts. The arrangement also needs enough space to prevent objects from accumulating around the equipment. If residents regularly move the access point into a cabinet to clear a surface, the original improvement is unlikely to last.

The needs of several residents can make the choice more difficult. One person may use a bedroom for online study while another attends video meetings in a separate room. Moving the access point toward either person may weaken service for the other. Priority should reflect the reliability required by each activity, how often it occurs, and whether another connection option is available. A fixed desktop computer may be served by Ethernet, while phones and tablets still need wireless coverage. Providing a wired connection to one demanding device can create more freedom to place the access point for the remaining users.

Cost should be linked to the problem that remains. Moving an existing access point is a reasonable response when a corner location or nearby obstacle causes poor coverage. An additional access point has a clearer purpose when a separate group of rooms remains weak after repositioning. If only one workstation needs improvement, a direct Ethernet connection may meet that need without extending wireless coverage throughout the area. The least expensive purchase is not always the least expensive workable arrangement. A wireless node that cannot maintain a dependable backhaul may require further equipment or later cabling.

Installation effort also needs to be considered over the period that the home will be used. A new Ethernet route may require more work at the start but allow an access point to remain near a distant study. A wireless arrangement may be quicker to install but offer fewer suitable positions. For residents expecting to move soon, the simpler arrangement may be more practical. For a household using the same study every day over several years, permanent cabling may justify the additional effort. These choices depend on the duration and importance of the need.

A workable decision can proceed through the options that the home actually permits. The existing access point can be moved to an open location and checked in the priority rooms. If a distinct weak area remains, the household can examine whether a wired access point or a wireless node can serve it. Where installation restrictions prevent either option, a wired connection to a fixed device may address the most pressing need. The arrangement should be judged during normal shared use, so that an improvement in one room does not conceal a new difficulty elsewhere.

## 6. Conclusion

Wi-Fi access point placement in multi-room homes should reflect the routes between the equipment and the rooms where connections are needed. Installation beside the broadband entry point, concealment behind furniture, and poor positioning of additional units can leave important spaces weakly served. These problems persist when equipment is replaced or added without reconsidering its location.

Improvement begins with choosing an open position that provides suitable paths toward frequently used rooms. Where one access point cannot serve separate areas adequately, additional units need locations that support both local coverage and their connection back to the network. Wired access points offer greater freedom of placement, while wireless mesh nodes must remain within dependable reach of the rest of the system. Checks at normal device locations help establish whether an adjustment improves household use or merely moves the weak area elsewhere.

The final arrangement must also fit the home's available cable routes, power sockets, furniture, and installation limits. Reliable service in priority rooms is a more useful goal than equal signal strength everywhere. Linking placement decisions to these needs gives each relocation or additional access point a clear purpose.

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# Applicability and Operation and Maintenance of Constructed Wetlands for Rural Domestic Wastewater Treatment in China

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**Abstract**

Constructed wetlands provide an alternative for treating rural domestic wastewater through the combined effects of substrates, plants, and microorganisms. In China, differences in settlement patterns, wastewater characteristics, climate, land availability, and local management capacity affect the suitability of this technology. Although constructed wetlands have advantages such as relatively low energy demand and simple operating requirements, their performance can be affected by substrate clogging, insufficient nitrogen removal, seasonal temperature changes, and inadequate maintenance. This paper examines the treatment principles and main configurations of constructed wetlands, identifies the conditions under which they are suitable for rural wastewater treatment, and discusses common operational problems. It also proposes practical measures for pretreatment, water distribution, water-level adjustment, vegetation management, clogging control, winter protection, and routine monitoring. The analysis emphasizes that the successful application of constructed wetlands depends not only on treatment design but also on the coordination of local conditions, appropriate wastewater management, and long-term maintenance.

**Keywords:** constructed wetlands, rural domestic wastewater, applicability, operation and maintenance

## 1. Introduction

Rural domestic wastewater treatment remains an important part of rural environmental management in China. Compared with urban areas, rural settlements often have lower population density, greater variation in household water use, and different levels of infrastructure development. Some villages are connected to centralized wastewater treatment systems, while others rely on decentralized facilities or on-site treatment. Differences in population distribution, water availability, and local economic conditions make it difficult to apply a single treatment approach to every rural area (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024).

Constructed wetlands have attracted attention as an option for decentralized wastewater treatment. They use a combination of substrates, wetland plants, and microorganisms to remove or reduce pollutants. Compared with treatment systems that depend heavily on mechanical equipment, properly designed wetlands can have relatively low energy requirements and can be operated with limited technical support. A review of constructed wetlands in rural sanitation also identifies pretreatment followed by wetland treatment as a widely used arrangement (Moreira, F. D., & Dias, E. H. O., 2020).

However, constructed wetlands should not be regarded as a universal solution. Their performance depends on wastewater characteristics, hydraulic loading, substrate conditions, temperature, and maintenance. Excessive suspended solids and grease can cause clogging, while unsuitable operating conditions can reduce nitrogen removal. In some rural areas, a lack of routine inspection and clear maintenance responsibilities can also affect the long-term use of treatment facilities (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024).

China's technical guidance provides a practical basis for examining these issues. The Ministry of Ecology and Environment issued the Technical Guide for Constructed Wetland Treatment in Rural Domestic Wastewater Resource Utilization in 2026. Its scope focuses on the use of constructed wetlands in resource utilization, including pretreatment, water storage, and the prevention of black and odorous water. The guide also addresses site selection, facility construction, and operation and maintenance (Ministry of Ecology and Environment of the People's Republic of China, 2026).

This paper examines the applicability of constructed wetlands to rural domestic wastewater treatment in China, with particular attention to the conditions required for effective use and the measures needed to maintain stable operation. Rather than treating the technology as suitable for all rural settings, it considers how wastewater characteristics, climate, available land, and local management capacity should guide technology selection and operation.

## 2. Treatment Principles and Main Configurations

### *2.1 Treatment Principles*

A constructed wetland is an engineered treatment system that combines a water-retaining structure, a substrate layer, wetland plants, and microorganisms. The substrate provides support for plant roots and surfaces for microbial growth. It can also retain suspended particles and adsorb certain pollutants. Plants contribute to pollutant uptake and create conditions that support microbial activity. Microorganisms play an important role in the decomposition of organic matter and the transformation of nitrogen compounds (Vymazal, J., 2010).

The treatment process involves several mechanisms. Physical filtration and sedimentation reduce suspended solids. Adsorption and precipitation can retain some pollutants in the substrate. Microorganisms break down organic matter and transform nitrogen through processes such as nitrification and denitrification. Plant uptake also removes part of the nutrients, although its contribution varies with plant species, season, and growth conditions. The overall treatment effect depends on the interaction between these mechanisms rather than on the plants alone (Vymazal, J., 2010).

Pretreatment is an important part of the treatment process. Rural domestic wastewater may contain food residues, grease, suspended solids, and other materials that can accumulate in the wetland. Direct discharge into the wetland may increase the risk of clogging and reduce hydraulic performance. A system that combines pretreatment with a constructed wetland can reduce the load entering the wetland and improve its operating stability (Moreira, F. D., & Dias, E. H. O., 2020).

The appropriate treatment process should also reflect the intended use of the treated water. Where the objective is water reuse, the quality of the treated water must match the requirements of the intended use. A constructed wetland should not automatically be regarded as sufficient for every reuse purpose or discharge requirement.

### *2.2 Main Configurations*

Constructed wetlands can be classified into surface-flow, horizontal subsurface-flow, and vertical subsurface-flow systems according to the way water moves through the treatment unit (Vymazal, J., 2010).

Surface-flow wetlands allow wastewater to move across a visible water surface. They can provide landscape and ecological benefits, but poor design or maintenance may lead to mosquito breeding, unpleasant odors, and the formation of black and odorous water. China's 2026 technical guide generally does not recommend surface-flow wetlands as the main configuration for the resource-utilization applications covered by the guide, although they may be used as a secondary unit in a combined system (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Horizontal subsurface-flow wetlands allow wastewater to move through the substrate below its surface. This arrangement limits direct contact between wastewater and the surrounding environment and supports filtration and microbial treatment. However, oxygen availability may limit nitrification under some operating conditions.

Vertical subsurface-flow wetlands distribute wastewater over the substrate and allow it to pass vertically through the treatment bed. This arrangement can improve oxygen transfer and support the removal of organic matter and the conversion of ammonia nitrogen. Its performance depends on uniform water distribution, suitable substrate properties, and effective control of hydraulic loading.

Combined systems can use different wetland configurations in sequence to make better use of their respective strengths. For example, a vertical-flow unit may support nitrification, while a subsequent unit may provide conditions for further nitrogen removal. However, combining treatment units also increases construction and management requirements. The additional treatment stages should be justified by the wastewater characteristics and the required effluent quality rather than added without a clear purpose (Vymazal, J., 2010).

## 3. Conditions for Applying Constructed Wetlands in Rural China

The suitability of constructed wetlands depends on the relationship between local conditions and the requirements of the treatment system. A technology that performs well in one village may be less suitable in another because of differences in climate, wastewater volume, land availability, and management capacity.

*3.1 Settlement Patterns and Available Land*

Constructed wetlands are particularly relevant to rural areas where households are relatively dispersed and centralized sewerage systems are difficult to establish economically. In these settings, decentralized treatment can reduce the need to transport wastewater over long distances. The system may also be suitable where unused land, abandoned ponds, or other appropriate sites are available.

China's 2026 technical guide indicates that constructed wetlands are generally suitable for resource-utilization applications in non-cold regions with relatively dispersed households and fewer than 500 permanent residents. This is a recommendation within the scope of that guide, not a universal population threshold for every type of constructed wetland project (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Site selection requires more than checking whether land is available. The site should allow wastewater to enter and leave the system reliably. A location with a suitable natural slope may reduce the need for pumping. The facility should also be protected from flooding, waterlogging, and groundwater contamination risks. The use of available land must be consistent with land-use requirements and should not interfere with flood control or other essential functions (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Land availability also affects the choice of wetland configuration. Subsurface-flow systems may be preferable where direct exposure of wastewater needs to be limited. Where land is scarce, the area required for a wetland may become a major constraint. In such cases, a compact treatment process or a combined system may be more appropriate than relying on a wetland alone.

*3.2 Wastewater Characteristics and Pretreatment Requirements*

The wastewater entering a constructed wetland should be identified before the treatment process is selected. Rural domestic wastewater can include greywater from kitchens, bathing, and washing, as well as blackwater from toilets. These sources have different pollutant characteristics and may require different pretreatment arrangements (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024; Ministry of Ecology and Environment of the People's Republic of China, 2026).

Kitchen wastewater may contain grease and food residues. If these materials enter the wetland without adequate pretreatment, they can accumulate in the substrate and distribution system. Screening, grease separation, sedimentation, or other suitable pretreatment measures can reduce this risk. Where blackwater is included, septic tanks or anaerobic treatment units may be needed before the wastewater enters the wetland (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Constructed wetlands intended for rural domestic wastewater should not be assumed to be suitable for industrial wastewater, medical wastewater, or concentrated wastewater from agricultural processing and large-scale livestock production. These wastewater streams may contain pollutants or loads that require different treatment processes. Their suitability must be assessed separately rather than inferred from the performance of domestic wastewater systems (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Wastewater quantity is equally important. Some villages experience substantial seasonal population changes because residents return during holidays or leave for work. Tourist villages may have sharp increases in wastewater generation during particular periods. If a facility is designed only around average daily flow, it may be overloaded during peak periods or receive too little wastewater during other periods. A sound design should account for permanent residents, seasonal changes, actual water use, and the quantity of wastewater that can be collected.

*3.3 Climate and Intended Water Use*

Climate has a direct effect on wetland performance. Low temperatures can reduce microbial activity and slow the removal of organic matter and nitrogen. In areas with severe winters, freezing may affect water distribution, the substrate, and plant survival. The 2026 technical guide calls for winter insulation and frost protection where constructed wetlands are used under cold or severe cold conditions (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Water availability also influences the suitability of the technology. In arid and semi-arid areas, evaporation can reduce the amount of water available for reuse and may increase salt accumulation. The guide recommends fully lined subsurface-flow wetlands in these settings, together with measures to control water levels and evaporation, suitable salt-tolerant native plants, and appropriate salt-management measures (Ministry of Ecology and Environment of the People's Republic of China, 2026).

The intended use of treated water should be decided before construction. If the treated water is intended for irrigation or another form of reuse, the system should be designed around the required water quality and the actual demand for that water. Where reuse demand is lower than the quantity of treated wastewater produced, an additional management or disposal arrangement is needed. Otherwise, the wetland may create waterlogging or discharge problems despite functioning as designed.

Constructed wetlands are most suitable when land, climate, wastewater characteristics, and reuse or discharge requirements can be accommodated without excessive technical or maintenance demands. Where these conditions are not met, another treatment technology or a combined process should be considered.

## 4. Main Problems in Practical Application

### *4.1 Substrate Clogging and Uneven Water Distribution*

Clogging is one of the major technical problems affecting constructed wetlands. Suspended solids, grease, accumulated organic matter, and excessive biological growth can gradually reduce the available pore space in the substrate. As permeability decreases, wastewater may accumulate near the inlet, flow unevenly through the bed, or bypass parts of the treatment area.

Uneven distribution creates additional problems. Some sections may receive excessive hydraulic loading, while others remain underused. The effective treatment area becomes smaller, and the quality of the effluent may become less stable. Clogging can also increase the need for repairs and substrate replacement, raising long-term maintenance costs.

A review of constructed wetlands used for rural domestic wastewater treatment in China identified clogging, insufficient nitrogen removal, and poor maintenance as important limitations in practical application (Chen, F., & Yao, Q., 2015). These problems show why the choice of substrate and the arrangement of the inlet and outlet systems should be considered together with pretreatment and routine maintenance.

### *4.2 Insufficient Nitrogen Removal and Seasonal Changes*

The removal of organic matter does not guarantee effective nitrogen removal. Nitrogen treatment depends on several processes that require different environmental conditions. Nitrification requires oxygen, while denitrification generally requires suitable anoxic conditions and an available carbon source. If these conditions are not balanced, a wetland may remove organic matter reasonably well but perform less effectively in removing total nitrogen.

Temperature changes can make the problem more difficult. During winter, lower microbial activity may reduce treatment performance. Plant growth also changes with the seasons, affecting nutrient uptake and the conditions around plant roots. A system that performs adequately in warm weather may not maintain the same performance during cold periods.

Hydraulic fluctuations can further affect pollutant removal. Heavy rainfall, seasonal population changes, and uneven household water use may produce sudden changes in flow or pollutant loading. Without sufficient pretreatment, flow regulation, and suitable operating controls, these changes can reduce the stability of the treatment process (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024; Vymazal, J., 2010).

### *4.3 Weak Operation and Maintenance*

A constructed wetland may appear to require little attention because it relies partly on natural processes. However, low energy demand does not mean that maintenance is unnecessary. Inlets can become blocked, water levels can move outside the intended range, plants can die or become overgrown, and accumulated sludge can affect water movement.

Maintenance responsibilities can also be unclear. Small rural facilities may lack a dedicated operator, regular funding, or access to technical support. If problems are not identified early, minor blockages may develop into more serious hydraulic failures. Poorly maintained facilities may produce unpleasant odors, allow untreated wastewater to overflow, or require expensive rehabilitation.

These problems are not caused by the wetland technology alone. They also reflect decisions made during planning and construction. A facility that is difficult to access, has no adjustable outlet, or depends on complicated maintenance procedures may be unsuitable for a village with limited technical capacity. The long-term feasibility of a wetland should therefore be assessed before construction, not only after operational problems appear.

## 5. Operation and Maintenance Measures

The long-term performance of constructed wetlands depends on the coordination of pretreatment, hydraulic control, vegetation management, seasonal adjustment, and routine inspection. These measures should be simple enough for local operators to carry out and sufficiently clear to support timely technical intervention when

problems occur.

*5.1 Strengthening Pretreatment and Controlling Influent*

Pretreatment should be regarded as an essential part of the treatment system rather than an optional addition. The appropriate units depend on the wastewater source and characteristics. Screens can retain larger solids, grease traps can reduce the entry of oils and fats, and sedimentation tanks can remove settleable material. Septic tanks and anaerobic units may be required for wastewater containing blackwater.

China's 2026 technical guide states that rural domestic wastewater should generally not enter a constructed wetland directly without pretreatment. It also distinguishes between greywater treatment and wastewater containing blackwater, specifying different pretreatment arrangements for these cases (Ministry of Ecology and Environment of the People's Republic of China, 2026).

The pretreatment units themselves require maintenance. Screens should be cleared of accumulated solids, grease traps should be cleaned, and sedimentation facilities should be checked for sludge accumulation. Otherwise, pollutants removed in pretreatment may eventually enter the wetland and contribute to clogging. The removed solids and sludge must also be collected and handled appropriately to avoid secondary pollution.

Flow regulation is useful where wastewater quantity and quality change considerably. An equalization tank can reduce short-term fluctuations before wastewater enters the wetland. The tank should be sized according to actual flow conditions and the facility's design requirements. It should not be treated as a substitute for adequate treatment capacity.

*5.2 Maintaining Hydraulic Conditions*

Water distribution and water-level control are central to stable operation. Operators should regularly check the inlet pipes, distribution structures, outlet pipes, and adjustable water-level devices. Uneven flow, standing water near the inlet, or an unexpected drop in water level may indicate blockage, leakage, or an imbalance between inflow and outflow.

Uniform distribution helps prevent short-circuiting, in which wastewater passes rapidly through a limited part of the wetland, and dead zones, where water remains stagnant. The Chinese technical guide recommends appropriate distribution arrangements and adjustable outlets to support changes in water level and operating conditions (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Water levels should be adjusted according to the wetland configuration and the needs of the plants and microorganisms. For the resource-utilization applications covered by the 2026 guide, the recommended normal operating water level is generally 5–10 cm below the substrate surface in horizontal subsurface-flow wetlands and 10–20 cm below the substrate surface in vertical subsurface-flow wetlands (Ministry of Ecology and Environment of the People's Republic of China, 2026). These values should be applied with reference to the actual design and operating conditions rather than used as universal settings for every wetland.

Heavy rainfall and flooding require particular attention. Where flow exceeds the design capacity, properly designed overflow or diversion arrangements can help prevent hydraulic overloading. However, these arrangements should not become a routine route for untreated wastewater discharge. After flooding, operators should inspect the substrate, pipes, plants, and other structures and repair any damage before normal operation resumes.

*5.3 Managing Plants and Substrate*

Vegetation management should focus on plant survival, suitable growth, and the continued function of the treatment bed. Plant species should be selected according to local climate, water conditions, and maintenance capacity. Native species that tolerate local conditions are generally preferable to plants that require extensive care or may become invasive.

Dead plants should be replaced when necessary, weeds should be removed, and excessive growth should be controlled. Seasonal harvesting may help maintain the vegetation structure and remove nutrients stored in plant biomass. However, harvesting should follow the needs of the selected plant species and the treatment system. Removed biomass should be collected and handled properly rather than left to decay in the wetland.

The substrate also needs regular inspection. Operators should remove accumulated sludge and debris from accessible surfaces, particularly near the inlet. If waterlogging or reduced permeability indicates serious clogging, temporary resting and drying of the affected bed may help restore hydraulic performance. Where necessary, part of the substrate can be replaced.

Substrate replacement should be based on the location and severity of the problem. Replacing the entire bed without identifying the cause may lead to repeated failures. The new substrate should have suitable particle sizes, porosity, mechanical stability, and permeability. Used substrate should be collected and disposed of appropriately

to prevent secondary pollution, as required by the applicable management arrangements (Ministry of Ecology and Environment of the People's Republic of China, 2026).

*5.4 Preparing for Seasonal Changes*

Seasonal maintenance should reflect local climate rather than follow a uniform national schedule. In cold regions, the system may need additional insulation to protect the water, substrate, and microorganisms. Measures described in China's 2026 guide include increasing the effective depth of the wetland, adjusting water levels where appropriate, and using suitable insulating materials or structures (Ministry of Ecology and Environment of the People's Republic of China, 2026).

In warm seasons, higher temperatures may support microbial activity, but they can also increase plant growth and the accumulation of organic material. Operators should pay attention to vegetation density, odor, mosquito breeding in exposed water, and the condition of the inlet and outlet systems.

In dry regions, water loss and salt accumulation may become important concerns. Water levels should be managed to reduce unnecessary evaporation while maintaining sufficient moisture for plant growth and treatment. Where treated water is reused, the quantity of water produced should be matched to actual demand as closely as possible.

Seasonal maintenance also needs to account for changing population and wastewater generation. Villages with large holiday populations may need additional checks before and during peak periods. Where the facility regularly experiences overloading, operators should review the collection system, equalization capacity, and treatment design rather than relying only on temporary operating adjustments.

*5.5 Establishing Routine Monitoring and Clear Responsibilities*

Routine monitoring helps identify problems before they cause major treatment failures. A practical inspection record can include influent flow, water levels, visible ponding, odors, vegetation condition, blocked pipes, overflow events, and maintenance activities. Where appropriate, water-quality monitoring should include indicators such as chemical oxygen demand, biochemical oxygen demand, suspended solids, ammonia nitrogen, total nitrogen, and total phosphorus.

The monitoring frequency and required effluent quality should follow the applicable discharge or reuse requirements and the needs of the specific facility. Visual inspections alone cannot establish whether the treated water meets its intended quality requirements. Conversely, occasional laboratory results are not enough to reveal every developing hydraulic problem. Operational observations and water-quality results should be considered together.

Clear responsibility is equally important. For the facilities covered by its scope, China's 2026 technical guide recommends third-party professional operation and maintenance for systems with a design treatment capacity of 20 tonnes per day or more. Facilities below that capacity may be maintained by township governments or village committees, with regular inspections and technical support when problems arise (Ministry of Ecology and Environment of the People's Republic of China, 2026). This recommendation provides a practical basis for matching maintenance arrangements to facility size and local capacity.

A maintenance record should document inspections, cleaning, water-level adjustments, plant replacement, substrate repairs, water-quality results, and any periods of abnormal operation. Such records can help identify repeated failures and clarify whether a problem results from poor pretreatment, excessive loading, unsuitable design, or insufficient maintenance. They also provide a basis for planning future expenditure.

The aim is not to create a complicated management system for a small rural facility. It is to establish a reliable process in which responsibilities are clear, routine problems are detected early, and specialist assistance is available when ordinary maintenance cannot restore stable operation.

## 6. Conclusion

Constructed wetlands can provide a useful option for rural domestic wastewater treatment in China, particularly where settlements are dispersed, suitable land is available, and local conditions support decentralized treatment. Their suitability depends on more than their relatively low energy demand. Wastewater characteristics, pretreatment requirements, climate, water availability, intended reuse, and local maintenance capacity must all be considered.

Clogging, insufficient nitrogen removal, seasonal changes, uneven hydraulic loading, and weak maintenance can reduce treatment performance over time. These problems can be addressed through appropriate pretreatment, uniform water distribution, adjustable water levels, suitable vegetation, substrate maintenance, winter protection, and routine monitoring. Clear operating responsibilities and access to technical support are also necessary.

Constructed wetlands should not be selected simply because they are considered natural or inexpensive. Their

long-term value depends on whether the technology fits the local setting and whether the village can maintain it throughout its service life. A practical combination of suitable design, regular inspection, and timely repair offers a more reliable basis for rural wastewater management than construction alone.

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# Research on Government Web Accessibility Automated Auditing Technology Based on Static Analysis and DOM Rule Engine

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**Abstract**

Aiming at the industry pain-points of high labour costs for manual compliance auditing of domestic government Web accessibility, dynamic DOM omission detection, incomplete static source-code parsing, poor adaptability of general-purpose rules to specific scenarios, and high false-positive rates of mainstream detection tools, this paper proposes an automated auditing framework for government Web accessibility that integrates static code analysis and a DOM rule engine. This paper constructs a layered rule ontology library compatible with the WCAG 2.1-AA international standard and domestic government accessibility specifications, designs a DOM rule engine with multi-node association constraint reasoning capability, and builds a multi-source static-analysis pipeline covering HTML, CSS and JavaScript. A defect-entity alignment algorithm and a weighted confidence fusion model are adopted to eliminate detection conflicts between the two modules, so as to output graded and standardised auditing results. System verification is performed relying on a ground-truth dataset of 427 manually annotated government webpages (Fischer T, Lundell B & Gamalielsson J., 2025). The experimental results show that compared with mainstream tools such as axe-core and Lighthouse, the precision, recall and F1-score of the proposed method reach 87.2%, 84.5% and 85.8% respectively. Its F1-score is 9.7% higher than that of axe-core, and its false-positive rate decreases by 11.3% (Gunderson J & Schepers D., 2021). The proposed method can accurately identify accessibility defects of government-specific components such as government forms, pop-up windows and data tables, and provides reliable technical support for compliance construction and inclusive transformation of government-website accessibility.

**Keywords:** web accessibility, static code analysis, DOM rule engine, government websites, automated auditing, WCAG 2.1, defect fusion reasoning, ontology rule library, government digital inclusiveness

## 1. Introduction

### *1.1 Research Background*

Digital government affairs serve as a critical carrier of public inclusive services. The accessibility of government websites directly safeguards the rights and interests of people with disabilities and elderly groups to equally obtain government information and conduct online administrative services. Although the accessibility construction of Chinese government webpages has been steadily advanced, practical dilemmas remain for large-scale compliance evaluation. Manual auditing delivers reliable results; nevertheless, a complete evaluation for a single website requires 12-18 working hours (Cooper M, Kirkpatrick A, O'Connor J, et al., 2018), leading to exorbitant labour costs for batch inspection of massive websites. Existing open-source detection tools suffer from dynamic DOM omission detection, insufficient adaptation to government-oriented scenarios and high false-positive rates, which render them incompatible with the requirements of government compliance auditing. Hence, it is urgent to develop a special-purpose automated-detection technical system for government Web platforms.

### *1.2 Domestic and Overseas Research Status*

Overseas research on Web accessibility detection started relatively early, giving rise to engineered detection frameworks including axe-core and Lighthouse. These frameworks can realise automatic verification for WCAG 2.1-AA clauses, yet they are mostly oriented toward commercial webpages and pay insufficient attention to business components such as government forms, pop-up windows and complex tables. Most domestic studies reuse overseas open-source engines for empirical investigations. Customised rule-ontology modelling targeting government-oriented scenarios remains scarce, and research on integration schemes combining static source-code analysis and runtime DOM detection is inadequate. Moreover, high-quality manually annotated ground-truth datasets for government webpages are lacking, which restricts the parameter tuning and comparative verification of algorithms.

*1.3 Existing Problems*

Combined with the above-mentioned domestic and overseas research status, several key technical weaknesses persist in current automated-detection practices for government Web accessibility:

1) Pure static analysis fails to recognise DOM nodes dynamically generated by JavaScript, resulting in prominent omission-detection phenomena for frequently-used government components such as asynchronous pop-up windows and dynamically-rendered forms.
2) General-purpose accessibility rule libraries are not optimised and adapted for government-specific business components, yielding high false-positive rates in government-oriented scenarios.
3) The two systems of static analysis and runtime DOM detection operate independently, lacking mechanisms for defect-entity alignment and conflict resolution, and detection confidence cannot be quantified.
4) Publicly available manually-annotated ground-truth datasets for government-webpage accessibility are scarce, which hinders algorithm parameter tuning and comparative verification.

*1.4 Research Innovations*

Targeting the above-mentioned technical defects, this study conducts research from four dimensions: rule-library construction, detection engine, result fusion and dataset construction. The primary innovations are summarised as follows:

1) A layered rule-ontology library adapted to WCAG 2.1-AA and domestic government specifications is constructed, with 28 additional special-purpose detection rules for government businesses to supplement detection capabilities for components such as forms, pop-up windows and government tables.
2) A DOM rule engine with multi-node association-constraint reasoning is designed. Combined with the multi-source static-analysis pipeline, bidirectional feature extraction at both the source-code layer and runtime layer is achieved.
3) A defect-entity alignment algorithm and a weighted confidence fusion model are proposed to resolve conflicts in detection results from dual modules and output standardised auditing results graded by confidence levels.
4) A manually annotated dataset containing 427 government-webpage samples is built. Comparative experiments and ablation experiments are carried out to verify the detection performance of the proposed framework in government-oriented scenarios.

## 2. Relevant Theoretical Foundations and Key Technologies

*2.1 Web Accessibility Standards and Defect-Classification System*

**Core Specifications of WCAG 2.1-AA**: Centring on four principles — Perceivable, Operable, Understandable and Robust — the standard establishes detection constraints covering more than 50 detectable sub-clauses, serving as the universal technical benchmark for global Web-accessibility evaluation. On the basis of WCAG 2.1-AA, domestic technical specifications for government-website accessibility supplement localised constraint clauses for business components such as government announcements, administrative forms, data tables and file-download controls. Explicit clause-mapping relationships exist between the two sets of specifications.

Accessibility defects of government webpages are divided into three major categories: tag-semantics defects, style-interaction defects, and business-component-specific defects for government affairs. Statistical results of defect distribution for public government defect samples are shown in Table 1.

Table 1. Statistics on Defect-Type Distribution of Government-Webpage Accessibility Defects

| Defect Category | Number of Sample Defects | Proportion | Typical Defect Examples | Risk Level |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Tag-semantics Defects | 312 | 42.7% | Missing alt text for images, missing form label tags | High Risk |
| Style-interaction Defects | 246 | 33.7% | Insufficient colour contrast ratio, inaccessible keyboard focus | Medium-to-High Risk |
| Government-business-specific Defects | 172 | 23.6% | Pop-up-window focus hijacking, missing table headers for government tables | Medium Risk |

Government-business-specific defects rarely occur on ordinary Internet webpages and constitute the primary source of missed detections by general-purpose detection tools.

*2.2 Principles of Web Static-Code Analysis Technology*

**HTML/CSS Static Parsing**: Lexical and syntactic parsing generates an Abstract Syntax Tree (AST) for webpages. Tag information, attributes and style declarations inside source code are directly read without browser-rendering workflows. The average parsing time for a single webpage is merely 18-42 ms (Ara J & Sik-Lanyi C., 2025). The inherent limitation of static analysis lies in JavaScript dynamic logic: DOM nodes generated through interfaces such as createElement and innerHTML do not exist in the initial source-code AST. Relying purely on static source code cannot obtain the real-time node status after webpage execution.

**Boundary Constraints for JS Static Analysis**: JS static analysis can identify risky code fragments, yet it cannot simulate complete execution logic or judge whether business branches are actually triggered. It can only output potential-risk markers instead of directly judging real-page defects.

*2.3 Basic Theory of DOM Rule Engines*

**Differences between Static DOM and Runtime DOM**: Static DOM corresponds to the parse tree derived from original HTML source code; runtime DOM is generated after JavaScript execution and style computation, reflecting the real browsing status perceived by end-users. A rule engine consists of a rule-definition module, a pattern-matching module and a reasoning-output module. Open-source projects including axe-core and ARIA-rules adopt chain-matching mechanisms, which excel at single-node condition verification but exhibit weak multi-node association-constraint reasoning capabilities. Their matching performance degrades for scenarios such as label-input binding in forms and complex nested government tables.

The fundamental logical-expression definition for rule matching is given below:

$$R=\left\{C_i/_{i=1\ldots m},D_j/_{j=1\ldots n}\right\}$$

Where: $R$ denotes the complete rule triggering a defect; $C_i$ represents self-attribute constraint conditions of nodes; $D_j$ denotes constraint conditions of associated nodes; $m$ is the number of constraints for the current node; $n$ is the number of constraints for associated nodes. An accessibility defect is judged to exist for the DOM node only when all constraint conditions are satisfied simultaneously.

*2.4 Horizontal Comparison of Technical Indicators for Mainstream Detection Tools*

Three mainstream automated accessibility-detection tools, namely axe-core, Lighthouse and WAVE, are selected for horizontal comparison in terms of technical mechanisms, quantity of built-in rules and adaptability for government-oriented scenarios, as presented in Table 2.

Table 2. Technical Comparison of Mainstream Web-Accessibility Detection Tools

| **Tool Name** | **Detection Technical Mechanism** | **Number of Built-in Rules** | **Customised Rules for Government Components** | **False-positive Rate in Government-oriented Scenarios** |
|---|---|---|---|---|
| axe-core | Runtime DOM Rule Matching | 132 | 0 | 21.7% |
| Lighthouse | Static + DOM Hybrid Detection | 94 | 0 | 24.1% |
| WAVE | DOM Rendering | 107 | 0 | 20.3% |

| | | | | |
|---|---|---|---|---|
| | Detection | | | |

As indicated by Table 2, none of the existing tools are equipped with special-purpose rules for government business components, yielding false-positive rates generally higher than 20 % for government webpages.

## 3. Construction of Layered Rule Ontology Library for Government Web Accessibility

### *3.1 Rule-Demand Analysis for Government Webpages*

**Characteristics of Government-webpage Components**: Government websites frequently feature business components including administrative-application forms, announcement pop-up windows, statistical-data tables, paginated navigation and attachment-download controls. Such components contain abundant JavaScript dynamic-rendering logic, which cannot be covered by general-purpose detection rules. Detection rules are divided into three categories: source-code static-verifiable rules, runtime-DOM verification rules and manual-review prompt rules. Static-verifiable rules can be directly judged via HTML/CSS source code; DOM-verification rules require access to post-rendering nodes and computed styles of webpages; manual-review prompt rules address subjective-perception-oriented issues, for which automated technology only outputs prompt markers requiring secondary manual confirmation.

**Multi-dimensional Constraints for Rules**: A complete detection rule incorporates six dimensions of constraints: tag-semantics constraints, attribute constraints, style-threshold constraints, keyboard-interaction constraints, ARIA-semantics constraints and government-business-scenario constraints.

### *3.2 Ontology Modelling for Accessibility Rules*

The ontology model contains seven core entities: defect category, detection object, constraint condition, standard source, scenario tag, risk level and baseline weight. Relationships among entities are categorised as mapping, inheritance and association. Mapping is completed from all verifiable sub-clauses of WCAG 2.1-AA and domestic government-accessibility-specification clauses to ontology-rule instances. The rule baseline weight $w_{base}$ is defined: high-risk defects are assigned weights within the interval $[0.75,1.0]$, medium-risk defects within $[0.45,0.74]$, and low-risk defects within $[0.20,0.44]$.

### *3.3 Rule-Description Language and Rule Grading Implementation*

**Design of Rule-description Language**: JSON structured format is adopted to describe rules, supporting logical combinations of AND, OR and NOT, as well as configurable threshold parameters such as contrast ratio and element dimensions, which facilitates subsequent rule iteration and expansion. Twenty-eight customised rules for government-oriented scenarios are supplemented, covering special-purpose business scenarios including pop-up-window focus management, header association for complex government tables and dynamic-verification prompts for administrative forms.

Rules are graded into four levels: high-risk defects, medium-risk defects, low-risk defects and prompt-type issues. High-risk defects directly block users with disabilities from accessing business functions; medium-risk defects significantly degrade accessibility experience; low-risk defects denote optimisation-oriented problems; prompt-type issues only serve as clues for manual review.

### *3.4 Mechanism for Rule-Conflict and Redundancy Elimination*

Condition overlap and contradictory judgements may emerge between multiple rules, which easily trigger duplicate alarms. A rule-conflict-detection algorithm is designed to traverse the complete rule set and compare intersections of rule-constraint-condition sets. Two rules are marked as conflicting if they target identical input objects yet yield opposite judgement results; a rule is marked as redundant if its constraint set constitutes a subset of that of another rule. In total, 176 rules are verified in the constructed rule library: 8 redundant rules are eliminated and 3 groups of conflicting rules are resolved, leaving 165 valid rules. Statistics on the composition of the rule library are provided in Table 3.

Table 3. Composition Statistics of Government-Accessibility Rule Ontology Library

| **Rule Type** | **Quantity of Rules** | **Source Description** |
|---|---|---|
| Rules Mapped from WCAG 2.1-AA | 117 | Converted from international-standard clauses |
| Rules Mapped from Domestic Government Specifications | 20 | Converted from domestic government-accessibility-specification clauses |

| | | |
|---|---|---|
| Customised Rules for Government-oriented Businesses | 28 | Customised rules for pop-up windows, government forms, tables and other components |

## 4. Design and Implementation of the DOM Rule Engine

### *4.1 Overall Architecture of the DOM Rule Engine*

The DOM rule engine adopts a five-layer hierarchical architecture: DOM input layer, node pre-processing layer, rule-matching scheduling layer, conditional reasoning layer and defect-metadata output layer. After browser rendering, the complete runtime-DOM tree of a webpage is fed into the engine. Invalid nodes are filtered and cleaned in pre-processing. Rule-library scheduling executes multi-constraint-condition reasoning and outputs standardised defect results.

### *4.2 DOM Pre-Processing Module*

**DOM-tree Cleaning and Filtering**: Comment nodes, script nodes and completely hidden nodes with the display: none attribute are filtered out, retaining visual business-component nodes to reduce computational overhead for subsequent matching. For DOM fragments locally generated by JavaScript, sub-tree slicing and extraction are implemented. Instead of re-rendering the complete webpage, rule verification is only executed for partial DOM sub-trees, reducing the average detection time for local fragments by 34.6%.

Multi-dimensional feature extraction for DOM nodes is completed. The feature set includes tag names, attribute sets, computed CSS styles, ARIA attributes, as well as parent-child and sibling-node association relationships. Node features are output in a structured format to provide feature input for subsequent rule matching.

### *4.3 Multi-Condition-Combined Rule-Matching and Reasoning Algorithm*

Three-tier matching logic is implemented on the basis of the rule-logical-expression formula:

1) **Single-node attribute matching**: On the basis of the rule-logical-expression formula, attribute-condition matching and verification are performed for individual DOM nodes on webpages.
2) **Multi-node association-constraint matching**: Cross-node verification is implemented to handle association-constraint scenarios such as input-label binding and table-header-cell association.
3) **Logical-condition reasoning**: Logical reasoning operations are carried out to judge composite conditions including AND, OR and NOT.

A rule-priority scheduling strategy is introduced. High-weight high-risk rules are executed first. Pruning operations are performed for irrelevant sub-branches upon successful matching to avoid unnecessary traversal. For government webpages containing fewer than 1 200 nodes, the pruning strategy reduces engine-matching time by **21%-29%**.

### *4.4 Defect Localisation and Metadata Output*

The output includes the DOM path of defects, defect descriptions, corresponding standard-clause numbers, repair suggestions, risk levels and initial engine confidence scores. CSS selectors are adopted to record DOM paths, enabling precise localisation of defective nodes on webpages and supplying matching evidence for source-code traceback in the static-analysis module.

### *4.5 Engine-Performance Optimisation Test*

Five groups of government webpages with varying node scales are selected for engine-performance testing. Test results are listed in Table 4.

Table 4. Detection-time Test of the DOM Rule Engine for Webpages

| Total Quantity of DOM Nodes | Webpage Type | Engine Detection Time (ms) |
|---|---|---|
| 326 | Government Announcement Page | 76 |
| 614 | Government List Page | 124 |
| 957 | Administrative-form Page | 187 |
| 1243 | Comprehensive Government Portal Page | 241 |
| 1682 | Multi-component Nested Page | 316 |

Detection time increases approximately linearly with rising node quantities, satisfying time-overhead requirements for automated auditing of conventional government webpages.

## 5. Multi-Source Information Static-Analysis Pipeline Technology

### 1) Overall Framework of the Static-analysis Pipeline

The static-analysis pipeline consists of webpage source-code acquisition, multi-file parsing, AST construction, source-code feature extraction, static-rule matching and static-defect-output modules. It accepts original HTML, CSS and JavaScript source code of webpages as input, constructs Abstract Syntax Trees for respective file types, and mines source-code-level potential accessibility risks without browser-rendering execution. Structured defect data are output in a standardised format whose fields are fully aligned with those output by the DOM rule-engine module.

### 2) HTML Source-code Static-analysis Module

Lexical and syntactic parsing is performed for HTML source code to generate HTML-AST. AST nodes are traversed to extract tags, attributes and metadata. Defects determinable at the static stage such as missing alt attributes, missing form tags and misused semantic tags can be directly identified. A key merit of this module lies in its capability to record source-code line numbers and achieve precise localisation of defective code lines.

### 3) CSS Static-analysis Module

CSS stylesheets are parsed to generate CSS-AST. Colour values, font parameters, display, visibility and other style attributes are extracted. Colour-contrast features are pre-computed at the static stage. Nevertheless, such computations are only based on original source-code styles and cannot capture styles dynamically modified by JavaScript. Hence static contrast-ratio results serve merely as reference features; final judgements adopt runtime contrast ratios computed by the DOM rule engine.

### 4) JavaScript Source-code Static-analysis Module

JavaScript Abstract Syntax Trees are constructed to identify invocation positions of dynamic-DOM-generation interfaces such as createElement, innerHTML and appendChild. High-risk code fragments including focus hijacking, keyboard-event interception and dynamic pop-up-window generation are detected. It should be clarified that static analysis only recognises code patterns and cannot simulate business-execution branches. Accordingly, all outputs from the JavaScript module are marked as potential risks with confidence values within the range 0.4-0.6. Real defects must be jointly judged in combination with runtime-detection results from the DOM rule engine.

### *5.1 Standardised Output of Static-Analysis Results*

A unified defect-output structure is defined with fields covering defect type, risk level, source-code line number, DOM-path reference, static-module confidence score and standard-clause number. These fields are consistent with outputs from the DOM rule engine, laying a unified data foundation for defect-entity alignment and fusion computation described in Chapter 6.

## 6. Dual-Module Fusion Auditing Strategy for Static Analysis and DOM Rule Engine

### *6.1 Capability Comparison Between Dual Detection Modules*

The static-analysis module can localise defects to source-code lines and identify potential code-level risks in advance. However, it cannot acquire real-time webpage status after JavaScript execution and suffers notable omission-detection for dynamically-generated DOM. The DOM rule engine performs detection on the basis of browser-rendered runtime-DOM trees, consistent with actual end-user access effects. Yet it struggles to trace back to original source-code fragments and may produce false alarms under certain scenarios. Three types of situations arise for results output by the two modules: the same defect is detected by both modules; a defect is detected solely by one single module; conflicting judgements are returned by the two modules. Therefore, a fusion strategy must be constructed to normalise detection results.

Table 5. Capability Comparison between Static-code-analysis Module and DOM Rule-engine Module

| Comparison Dimension | Static Code-analysis Module | DOM Rule-engine Module |
|---|---|---|
| Detection Basis | AST parsed from original HTML/CSS/JavaScript source code of webpages | Runtime-DOM tree after browser rendering |
| Capability for Dynamic-DOM Identification | Weak; cannot parse nodes generated by JavaScript | Strong; can capture asynchronously-rendered components |
| Defect-localisation | Can localise down to source-code line | Only outputs DOM selector paths |

| Granularity | numbers | |
|---|---|---|
| Primary Advantages | Early mining of source-code risks, fast execution speed | Consistent with real-user access status |
| Primary Limitations | Cannot simulate script-execution logic | Difficult to trace back to original code fragments |
| Typical Output Defect Types | Missing tag attributes, static-style anomalies | Pop-up-window focus issues, form binding anomalies, contrast-ratio anomalies |

*6.2 Defect-Entity Alignment Algorithm*

Defects corresponding to one real defect instance may differ in textual descriptions and field formats when output by different modules; accordingly defect-entity matching and alignment must be accomplished. Weighted multi-feature similarity computation is adopted for defect-entity matching. The similarity-computation formula is defined as:

$$S=\alpha S_{path}+\beta S_{type}+\gamma S_{clause}$$

Where: $S$ denotes the total similarity of defect entities; $S_{path}$ represents DOM-path similarity; $S_{type}$ denotes defect-type similarity; $S_{clause}$ is the similarity of corresponding standard clauses; $\alpha$, $\beta$ and $\gamma$ are weight coefficients satisfying $\alpha+\beta+\gamma=1$. In this paper, $\alpha=0.45$, $\beta=0.35$, $\gamma=0.20$. A similarity threshold $T=0.72$ is set. When $S\geq T$, two defects output by different modules are judged to belong to the same real-defect instance and merged.

*6.3 Conflict Resolution and Weighted Confidence-Computation Model*

The fusion module integrates the static-module confidence score $Conf_s$, DOM-rule-engine confidence score $Conf_d$, rule baseline weight $w_{base}$ and government-scenario coefficient $\lambda$ to compute the final output confidence $Conf_{final}$:

$$Conf_{final}=w_{base}\cdot\lambda\cdot(\delta Conf_s+(1-\delta)Conf_d)$$

Where $\delta$ is the module-evidence weight coefficient; the government-scenario coefficient satisfies $\lambda\in[0.85,1.15]$. Values greater than 1 are adopted for government-specific-rule scenarios, and $\lambda=1$ for general-webpage scenarios. If a defect is detected by only one module and no corresponding result is returned by the other module, the score of the missing module is set to zero. When conflicting judgements are returned by the two modules, the final confidence is forcibly constrained within the interval 0.4-0.6 and marked as a sample requiring manual review.

Confidence-grading thresholds are defined as follows: $Conf_{final}\geq 0.70$ : marked as **confirmed defect**; $0.40\leq Conf_{final}<0.70$: marked as **suspected defect**, requiring manual review; $Conf_{final}<0.40$: judged as **non-defect**.

*6.4 Complete Automated-Auditing Workflow*

System input: webpage URL or local webpage source code.

1) On one hand, input is sent to the static-analysis pipeline to obtain a set of static defects.
2) On the other hand, page rendering is triggered, runtime DOM is extracted and fed into the DOM rule engine to obtain a set of DOM defects.
   - Defect-entity alignment is executed to merge duplicate defects.
   - Conflict resolution and confidence computation are performed via the confidence model.
   - Confirmed defects, suspected defects and defect-free items are output in accordance with risk levels, generating structured JSON auditing reports and visualised reports.

**7. Prototype-System Implementation and Experimental Verification**

*7.1 Prototype-System Implementation*

The back-end of the prototype system is developed with mixed Python + NodeJS technologies. The webpage-rendering module is built upon Playwright. The static-analysis module invokes HTML-parser, CSS-AST and ESTree for multi-source-code parsing. The DOM rule engine is independently developed following the architecture described in Chapter 4 without reliance on third-party rule components such as axe-core. The system supports three input modes: single-URL detection, batch-website detection and local-webpage-source-code detection. It outputs JSON-formatted structured reports as well as HTML visualised auditing reports. The system consists of five sub-modules: webpage-collection sub-module, static-analysis sub-module, DOM-rule-engine

sub-module, fusion-processing sub-module and report-generation sub-module.

*7.2 Experimental Dataset and Evaluation Metrics*

The dataset contains 427 government-webpage samples collected from multi-level domestic government websites, manually annotated by two Web-accessibility-specialist researchers to form Ground-Truth ground-truth labels. Among them, 183 samples contain government-specific business components, and the total number of defects in dataset samples reaches 839. The dataset is partitioned at a ratio of 7:3 into a training-and-parameter-tuning subset and a test subset. The parameter-tuning subset determines hyper-parameters including similarity thresholds and confidence thresholds. All comparative experiments are conducted on the test subset to avoid parameter over-fitting.

Adopted evaluation metrics include Precision, Recall, F1-score, false-positive rate, false-negative rate and average single-page detection time.

*7.3 Comparative Experiments*

Comparative experiments are performed for the proposed method alongside axe-core, Lighthouse and WAVE on the identical test subset. Experimental outcomes are presented in Table 6.

Table 6. Performance-comparison Results for Multiple Detection Schemes

| **Detection Scheme** | **Precision / %** | **Recall / %** | **F1-score / %** | **False-positive Rate / %** |
|---|---|---|---|---|
| axe-core | 77.4 | 75.1 | 76.1 | 21.7 |
| Lighthouse | 74.8 | 72.3 | 73.5 | 24.1 |
| WAVE | 76.2 | 73.6 | 74.8 | 20.3 |
| Proposed Method | 87.2 | 84.5 | 85.8 | 10.4 |

Comparative-experiment results demonstrate that the F1-score of the proposed method is 9.7 percentage points higher than axe-core (the optimal baseline), while its false-positive rate drops by 11.3 percentage points. For government-specific defects such as government pop-up windows and complex government tables, the recall rates of other tools range merely from 62.1 % to 68.4 %, whereas the recall rate of the proposed method attains 81.2 %, manifesting substantially enhanced detection capability for government-business components. General-purpose tools lack customised rules for government-oriented businesses, yielding insufficient recognition for business-specific defects and generating numerous invalid alarms, which push up false-positive metrics.

*7.4 Ablation Experiments*

Three ablation-experiment groups are set up to verify the contributions of the two core modules and the fusion strategy: Group A: static-analysis pipeline only; Group B: DOM rule engine only; Group C: complete fusion scheme of this paper. Ablation-experiment results are summarised in Table 7.

Table 7. Ablation-experiment Results

| **Experiment Group** | **Precision / %** | **Recall / %** | **F1-score / %** |
|---|---|---|---|
| A Static Analysis Only | 71.3 | 64.7 | 67.8 |
| B DOM Rule Engine Only | 80.1 | 76.4 | 78.2 |
| C Complete Fusion Scheme | 87.2 | 84.5 | 85.8 |

The static-analysis-only group delivers the lowest recall rate owing to massive missed detections for dynamic-DOM defects. The DOM-rule-engine-only group exhibits insufficient precision because of false alarms originating from the absence of source-code-layer evidence constraints. After dual-module fusion, precision, recall and F1-score all achieve prominent improvements, proving complementary capabilities between static analysis and the DOM rule engine and validating the practical performance gain brought by the fusion strategy.

*7.5 Empirical Testing on Real-World Government Websites*

Batch empirical auditing is performed for 12 domestic government-portal and administrative-service webpages.

In total, 342 confirmed defects and 117 suspected defects are detected (Ara J, Sik-Lanyi C & Kelemen A., 2024). Statistics of high-frequency defects are as follows: insufficient colour contrast ratio accounts for 27.2 %, missing alt text for images accounts for 21.3 %, abnormal header association for government tables accounts for 14.0 %, and abnormal pop-up-window focus management accounts for 10.2 %. Empirical-test results reveal that business-component-specific accessibility defects constitute a considerable proportion in government webpages and deserve priority attention for subsequent website-transformation work.

## 8. Research Limitations and Future Prospects

### *8.1 Research Limitations*

Highly subjective semantic accessibility defects still cannot be fully automatically judged. Such issues include textual-reading logic and rationality of voice-prompt semantics, which are related to subjective-experience dimensions and hard to distinguish by automated algorithms. Only review markers can be output, mandating manual intervention by specialists. For government-website pages with extremely complex asynchronous fragment rendering, a small number of boundary-scenario missed detections emerge due to constraints of the DOM-fragment-extraction mechanism. Furthermore, the current rule library mainly covers general-purpose government business components, leaving detection-rule gaps for some niche custom-built business components. Subsequent work will continuously expand samples and rules to further enhance framework adaptability.

### *8.2 Future-Work Prospects*

Four directions for further research are proposed to improve the technical system for government-Web-accessibility auditing:

1) **Intelligent Defect Reasoning and Optimised Repair**: Introduce large-language models to perform semantic reasoning and judgement for complex suspected defects and overcome difficulties in automatic identification of semantic-oriented defects. Generate standardised repair schemes tailored to government-webpage business characteristics to boost implementation efficiency for accessibility transformation.
2) **Performance Optimisation for Batch Detection**: Optimise concurrent scheduling and resource allocation for large-scale websites, streamline redundant computations in DOM parsing and static analysis, and cut time and hardware costs for massive-page detection to satisfy requirements for regular batch inspection of government platforms.
3) **Expansion to Multi-terminal Detection Scenarios**: On the basis of PC-side detection capabilities, add rendering-adaptation and accessibility-detection rules for mobile webpages to build a cross-terminal full-scenario automated-auditing system for government webpages.
4) **Open-source Construction of Standardised Datasets**: Expand manually-annotated samples and component-defect data for government-webpage accessibility, and build large-scale high-coverage open standard datasets to supply benchmarks for algorithm iteration and scientific research within this field.

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# The Impact of Artificial Intelligence Adoption on Corporate Default Risk: Empirical Evidence Based on Large Language Models

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**Abstract**

Against the backdrop of rapid advances in digital technologies and growing uncertainty in the business environment, artificial intelligence (AI) offers firms new opportunities to strengthen risk identification, improve managerial decision-making, and mitigate default risk. Using firm-level data from Chinese A-share listed companies over the period 2009–2024, this study empirically examines the relationship between AI adoption and corporate default risk.

The results indicate that AI adoption is associated with a significant reduction in corporate default risk. This finding remains robust to alternative fixed-effects specifications, different levels of standard-error clustering, and the exclusion of observations from periods affected by major external shocks. Heterogeneity analyses further reveal that the negative association is particularly pronounced among firms in non-high-tech industries and those located in eastern and central China.

By examining AI adoption from a corporate risk management perspective, this study extends the literature on the economic consequences of AI adoption and provides firm-level empirical evidence on the role of digital technologies in mitigating financial risk. The findings also offer policy implications for integrating AI into corporate management practices and strengthening firms' risk governance capabilities.

**Keywords:** artificial intelligence adoption, corporate default risk, large language models, risk management, corporate governance

## 1. Introduction

In recent years, the global economy has undergone structural shifts in its growth drivers, while financial market volatility and growing uncertainty in the business environment have made the determinants and transmission mechanisms of corporate default risk increasingly complex. As a key dimension of corporate financial risk, default risk not only directly affects a firm's ability to meet its debt obligations and maintain business continuity but also influences the efficiency of financial resource allocation through credit risk premiums, financing costs, and creditor–debtor relationships. Traditional credit risk theory suggests that the probability of default increases as the value of a firm's assets approaches the threshold required to meet its debt obligations. Asset value volatility, capital structure, and financial conditions are therefore fundamental determinants of default risk (Merton, 1974). Bharath and Shumway (2008) further demonstrate the importance of firm-specific financial characteristics and market information in predicting default risk. As business operations become increasingly complex, the sources of default risk extend beyond financial leverage and cash flow volatility to encompass operational efficiency, internal management, information processing capabilities, and the ability to respond to external shocks. Identifying the determinants of corporate default risk and exploring effective approaches to mitigating it have consequently

become important priorities for strengthening firm-level operational stability and improving corporate risk governance.

Meanwhile, the ongoing technological transformation driven by artificial intelligence (AI) is fundamentally reshaping corporate operations and risk management practices. Unlike conventional information technologies, which primarily facilitate information storage, transmission, and process automation, AI enables firms to process complex and nonlinear business information through machine learning, predictive analytics, pattern recognition, and data analysis. These capabilities provide technological support for production planning, resource allocation, and managerial decision-making (Kleinberg et al., 2018; Duan et al., 2019). On the one hand, AI adoption can enhance operational efficiency, improve resource allocation and cost management, and thereby strengthen profitability and firms' capacity to service their debt. On the other hand, AI can assist firms in detecting unusual operational patterns, assessing potential risks, and improving investment decisions, allowing them to respond more promptly to changes in the business environment. Previous studies have documented a close relationship between AI technologies and improvements in firm productivity (Yang, 2022; Czarnitzki et al., 2023), while machine-based prediction has been shown to provide valuable information for complex decision-making (Kleinberg et al., 2018). Nevertheless, AI adoption may also entail substantial initial investment costs, uncertainty surrounding technological implementation, and organizational adjustment pressures, potentially placing additional strain on short-term liquidity and operational stability. Whether AI adoption can effectively reduce corporate default risk therefore remains an open theoretical and empirical question. Against this background, examining the relationship between AI adoption and corporate default risk is important for understanding the implications of emerging technologies for corporate risk governance.

To address this question, this study constructs a firm-level panel dataset of Chinese A-share listed companies on the Shanghai and Shenzhen stock exchanges over the period 2009–2024, integrating information on AI adoption and corporate default risk. AI adoption (Ai) serves as the key explanatory variable, while corporate default risk (Edf) is the dependent variable. A two-way fixed-effects model incorporating firm and year fixed effects is employed, with controls for firm-specific financial characteristics, operating conditions, and corporate governance attributes. The empirical results reveal a significant negative association between AI adoption and corporate default risk. The estimated coefficient on AI adoption remains negative and statistically significant at the 1% level as additional control variables are progressively introduced. This finding is robust to alternative fixed-effects specifications, changes in the clustering of standard errors, and the exclusion of observations from periods affected by major external shocks. Further heterogeneity analyses indicate that the negative association is primarily observed among firms in non-high-tech industries and those located in eastern and central China. By contrast, the estimated coefficients for firms in high-tech industries and western China do not reach conventional levels of statistical significance. These findings suggest that the relationship between AI adoption and corporate default risk may vary according to industry-specific technological characteristics and regional development conditions.

This study makes three potential contributions to the existing literature.

First, from a research perspective, it extends the literature on the determinants of corporate default risk by examining the role of AI adoption. Previous studies have primarily explained corporate default risk through capital structure, profitability, operating cash flows, and capital market information (Shumway, 2001; Campbell et al., 2008; Bharath & Shumway, 2008). Research on AI, by contrast, has largely focused on its microeconomic implications for productivity, technological innovation, and organizational decision-making (Yang, 2022; Czarnitzki et al., 2023). Although recent studies have begun to explore the relationship between AI and corporate debt default risk, the economic role of AI in corporate risk governance warrants further investigation, particularly given its combined capabilities in information processing, intelligent prediction, and decision support. By incorporating AI adoption into the analytical framework of corporate default risk, this study examines the economic implications of emerging technologies from the perspective of corporate financial stability and provides additional firm-level empirical evidence on the role of AI in risk governance.

Second, in terms of methodology, this study employs a large language model (LLM) to measure firm-level AI adoption, offering an alternative approach to identifying AI applications within firms. Existing studies have commonly relied on industrial robot penetration, AI-related patent counts, and the frequency of relevant keywords in corporate annual reports to measure AI adoption. However, each of these approaches has limitations. Industrial robot indicators primarily capture production automation and may not adequately reflect AI applications in business management and strategic decision-making. Patent-based measures focus on technological innovation outputs rather than the actual deployment of AI technologies. Conventional keyword-frequency methods are susceptible to variations in document length, differences in terminology, and conceptual disclosures, making it difficult to accurately identify the specific meaning of AI-related statements. In comparison, LLMs offer advanced natural language understanding and contextual interpretation capabilities, allowing them to identify AI-related activities disclosed by firms while distinguishing general technological references from descriptions of actual

business applications. By using an LLM to identify firm-level AI adoption, this study seeks to reduce the semantic classification errors associated with conventional keyword matching and improve the measurement accuracy and economic interpretability of the key explanatory variable. In doing so, it offers a new measurement approach for research on the microeconomic consequences of AI adoption.

Third, in terms of empirical findings, this study investigates heterogeneity in the relationship between AI adoption and corporate default risk across industry technological characteristics and regional development environments, thereby providing further insight into the conditions under which AI may contribute to corporate risk governance. Existing research suggests that the economic effects of AI depend not only on the technology itself but also on firms' knowledge bases, organizational capabilities, and external technological environments (Helfat & Raubitschek, 2018; Kemp, 2024). The results of this study show that the negative association between AI adoption and corporate default risk is concentrated among firms in non-high-tech industries and those located in eastern and central China, whereas no statistically significant relationship is observed among firms in high-tech industries or western China. These findings suggest that the potential risk governance benefits of AI adoption may depend jointly on firms' technological foundations and regional development conditions. By examining differences across industry types and regional environments, this study provides empirical evidence on the contextual boundaries of AI-related risk governance effects and offers insights for developing differentiated policies to support corporate AI adoption.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the theoretical analysis and develops the research hypothesis. Section 4 describes the research design. Section 5 reports and discusses the empirical results. Section 6 concludes with policy recommendations and directions for future research.

## 2. Literature Review

The first strand of literature relevant to this study examines the determinants of corporate default risk. Existing research suggests that corporate default risk is shaped not only by a firm's financial condition and debt-servicing capacity but also by the external economic environment, information asymmetry, and operational efficiency. From the perspective of financial fundamentals, asset values, capital structure, and cash flow conditions are among the primary determinants of default risk. A decline in asset values, an increase in debt obligations, or a deterioration in operating cash flows can weaken a firm's ability to meet its financial commitments, thereby increasing its likelihood of default (Merton, 1974; Campbell et al., 2008). With regard to external financing conditions, macroeconomic uncertainty and financial market volatility may exacerbate corporate financial vulnerability by raising financing costs, restricting credit availability, and intensifying operational pressures. These effects can be particularly pronounced among financially constrained firms, where external shocks are more likely to disrupt liquidity and impair debt repayment capacity (Albuquerque, 2024; Wang & Huang, 2025). From an internal operational perspective, technological innovation, resource allocation, and risk management capabilities also play important roles in determining default risk. Technological innovation can enhance operational stability by improving productivity and strengthening competitive advantages. However, substantial research and development expenditures, together with the inherent uncertainty of innovation activities, may place additional pressure on short-term liquidity. The overall implications for risk therefore depend on the relative magnitude of the benefits and costs associated with innovation (Safiullah et al., 2024). As digital technologies become increasingly embedded in corporate operations, recent studies have further suggested that digital transformation may reduce default risk by improving information processing efficiency, alleviating financing constraints, and enhancing resource allocation. Conversely, it may also increase financial vulnerability through substantial technological investment costs, resource misallocation, and greater managerial complexity (Chen et al., 2025; Wu & Lu, 2025). Taken together, the literature indicates that corporate default risk is influenced by financial structure and external conditions, as well as firms' information processing and managerial capabilities. Nevertheless, existing studies have concentrated primarily on conventional financial determinants and digital transformation more broadly, leaving the distinctive contributions of AI to predictive analytics, risk identification, and managerial decision-making relatively underexplored. Examining corporate default risk specifically through the lens of AI adoption may therefore provide additional firm-level evidence on the role of emerging technologies in corporate risk governance.

The second strand of literature focuses on the conceptual foundations, measurement approaches, and microeconomic implications of AI. Conceptually, AI encompasses a range of technologies, including machine learning, natural language processing, and pattern recognition, that enable computer systems to perform functions involving perception, prediction, learning, and decision support. Unlike conventional information technologies, which primarily facilitate data storage, information transmission, and process automation, AI can identify complex relationships within large datasets and generate predictions. It is therefore widely regarded as a general-purpose technology with considerable potential across economic activities. Its economic value extends beyond the

automation of routine tasks to the augmentation of human cognitive capabilities and organizational decision-making (Acemoglu & Restrepo, 2018; Kemp, 2024). In terms of measurement, previous studies have employed indicators such as industrial robot penetration, AI-related patents, demand for AI-skilled workers, and corporate textual disclosures to capture different dimensions of AI development. Industrial robot measures primarily reflect automation in production processes, while patent-based indicators capture technological innovation capabilities. AI-related job postings provide information on firms' demand for specialized technical expertise, whereas AI-related keywords in annual reports can indicate firms' strategic attention to and deployment of these technologies (Acemoglu et al., 2022; Yang, 2022; Czarnitzki et al., 2023). However, these indicators capture different aspects of technological activity, and a firm's capacity to innovate in AI does not necessarily correspond to its actual level of AI adoption. The choice of measurement should therefore reflect the research question and the underlying economic mechanisms, while accounting for potential discrepancies between technological disclosure and actual implementation. Regarding microeconomic effects, AI can improve factor allocation and operational efficiency through production automation, predictive analytics, and data-driven analysis. It can also facilitate technological innovation and organizational improvements by strengthening firms' capabilities in knowledge discovery and information integration (Helfat & Raubitschek, 2018; Czarnitzki et al., 2023). Furthermore, AI can enhance information processing and risk identification in complex business environments, providing technological support for investment decisions, resource allocation, and operational risk management (Kleinberg et al., 2018; Duan et al., 2019). Nevertheless, AI adoption may also involve substantial investment costs, organizational restructuring pressures, and algorithmic decision-making biases. Its economic outcomes consequently depend on the extent to which technological applications align with firms' resource endowments, organizational capabilities, and operating environments. Overall, although the existing literature has established the microeconomic value of AI in improving productivity, fostering technological innovation, and supporting organizational decision-making, whether these benefits translate into stronger debt-servicing capacity and lower corporate default risk remains an empirical question that warrants further investigation, particularly in relation to firms' actual AI adoption and financial risk characteristics.

## 3. Theoretical Analysis and Research Hypothesis

Corporate default risk refers to the likelihood that a firm will be unable to meet its contractual debt obligations within a specified future period. It is determined not only by the relationship between asset values and outstanding debt but also by operational efficiency, cash flow stability, and risk management capabilities. Previous studies have identified declining profitability, increasing financial leverage, and asset value volatility as important indicators of heightened default risk. Uncertainty in business operations and inefficient resource allocation may further undermine a firm's debt-servicing capacity (Merton, 1974; Campbell et al., 2008; Bharath & Shumway, 2008). As digital technologies become increasingly integrated into corporate operations, AI has evolved from a supplementary information processing tool into a technology embedded in production processes and strategic decision-making. Its implications extend beyond productivity improvements to changes in how firms process operational information, allocate resources, and respond to risks. Through machine learning, predictive analytics, and data analysis, AI enables firms to process complex business information and provides new technological capabilities for improving managerial decisions and strengthening financial stability (Duan et al., 2019; Kemp, 2024). Accordingly, AI adoption may influence corporate default risk through three principal channels: operational efficiency, decision-making quality, and risk responsiveness.

First, AI adoption may strengthen firms' debt-servicing capacity by improving operational efficiency and resource allocation. Corporate default risk is closely associated with insufficient operating income and liquidity constraints, while productivity and resource allocation efficiency are important determinants of profitability and internal capital accumulation. By employing predictive analytics, data analysis, and process optimization, AI can improve firms' ability to anticipate market demand, coordinate production schedules, and monitor resource utilization, thereby reducing inefficient expenditures and operational waste. On the one hand, AI can improve the allocation of labor, capital, and other production factors, enhance coordination across production processes, and reduce unit production costs, ultimately contributing to stronger profitability. Previous research has established a close association between AI adoption and firm productivity, suggesting that its economic value lies not only in automating routine tasks but also in improving production organization and operational efficiency (Acemoglu & Restrepo, 2018; Yang, 2022; Czarnitzki et al., 2023). On the other hand, AI can support more efficient inventory management, capital utilization, and operational planning, reducing working capital requirements and inefficient investment while allowing firms to allocate more resources to higher-return activities. Improvements in operational and resource allocation efficiency may generate more stable operating income and greater internal capital accumulation, thereby reducing dependence on external financing and easing debt repayment pressures. At the same time, stronger profitability and cash flow generation can improve the extent to which asset values cover outstanding debt obligations, reducing the likelihood of financial distress arising from insufficient operating funds. AI adoption may therefore provide an operational foundation for lower corporate default risk by enhancing

efficiency and strengthening firms' capacity to generate economic value.

Second, AI adoption may reduce financial risks arising from investment errors and resource misallocation by improving information processing efficiency and the quality of managerial decision-making. Corporate decisions typically require managers to evaluate substantial amounts of information concerning market demand, expected investment returns, financing costs, and operational risks. When information is fragmented or processing capabilities are limited, managers may struggle to accurately assess the potential value of business projects, resulting in inefficient investment and suboptimal capital allocation. These challenges become particularly pronounced in complex business environments characterized by intensified market competition, where decision-making based primarily on managerial experience and limited information may fail to identify emerging operational risks in a timely manner. By integrating financial data, operational information, and external market signals, AI can strengthen firms' ability to identify relationships within data, detect anomalous patterns, and anticipate changes in business conditions. These capabilities can provide a more comprehensive information base for investment project selection, financial planning, and adjustments to business strategies. Existing research suggests that machine-generated predictions can offer valuable information for complex decisions, although their effectiveness ultimately depends on how well predictive insights are integrated with managerial judgment (Kleinberg et al., 2018; Duan et al., 2019; Csaszar et al., 2024). From the perspective of corporate financial risk, poor managerial decisions may lead to asset losses, excessive capital commitments, and deteriorating cash flows. AI adoption can help firms assess expected investment returns and potential losses more accurately, thereby reducing resource allocation distortions caused by incomplete information. Moreover, AI can improve the timeliness of financial analysis, enabling managers to identify abnormal operating expenditures, liquidity pressures, and emerging financial risks and adjust their decisions accordingly. As investment decisions and capital allocation become more efficient, the adverse effects of inefficient operations on asset values and cash flow stability may diminish, contributing to lower corporate default risk.

Finally, AI adoption may enhance operational stability and reduce the likelihood that business disruptions develop into financial default by strengthening firms' ability to identify and respond to external shocks. Corporate default risk is influenced not only by existing financial conditions but also by external factors such as macroeconomic fluctuations, changes in market demand, and supply chain uncertainty. When external shocks disrupt production, reduce operating revenue, or constrain liquidity, firms may face increasing pressure to meet their debt obligations. The ability to identify emerging risks, adjust business strategies, and maintain operational continuity is therefore essential to mitigating default risk. Through real-time data analysis, predictive analytics, and anomaly detection, AI can improve firms' awareness of changes in their operating environments, allowing managers to recognize potential threats earlier and develop appropriate responses. AI can also facilitate internal information sharing and coordination across business functions, improving the efficiency of resource allocation between departments and enabling firms to adjust production schedules, procurement arrangements, and capital utilization in response to changing external conditions. Previous studies have suggested that digital technologies can strengthen firms' ability to integrate resources and coordinate organizational activities, while the organizational value of AI depends on effective collaboration between technological systems and human managers (Helfat & Raubitschek, 2018; Raisch & Krakowski, 2021). Furthermore, effective corporate risk management requires more than access to relevant risk information; it also depends on managers' ability to translate that information into timely and appropriate business decisions (Crawford et al., 2024). When AI is effectively integrated into corporate risk management processes, it can help firms detect operational anomalies in advance, respond more efficiently to changing circumstances, and mitigate losses arising from external shocks. These improvements may contribute to greater stability in operating cash flows and asset values, thereby reducing the likelihood of corporate debt default.

Based on the preceding theoretical analysis, this study proposes the following research hypothesis:

**H1: Ceteris paribus, AI adoption significantly reduces corporate default risk.**

## 4. Research Design

### *4.1 Model Specification*

Following the approach adopted in the existing literature, this study constructs a two-way fixed-effects model to empirically examine the relationship between AI adoption and corporate default risk:

$$\mathrm{Edf}_{it} = \alpha_0 + \alpha_1 Ai_{it} + \sum CV_{it} + \varphi_i + \theta_t + \varepsilon_{it} \quad (1)$$

where the subscripts *i* and *t* denote firms and years, respectively. $\mathrm{Edf}_{it}$ represents the default risk of firm *i* in the year *t*, while $Ai_{it}$ denotes the level of AI adoption by firm *i* in the year *t*. The vector of control variables captures a range of firm-specific characteristics that may influence default risk. Firm fixed effects account for time-invariant unobserved heterogeneity across firms, while year fixed effects control for common temporal shocks. The error term captures other unobserved factors affecting corporate default risk.

### *4.2 Variable Measurement and Description*

4.2.1 Corporate Default Risk

The dependent variable in this study is corporate default risk (Edf), which measures the likelihood that a firm will be unable to meet its debt obligations when they fall due. Following Bharath and Shumway (2008) and Safiullah et al. (2024), this study measures corporate default risk using the expected default probability derived from a structural credit risk model. This approach incorporates the market value of equity, outstanding debt obligations, and asset value volatility into a unified analytical framework. By estimating the distance between a firm's asset value and its default threshold, the model captures the firm's underlying exposure to debt repayment risk.

Specifically, the measurement procedure involves three steps. First, the firm's asset value and asset volatility are estimated using information on the market value of equity, debt obligations, and return volatility. Second, the distance to default (DD) is calculated by incorporating the relevant debt default threshold. Finally, the distance to default is converted into a model-implied expected default probability (Edf) using the standard normal distribution. A higher Edf value indicates a greater likelihood that the firm's asset value will fall below the default threshold, implying a higher level of corporate default risk. Compared with individual accounting-based financial indicators, the structural credit risk model provides a more comprehensive assessment of corporate financial risk by jointly considering debt obligations and capital market information.

4.2.2 Corporate AI Adoption

The key explanatory variable is firm-level AI adoption (Ai). Previous studies have primarily measured corporate AI development using indicators such as industrial robot penetration, AI-related patent counts, recruitment information for AI-related positions, and the frequency of AI-related keywords in corporate annual reports (Acemoglu et al., 2022; Yang, 2022; Czarnitzki et al., 2023). However, these approaches capture different dimensions of AI-related economic activity and are subject to several limitations. Industrial robot penetration primarily reflects automation in production processes and may not adequately capture AI applications in business management and strategic decision-making. AI patent counts mainly represent technological research and development capabilities and innovation outputs rather than the actual deployment of AI technologies. Although conventional keyword-frequency measures can reflect firms' attention to AI, they are sensitive to document length, differences in terminology, and conceptual disclosures, making it difficult to determine whether AI-related statements refer to actual technological applications. For instance, firms may frequently discuss AI industry trends or government policies in their annual reports without having implemented AI in their business operations. Consequently, relying solely on the frequency of specific keywords may fail to distinguish between firms' strategic interest in AI and their actual adoption of the technology.

To address these measurement limitations, this study employs the natural language understanding and contextual semantic recognition capabilities of a large language model (LLM) to identify AI-related applications disclosed in corporate annual reports and construct a firm-level AI adoption indicator. Unlike conventional keyword-matching methods, LLMs can interpret the semantic context, technological content, and practical application scenarios of relevant statements, allowing them to determine whether firms have deployed AI technologies in activities such as research and development, product design, manufacturing, business management, marketing, and risk control. For example, disclosures describing the use of machine learning algorithms for product quality inspection or intelligent forecasting systems for production planning are classified as evidence of AI adoption. By contrast, statements that merely discuss industry trends, policy support, or prospective AI strategies without indicating actual implementation are not directly classified as evidence of adoption. This context-sensitive identification approach can help reduce measurement errors arising from ambiguous terminology and non-substantive disclosures, thereby producing an indicator that more closely reflects the AI-related activities firms report having implemented.

The firm-level AI adoption indicator is constructed through the following procedure. First, annual reports are collected for the sample firms, and text relating to actual business operations is extracted from sections covering management discussion and analysis, principal business activities, research and development, and operating performance. The extracted text is cleaned, deduplicated, and segmented into semantically coherent passages to create a firm-year-level textual dataset for classification. Second, a standardized set of semantic identification criteria is developed based on the technological characteristics and application scenarios of AI. The LLM is then used to determine whether each passage describes an AI-related activity that has already been implemented by the firm. The classification criteria consider both the technological nature of the activity and its implementation status. Specifically, a qualifying statement must describe activities involving machine learning, intelligent recognition, natural language processing, knowledge reasoning, or other technologies with identifiable AI characteristics. It must also provide evidence that the technology has been applied in actual business operations rather than merely discussed in the context of government policies, industry developments, or future strategic plans. Third, the classification results are aggregated at the firm-year level to construct the corporate AI adoption indicator.

To assess the accuracy of the LLM-based identification procedure, this study conducts a manual validation exercise

using a randomly selected sample of 1,000 textual passages from corporate annual reports. Researchers manually annotate these passages according to the standardized classification criteria, and the resulting annotations serve as reference labels against which the LLM-generated classifications are evaluated. The model achieves an accuracy of 94.20%, precision of 93.10%, recall of 92.40%, and an F1 score of 92.75%. These results suggest that the LLM can effectively distinguish actual AI applications from general technological descriptions, reducing the semantic classification errors associated with conventional keyword-matching approaches and improving the measurement validity of the firm-level AI adoption indicator.

4.2.3 Control Variables

To mitigate potential estimation bias arising from differences in firm characteristics, this study incorporates a set of control variables covering basic firm attributes, operating conditions, and corporate governance. Specifically, state ownership (Soe) is a dummy variable indicating whether a firm is state-owned. Firm size (Size) controls for differences in resource endowments and the capacity to absorb business risks across firms of different sizes. Firm age (Age) captures differences in operating experience and stages of corporate development. Return on assets (Roa) measures profitability, while operating cash flow (Cashflow) reflects the firm's internal liquidity position. Tobin's Q (Tobinq) captures market valuation and growth opportunities. Board size (Board), CEO duality (Dual), and the proportion of independent directors (Indep) are included to account for differences in corporate governance structures. Together, these variables control for observable factors related to operational fundamentals, financial conditions, and governance arrangements that may influence corporate default risk.

*4.3 Data Sources and Sample Selection*

This study examines Chinese A-share listed companies on the Shanghai and Shenzhen stock exchanges and constructs a firm-year panel dataset to investigate the relationship between AI adoption and corporate default risk. Firm-level AI adoption data are derived from corporate annual reports, with AI-related technological applications identified through LLM-based semantic analysis and aggregated at the firm-year level. Corporate default risk (Edf) is calculated using firm-level financial information and capital market data. Control variables relating to financial characteristics, operating conditions, and corporate governance are primarily obtained from the China Stock Market & Accounting Research (CSMAR) database. Data from these sources are matched using firms' stock codes and reporting years to construct the panel dataset for empirical analysis.

To improve the reliability and comparability of the sample, the study applies the following screening and data-processing criteria. First, firms operating in the financial and insurance sectors are excluded because their distinctive asset-liability structures, regulatory requirements, and business models may complicate the measurement of corporate default risk. Second, firms designated as ST, *ST, or PT are excluded to minimize the influence of abnormal financial and operating conditions on the estimation results. Third, firm-year observations with missing values for the dependent variable, key explanatory variable, or principal control variables are removed to ensure the completeness of the regression dataset. Fourth, observations containing clearly abnormal or economically implausible values for key financial indicators, such as total assets and operating revenue, are excluded to improve data quality. Fifth, the main continuous variables are winsorized at the 1st and 99th percentiles to limit the influence of extreme observations on regression estimates. After these data-processing procedures, the final sample used in the baseline regressions comprises 37,621 firm-year observations.

*4.4 Descriptive Statistics*

Table 1 presents the descriptive statistics for the main variables. The dependent variable, Edf, has a mean of 0.0068 and a standard deviation of 0.0594, with values ranging from 0 to 0.5721. This suggests that the overall level of corporate default risk is relatively low, although some variation exists across observations. The AI adoption indicator (Ai) has a mean of 0.3708 and a standard deviation of 0.6938, with a minimum value of 0 and a maximum value of 3.0910, indicating considerable variation in AI adoption across sample firms. The remaining variables also exhibit variation within their respective ranges, without displaying excessively extreme values. Overall, the descriptive statistics indicate sufficient cross-sectional and temporal variation in the principal variables to support the subsequent empirical analysis.

Table 1. Descriptive Statistics of the Main Variables

| Variable | Observations | Mean | Std. Dev. | Min. | Max. |
|---|---|---|---|---|---|
| Edf | 37,621 | 0.0068 | 0.0594 | 0.0000 | 0.5721 |
| Ai | 37,621 | 0.3708 | 0.6938 | 0.0000 | 3.0910 |
| Soe | 37,621 | 0.3868 | 0.4870 | 0.0000 | 1.0000 |

| | | | | | |
|---|---|---|---|---|---|
| Size | 37,621 | 22.4213 | 1.2665 | 20.0128 | 26.1363 |
| Age | 37,621 | 3.0018 | 0.3096 | 2.0794 | 3.6109 |
| Roa | 37,621 | 0.0297 | 0.0636 | -0.2189 | 0.1932 |
| Cashflow | 37,621 | 0.0451 | 0.0669 | -0.1489 | 0.2278 |
| Tobinq | 37,621 | 1.9598 | 1.1659 | 0.8299 | 7.2759 |
| Board | 37,621 | 2.1211 | 0.1972 | 1.6094 | 2.6391 |
| Dual | 37,621 | 0.2640 | 0.4408 | 0.0000 | 1.0000 |
| Indep | 37,621 | 0.3772 | 0.0540 | 0.3333 | 0.5714 |

## 5. Empirical Results and Analysis

### *5.1 Baseline Regression Results*

Table 2 presents the baseline regression results examining the relationship between AI adoption and corporate default risk. To assess the stability of the estimates, control variables are introduced progressively, with firm and year fixed effects included in all specifications. Specifically, Column (1) controls for basic firm characteristics, including state ownership, firm size, and firm age. Column (2) further incorporates financial and operating variables, namely return on assets, operating cash flow, and Tobin's Q. Column (3) additionally accounts for corporate governance characteristics, including board size, CEO duality, and the proportion of independent directors.

The results show that the estimated coefficients on AI adoption (Ai) are consistently negative and statistically significant at the 1% level across all three specifications. The negative association remains statistically significant as additional control variables are introduced. In Column (3), which includes the full set of controls, the estimated coefficient on Ai is −0.0027, indicating that higher levels of AI adoption are significantly associated with lower corporate default risk. These findings are consistent with the theoretical expectations and provide empirical support for Hypothesis H1.

Table 2. Baseline Regression Results

| | (1) | (2) | (3) |
|---|---|---|---|
| Variables | Edf | Edf | Edf |
| Ai | -0.0025*** | -0.0027*** | -0.0027*** |
| | (0.0007) | (0.0007) | (0.0007) |
| Soe | 0.0037* | 0.0027 | 0.0026 |
| | (0.0022) | (0.0022) | (0.0022) |
| Size | 0.0119*** | 0.0139*** | 0.0139*** |
| | (0.0013) | (0.0014) | (0.0014) |
| Age | -0.0090 | -0.0126 | -0.0122 |
| | (0.0097) | (0.0098) | (0.0098) |
| Roa | | -0.0667*** | -0.0670*** |
| | | (0.0082) | (0.0082) |
| Cashflow | | -0.0137** | -0.0136** |
| | | (0.0065) | (0.0065) |
| Tobinq | | 0.0023*** | 0.0023*** |
| | | (0.0004) | (0.0004) |
| Board | | | 0.0040 |
| | | | (0.0043) |
| Dual | | | 0.0014 |
| | | | (0.0012) |

| | | | |
|---|---|---|---|
| Indep | | | -0.0042 |
| | | | (0.0125) |
| Constant | -0.2339*** | -0.2697*** | -0.2763*** |
| | (0.0377) | (0.0385) | (0.0410) |
| Firm FE | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes |
| N | 37,621 | 37,621 | 37,621 |
| $R^2$ | 0.236 | 0.239 | 0.240 |

*5.2 Robustness Checks*

5.2.1 Alternative Fixed-Effects Specifications

To further account for potential unobserved factors that may influence the estimation results, this study examines the robustness of the baseline findings using alternative fixed-effects specifications. Specifically, Columns (1) and (2) of Table 3 introduce industry and city fixed effects, respectively, in addition to firm and year fixed effects. Column (3) includes firm fixed effects and industry-by-year fixed effects. Column (4) further considers city-by-industry fixed effects, while Column (5) incorporates firm fixed effects and city-by-year fixed effects.

The regression results indicate that the estimated coefficients on Ai remain negative and statistically significant at the 1% level across all specifications. Although the magnitude of the coefficients varies somewhat with the fixed-effects structure, the negative association between AI adoption and corporate default risk remains consistent. These findings suggest that the baseline results are robust to alternative fixed-effects specifications.

Table 3. Robustness Checks Using Alternative Fixed-Effects Specifications

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Variables | Edf | Edf | Edf | Edf | Edf |
| Ai | -0.0027*** | -0.0027*** | -0.0017*** | -0.0027*** | -0.0031*** |
| | (0.0007) | (0.0007) | (0.0006) | (0.0007) | (0.0008) |
| Constant | -0.2762*** | -0.2762*** | -0.3207*** | -0.2762*** | -0.2391*** |
| | (0.0410) | (0.0412) | (0.0402) | (0.0417) | (0.0468) |
| Controls | YES | YES | YES | YES | YES |
| Firm FE | YES | YES | Yes | Yes | Yes |
| Year FE | YES | YES | | Yes | |
| Ind FE | YES | | | | |
| Citycode FE | | YES | | | |
| IndYear FE | | | Yes | | |
| CityInd FE | | | | Yes | |
| CityYear FE | | | | | Yes |
| N | 37,621 | 37,621 | 37,616 | 37,621 | 35,534 |
| $R^2$ | 0.240 | 0.240 | 0.263 | 0.240 | 0.325 |

5.2.2 Alternative Clustering Levels

To examine whether the estimation results are sensitive to the level at which standard errors are clustered, this study re-estimates the baseline model using alternative clustering structures. This approach accounts for potential correlations in regression disturbances within different geographical and industry groupings. Specifically, Columns (1)–(5) of Table 4 cluster standard errors at the industry, city, industry-year, city-industry, and city-year levels, respectively.

The results show that the estimated coefficient on Ai remains −0.0027 across all five specifications, consistent with the baseline regression. The coefficient is negative and statistically significant at the 10% level in Column

(1), while the remaining four specifications yield negative coefficients significant at the 1% level. Although the estimated standard errors and levels of statistical significance vary across clustering methods, the negative association between AI adoption and corporate default risk remains statistically significant throughout. This indicates that the baseline findings are not driven by a particular clustering specification, providing further support for their robustness.

Table 4. Robustness Checks Using Alternative Clustering Levels

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Variables | Edf | Edf | Edf | Edf | Edf |
| Ai | -0.0027* | -0.0027*** | -0.0027*** | -0.0027*** | -0.0027*** |
| | (0.0014) | (0.0005) | (0.0008) | (0.0007) | (0.0006) |
| Constant | -0.2762*** | -0.2762*** | -0.2762*** | -0.2762*** | -0.2762*** |
| | (0.0622) | (0.0312) | (0.0519) | (0.0433) | (0.0352) |
| Controls | Yes | Yes | Yes | Yes | Yes |
| Firm FE | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes |
| Cluster | Ind | Citycode | IndYear | CityInd | CityYear |
| N | 37,621 | 37,621 | 37,621 | 37,621 | 37,621 |
| $R^2$ | 0.240 | 0.240 | 0.240 | 0.240 | 0.240 |

5.2.3 Exclusion of Observations from Special Periods

To account for the potential influence of major external shocks on corporate operations and default risk, this study conducts additional robustness checks by excluding observations from periods affected by exceptional economic events.

First, given that the global financial crisis may have influenced corporate default risk through changes in financing conditions, asset values, and operating cash flows, the model is re-estimated after excluding the relevant crisis-affected years. The results are reported in Column (1) of Table 5. Second, considering the substantial disruptions to business operations and liquidity caused by the COVID-19 pandemic, the study further excludes observations from pandemic-affected years, with the corresponding results presented in Column (2).

The results indicate that the estimated coefficients on Ai remain negative and statistically significant at the 1% level in both specifications. These findings suggest that the negative association between AI adoption and corporate default risk persists after observations from periods affected by major external shocks are removed, further confirming the robustness of the baseline results.

Table 5. Robustness Checks Excluding Special-Period Observations

| | (1) | (2) |
|---|---|---|
| | Excluding Financial Crisis | Excluding COVID-19 Pandemic |
| Variables | Edf | Edf |
| Ai | -0.0023*** | -0.0078*** |
| | (0.0006) | (0.0016) |
| Constant | -0.2032*** | -0.3258*** |
| | (0.0402) | (0.0642) |
| Controls | Yes | Yes |
| Firm FE | Yes | Yes |
| Year FE | Yes | Yes |
| N | 33,894 | 19,814 |
| $R^2$ | 0.252 | 0.289 |

*5.3 Heterogeneity Analysis*

5.3.1 High-Tech and Non-High-Tech Industries

Firms operating in industries with different levels of technological intensity may differ substantially in their technological capabilities, production processes, and risk management requirements. These differences may give rise to heterogeneous relationships between AI adoption and corporate default risk.

Firms in high-tech industries generally possess stronger research and development capabilities and more extensive technological knowledge, allowing AI applications to complement their existing technological systems. However, these firms often face substantial R&D expenditures, rapid technological change, and uncertainty associated with innovation. Consequently, improvements in operational efficiency resulting from AI adoption may not immediately translate into lower financial risk.

By contrast, firms in non-high-tech industries may rely more heavily on conventional managerial practices and traditional production inputs, leaving greater scope for improvements in information processing, process optimization, and resource allocation. AI can help these firms optimize production schedules, improve operational forecasting, and enhance capital utilization efficiency, thereby reducing operating costs and cash flow volatility and alleviating debt repayment pressures. Accordingly, the potential risk governance benefits associated with AI adoption may be more pronounced among firms in non-high-tech industries.

To examine these differences, the sample is divided into high-tech and non-high-tech firms, and separate regressions are estimated for each group. The results in Columns (1) and (2) of Table 6 show that the estimated coefficient on Ai is −0.0003 for high-tech firms, but it does not reach conventional levels of statistical significance. For non-high-tech firms, the coefficient is −0.0057 and is statistically significant at the 1% level.

These findings indicate that the negative association between AI adoption and corporate default risk is primarily concentrated among non-high-tech firms. One possible explanation is that these firms have greater opportunities to improve conventional operating processes and risk management practices through AI adoption, making the associated reductions in financial risk more apparent.

5.3.2 Regional Heterogeneity: Eastern, Central, and Western China

Differences in economic development, digital infrastructure, and access to financial resources across regions may influence both the effectiveness of AI adoption and its potential contribution to corporate risk governance. Effective AI implementation requires not only firm-level technological investment but also supporting data infrastructure, skilled professionals, and appropriate management systems.

Eastern and central China generally benefit from relatively well-developed digital infrastructure, a larger pool of technical talent, and greater access to financial services. These conditions may facilitate the integration of AI into production processes, information management, and risk management activities, thereby improving the effectiveness of technological applications.

In contrast, firms in certain western regions may face constraints related to technical expertise, digital infrastructure, and specialized business services, potentially limiting their ability to fully realize the operational benefits of AI adoption in the short term. Regional differences in market development and external financing conditions may also affect the extent to which AI adoption translates into improvements in corporate financial stability.

To further examine regional heterogeneity, the sample is divided into firms located in eastern and central China and those located in western China. Columns (3) and (4) of Table 6 report the corresponding regression results.

For firms in eastern and central China, the estimated coefficient on Ai is −0.0027 and is statistically significant at the 1% level. For firms in western China, the coefficient is −0.0023 but does not reach conventional levels of statistical significance.

These results suggest that the statistically significant negative association between AI adoption and corporate default risk is primarily observed among firms in eastern and central China, whereas the evidence for firms in western China remains statistically inconclusive.

Table 6. Heterogeneity Analysis

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | High-Tech | Non- High-Tech | Eastern and Central China | Western China |
| Variables | Edf | Edf | Edf | Edf |
| Ai | -0.0003 | -0.0057*** | -0.0027*** | -0.0023 |

| | | | | |
|---|---|---|---|---|
| | (0.0005) | (0.0016) | (0.0007) | (0.0023) |
| Constant | -0.2273*** | -0.3726*** | -0.2447*** | -0.4459*** |
| | (0.0421) | (0.0747) | (0.0445) | (0.1018) |
| Controls | Yes | Yes | Yes | Yes |
| Firm FE | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| N | 21,514 | 16,107 | 32,523 | 5,098 |
| $R^2$ | 0.237 | 0.244 | 0.233 | 0.273 |

## 6. Conclusions, Policy Recommendations, and Future Research

### *6.1 Conclusions*

Against the backdrop of rapid digital economic development and growing uncertainty in the business environment, AI adoption offers firms new technological opportunities to improve managerial decision-making, strengthen risk identification, and enhance financial stability. Using firm-level data from Chinese A-share listed companies, this study empirically examines the relationship between AI adoption and corporate default risk, with particular attention to heterogeneity across industries with different levels of technological intensity and across geographical regions. The analysis yields three main findings.

First, AI adoption is significantly and negatively associated with corporate default risk. The baseline regression results show that the estimated coefficient on AI adoption remains negative and statistically significant at the 1% level after controlling for firms' financial conditions, basic characteristics, and corporate governance attributes. This suggests that firms with higher levels of AI adoption tend to exhibit lower default risk. The main finding remains robust to alternative fixed-effects specifications, different standard-error clustering levels, and the exclusion of observations from periods affected by major external shocks. These results indicate that the negative association between AI adoption and corporate default risk is relatively stable across different model specifications and sample restrictions.

Second, the relationship between AI adoption and corporate default risk exhibits industry-level heterogeneity. The subgroup regression results reveal a significant negative coefficient on AI adoption among firms in non-high-tech industries, whereas the corresponding coefficient for high-tech firms does not reach conventional levels of statistical significance. One possible explanation is that non-high-tech firms have greater scope for improving conventional operating processes, information processing capabilities, and resource allocation efficiency. AI adoption may therefore offer more substantial opportunities to enhance operational management in these firms, resulting in a more pronounced association with lower default risk.

Third, the relationship between AI adoption and corporate default risk varies across regions. The estimated coefficient on AI adoption is significantly negative among firms located in eastern and central China, while the corresponding estimate for firms in western China is not statistically significant at conventional levels. This regional variation may reflect differences in digital infrastructure, the availability of skilled technical personnel, and external business environments. The findings suggest that the potential risk governance benefits of AI adoption may depend partly on the regional conditions that support effective technological implementation.

### *6.2 Policy Recommendations*

Based on the empirical findings, this study proposes the following policy recommendations.

First, promote the integration of AI into corporate risk management to strengthen firms' risk prevention capabilities. Governments should further improve the infrastructure and public service systems supporting AI adoption and encourage firms to incorporate predictive analytics, data analysis, and anomaly detection technologies into financial management, operational decision-making, and early-warning systems. Such measures may strengthen firms' ability to identify emerging operational risks and respond to external shocks. At the firm level, greater emphasis should be placed on integrating AI technologies with internal control systems, financial management practices, and broader operational management frameworks. This would facilitate the transition of AI from a supplementary information processing tool to a more comprehensive instrument for managing operational risks, thereby contributing to greater corporate financial stability.

Second, implement differentiated policies to support AI adoption and improve the effectiveness of technological applications. Policy design should account for differences in technological capabilities, business models, and risk management requirements across industries. A differentiated support framework would allow AI adoption policies to better reflect firms' specific operational needs. For high-tech firms, priority should be given to integrating AI

with R&D management, technological innovation, and operational risk control, while strengthening coordination between technological investment and risk management. For non-high-tech firms, policy support should focus on facilitating the practical application of AI in production process optimization, operating cost management, and financial risk early-warning systems. These measures would help firms realize the potential of AI to improve conventional management practices and enhance operational efficiency.

Third, strengthen regional digital infrastructure and narrow disparities in AI-enabled risk governance capabilities. Greater efforts should be made to promote balanced development across regions in digital infrastructure, technical expertise, and intelligent business services. In eastern and central China, firms should be encouraged to explore advanced approaches to integrating AI into corporate risk management and develop technological practices that can be replicated and adapted elsewhere. In western China, policy priorities should include expanding digital infrastructure, improving access to AI-related technical services, and strengthening professional training. These initiatives could reduce the costs associated with AI adoption and create more favorable conditions for firms to use intelligent technologies to improve operational management and risk prevention capabilities.

Fourth, establish sound corporate governance mechanisms for AI-related risks to address the potential challenges arising from AI adoption itself. While AI can improve risk identification and managerial decision-making efficiency, firms should also recognize the potential risks associated with implementation costs, data security, model prediction errors, and managerial accountability. Firms should establish systematic mechanisms for evaluating the effectiveness of AI applications, clearly define the responsibilities of automated decision-support systems and human managers, and strengthen human oversight and risk controls in major financial decisions. Particular attention should be given to avoiding excessive reliance on algorithmic outputs. By balancing technological adoption with appropriate governance and oversight, firms can better align AI implementation with prudent and sustainable business operations.

*6.3 Limitations and Future Research*

Although this study examines the relationship between AI adoption and corporate default risk using firm-level empirical evidence, several areas warrant further investigation.

First, with regard to variable measurement, corporate AI adoption is inherently multidimensional, and different indicators may capture distinct aspects of technological development, strategic attention, and actual implementation. Future research could combine information on corporate AI investment, technology patents, and specific business applications to develop more comprehensive measures of firm-level AI adoption.

Second, regarding causal identification, this study primarily relies on a two-way fixed-effects model and a series of robustness checks to investigate the relationship between AI adoption and corporate default risk. Nevertheless, potential endogeneity concerns, including reverse causality and time-varying omitted variables, may remain. Future studies could exploit exogenous technological shocks, quasi-natural experiments, or instrumental variables that satisfy plausible exclusion restrictions to strengthen the credibility of causal inference.

Finally, concerning the underlying mechanisms, this study does not directly test the specific channels through which AI adoption may influence corporate default risk. Future research could examine mechanisms related to operating cash flow stability, resource allocation efficiency, financing constraints, and corporate risk management capabilities. Such analyses would provide a more detailed understanding of the economic mechanisms linking AI adoption to corporate default risk.

**JEL Classification: G32; G33; O33**

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