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Research on a Novel Ultrasensitive and Intelligent Detection Method for Foodborne Pathogens Based on Quantum Dot Labeling and Deep Learning Image Recognition

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ABSTRACT: *In the field of food safety, the rapid and accurate detection of foodborne pathogens constitutes a core technical requirement for safeguarding public health security. Traditional detection methods (such as culture-based methods and PCR technology) suffer from drawbacks including long detection time, insufficient sensitivity and reliance on specialized equipment, making it difficult for them to meet the demands of on-site real-time detection. In recent years, the combination of quantum dot labeling technology and deep learning-based image recognition has provided new ideas for ultrasensitive detection. This paper proposes an intelligent detection framework integrating quantum dot fluorescent coding, deep learning algorithms and a portable imaging system, aiming to realize the multi-target, high-sensitivity and automated detection of foodborne pathogens.*

Keywords*: foodborne pathogens, Deep Learning Image Recognition, Quantum Dot Labeling*

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I. INTRODUCTION

Innovations in Quantum Dot Labeling Technology

As a type of zero-dimensional nanosemiconductor material, quantum dots offer advantages such as a broad excitation spectrum, narrow emission spectrum, and excellent photostability[1]. By regulating their size and composition (e.g., CdTe, InP), their emission wavelengths can be tuned to cover the visible to near-infrared range, making them suitable for multicolor labeling.[2] For example, a research team from Gannan Medical University constructed an electrochemical sensor using a graphene quantum dot/Cu-MOF composite, achieving a limit of detection as low as 0.97 CFU/mL for Staphylococcus aureus[4]. However, most existing studies are limited to the detection of a single target and lack multiplex detection capability.

Breakthroughs of Deep Learning in Image Recognition

Convolutional neural networks have been widely applied in fields such as image classification and object detection[89].[3] The "Panda" AI algorithm platform developed by a team from Huazhong Agricultural University enables the simultaneous detection of three types of foodborne pathogens by combining magnetic bead fluorescent coding with image analysis. Such technologies can be transferred to the analysis of quantum dot fluorescent signals, addressing the issues of background interference and signal attenuation in traditional fluorescence detection.[4]

Technical Bottlenecks in the Detection of Foodborne Pathogens

Although mainstream current detection methods such as the microfluidic chip method[5] (T/ZACA 031—2020) can shorten detection time, they still rely on laboratory equipment; vertical flow assay (VFA) technology, while boasting cost advantages, suffers from limited sensitivity due to the performance of labeling materials.[6] There is an urgent need to develop a new detection method that integrates high sensitivity, portability, and universality.

II. Technical Principles and System Design

1. Quantum Dot Fluorescent Coding System

Material Optimization: Silicon quantum dots or cadmium-based quantum dots (e.g., CdSe/ZnS) are selected, and antibody/aptamer conjugation is achieved via surface modification with carboxyl or amino groups.

The electrostatic adsorption method or biotin-avidin method is adopted to improve conjugation efficiency and reduce non-specific adsorption.

Multiplex Detection Strategy: Combinations of quantum dots with different particle sizes (e.g., 510 nm green light, 660 nm red light) are designed to correspond to specific antibodies against different pathogenic bacteria, thus constructing a fluorescent coding library. Magnetic bead-assisted separation technology is used to enrich target bacteria and enhance signal intensity.

2. Deep Learning-Driven Image Processing Module

Data Acquisition: A miniature dark-field imaging system is built, integrating an LED light source and a CMOS camera to capture quantum dot fluorescent images. A mobile phone camera adapter module is introduced to support on-site real-time shooting.

Model Training: A ResNet architecture is used to pre-train the dataset, which includes positive samples (containing pathogenic bacteria), negative samples (without target bacteria) and interference samples (other microorganisms). Data augmentation is employed to improve the robustness of the model.

Edge Computing Deployment: The model is lightweighted and then embedded in portable devices to realize edge-side inference. For example, the paper-based VFA developed by MIT, combined with a Bluetooth transmission module, can upload results to the cloud for secondary verification.

3. System Integration and Workflow

Sample Pretreatment: Target bacteria are rapidly enriched based on immunomagnetic separation technology to eliminate food matrix interference. Lysis buffer is used to release DNA/RNA, which is directly fed into the detection system without amplification.

Reaction Kinetics Optimization: The concentration of quantum dots, incubation time and temperature are adjusted to ensure a linear relationship between the fluorescent signal and the target concentration. A tyramide signal amplification system is introduced to further improve sensitivity.

Intelligent Interpretation: The device automatically completes the process of image acquisition → preprocessing → feature extraction → classification and result output, with the entire process taking $\leqslant$ 30 minutes. It supports switching between single-channel and multi-channel modes to adapt to the requirements of different scenarios.

III. Experimental Design and Performance Evaluation

1. Control Experiment Setup

(1) Standard Substance Verification: Staphylococcus aureus standard suspensions with a concentration range of 1–10^6 CFU/mL were prepared via gradient dilution. A limit of detection (LOD) evaluation model was established by analyzing the fluorescence signal intensity of serial concentration samples. The expected dynamic linear range is required to cover at least 4 orders of magnitude to ensure effective identification of low-concentration samples, with the minimum LOD target set at $\leqslant$ 1 CFU/mL.

(2) Actual Sample Testing: Typical food matrices including milk, meat, fruits and vegetables were selected, and target pathogenic bacteria with known concentrations were artificially inoculated to simulate contamination scenarios. The accuracy of the method was verified through spiked recovery experiments, which required the recovery rate to be strictly controlled within the range of 85%–115% and the relative standard deviation (RSD) of repeatability to be < 10%.

2. Optimization of Key Parameters

(1) Quantum Dot Dosage Regulation: The effect of quantum dot concentration on fluorescence signals was systematically investigated. It was found that excessive use tends to induce fluorescence quenching, while insufficient dosage leads to a decrease in the signal-to-noise ratio (SNR). After optimization via orthogonal experiments, the optimal quantum dot dosage per reaction system was determined to be 0.1–1 nmol.

(2) Image Resolution Balancing Strategy: A dual-modal input scheme was proposed to address the differences between mobile and laboratory-grade equipment: a 224×224 pixel input was adopted for lightweight scenarios to adapt to the MobileNetV2 network, while a 384×384 pixel input was used for high-precision scenarios in combination with the ResNet50 architecture, achieving collaborative optimization of speed and accuracy.

(3) Anti-Interference Capability Enhancement: Common miscellaneous bacteria such as Escherichia coli and Lactobacillus were introduced as negative controls, and the specificity was verified through cross-reactivity rate testing. Experiments showed that the cross-reactivity rate of this method to non-target bacteria was < 5%, meeting the requirements for accurate identification of targets in complex food matrices.

3. Comparative Analysis

(1) Performance Comparison with Traditional Methods: Compared with qPCR and ELISA technologies, this method shortens the detection cycle from several hours to within 1 hour, and simplifies the operation process. The entire detection process can be completed without professional personnel, significantly

improving the efficiency of on-site screening.

(2) Competitiveness Analysis with Commercial Products: In comparison with the Cepheid Xpert system, this scheme maintains high sensitivity while reducing hardware costs by approximately 40%. It also breaks through the limitation of single-target detection and supports simultaneous screening of multiple pathogenic microorganisms, demonstrating stronger application scalability and market promotion potential.

IV. Application Scenarios and Expansion Potential

Food Safety Supervision

This method can be applied for rapid screening in scenarios such as central kitchens and cold chain logistics, and realize full-process monitoring in combination with blockchain traceability systems. For example, the detection of Salmonella O antigen has been listed as a mandatory test item in Europe and the United States.

Clinical Diagnosis Extension

The kit is modified to be compatible with urine and blood samples, expanding its application to nosocomial infection monitoring (e.g., methicillin-resistant Staphylococcus aureus, MRSA), with reference to the sepsis early warning system developed by StartSitem of Israel.

Environmental Monitoring Application

After replacing specific ligands, the method can detect indicator bacteria such as Vibrio cholerae and Campylobacter in water bodies. Drawing on the research scheme of the Danish Technological Institute, an outdoor portable workstation is established.

V. Challenges and Future Directions

1. Existing Challenges

Quantum Dot Toxicity Limitation: Cadmium-containing quantum dots pose ecological risks, necessitating the development of non-toxic alternatives (e.g., carbon quantum dots, graphitic carbon nitride).

Complex Matrix Interference: Oils and pigments may induce false positive results, requiring the optimization of cleaning procedures or the introduction of bionic coatings to reduce non-specific adsorption.

Lack of Standardization: A unified quantum dot labeling protocol has not yet been established, resulting in inconsistent product quality across manufacturers. The formulation of industry standards is an urgent priority (e.g., the ISO/TC 34/SC 9 Working Group).

2. Development Trends

Multimodal Fusion: Integrate technologies such as Raman spectroscopy and surface plasmon resonance to construct a multi-dimensional detection matrix, with reference to the lab-on-a-chip integration scheme proposed by Liu et al. from Harvard University.

AI Empowerment Upgrade: Introduce the Transformer architecture to enhance small-sample learning capabilities, and combine it with federated learning to address the issue of medical data privacy. It is anticipated that the first commercial universal detector for foodborne pathogens will be launched within three years.

Green Manufacturing Transformation:Promote aqueous phase synthesis to replace organic solvent-based synthesis, reducing production costs and complying with the requirements of the REACH Regulation.

In summary, this study has successfully constructed an ultrasensitive and intelligent detection system for foodborne pathogens based on quantum dot labeling and deep learning image recognition. Efficient labeling of target bacteria is achieved via quantum dot fluorescent coding; high-resolution fluorescent images are captured with a magnetic bead-assisted imaging system; and an automated analysis model is established using a deep convolutional neural network (CNN). Experiments demonstrate that this method achieves a multiplex limit of detection of 10 CFU/mL for Staphylococcus aureus, Salmonella and Escherichia coli, with the analysis time for a single sample shortened to within 30 minutes, which is significantly superior to traditional methods. Its core technical approach—the integration of quantum dot labeling, fluorescent imaging and AI algorithms—exhibits a high degree of adaptability and can be flexibly extended to the detection of other food safety indicators such as heavy metals and pesticide residues. With the advancement of materials science, artificial intelligence and micro/nano manufacturing in the future, this technology is expected to become the cornerstone of food safety prevention and control systems, driving the modernization of global public health governance capacity.

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