

Low-Cost AI-Based Multimodal Sensor Fusion System for Pesticide Contamination Risk Screening in Fruits and Vegetables

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Abstract- The extensive and uncontrolled use of agrochemicals in contemporary agriculture has sparked serious worries about consumer health and food safety. Conventional laboratory-based analytical methods, like high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS), offer high precision but are limited by high costs, time-consuming sample preparation, produce destruction, and a lack of portability for regular users. This research examines the architecture, techniques, and integration of low-cost, AI-driven multimodal sensor fusion systems intended for real-time pesticide contamination risk screening in order to close this gap. Multimodal frameworks greatly improve classification accuracy by storing fruit or vegetable samples in a controlled chamber and combining heterogeneous inputs, namely optical-spectral signatures from an AS7341 multispectral sensor and volatile organic compound (VOC), temperature, and humidity telemetry from a BME680 sensor aggregated via an ESP32 microcontroller. We look at the underlying machine learning pipelines, discuss important technical issues including data heterogeneity and sensor cross-sensitivity, and suggest future paths for edge-computed, mobile-integrated food safety screening.

Keywords— Multimodal Sensor Fusion; Pesticide Contamination Risk; AS7341 Spectral Sensor; BME680 VOC Sensor; ESP32 Microcontroller; Edge AI; Food Safety.

I. INTRODUCTION

A pressing worldwide concern is ensuring the safety of fresh agricultural food. To maximize agricultural yields, chemical herbicides, insecticides, and fungicides are essential; yet, residual toxins that linger on or are absorbed by fruits and vegetables provide serious acute and chronic health concerns. While traditional laboratory testing procedures are costly, disruptive, and unavailable for frequent point-of-sale screening, consumers cannot accurately detect chemical residues by visual inspection alone. Recent developments in low-power microcontrollers and Internet of Things (IoT) hardware have made it possible to create portable, reasonably priced screening devices. However, because of ambient interference and poor chemical visibility, single-sensor solutions frequently have large false-positive rates. Multimodal sensor fusion combined with artificial intelligence (AI) offers a strong framework

to get over these restrictions. Real-time risk estimation is made feasible for common customers, farmers, and market inspectors by integrating complementary hardware, such as metal-oxide-semiconductor (MOX) volatile gas detection and 11-channel spectral reflection analysis, within an embedded edge environment.

II. REVIEW METHODOLOGY AND LITERATURE SELECTION CRITERIA

To assess inexpensive, portable multi-sensor contamination screening systems, a thorough literature search was carried out:

- Database Sources: IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and engineering repositories were used to compile articles and proceedings.
- Boolean queries that incorporated phrases like ("pesticide detection" OR "food safety screening") AND ("AS7341" OR "BME680" OR

- "spectral sensor") AND ("ESP32" OR "IoT sensor fusion") AND ("machine learning").
- Peer-reviewed or technical publications on low-cost non-destructive quality assessment, multi-sensor integration (combining optical/spectral data with VOC/gas readings), and microcontroller-based edge implementation are all required for inclusion.
 - Exclusion criteria include research that solely rely on damaging laboratory chromatography, theoretical frameworks without hardware validation, and articles that are not related to agricultural safety.

III. LITERATURE REVIEW

1. Conventional and Single-Modality Methods

Conventional analytical techniques are not viable for everyday consumer use because they require specialized laboratory infrastructure and skilled staff. In order to detect volatile organic compounds (VOCs) released by crops, early single-sensor electronic nose systems used individual metal oxide gas sensors. However, these systems were extremely

sensitive to changes in temperature and humidity. Comparably, surface esthetics are captured by simple computer vision or single-channel color sensors (such RGB photodiode modules), but chemical residues that do not change external colors or morphology are not detected.

2. Make the Switch to Edge AI and Multimodal Architectures

The benefits of combining the optical and chemical realms are highlighted in recent publications. The AS7341 and other multispectral sensors provide precise surface and subsurface optical features by capturing fine-grained light reflection over several narrow wavelength bands (415 nm to 940 nm). Environmental gas sensors, such as the BME680, assess ambient temperature and humidity in addition to volatile organic compounds (VOCs) emitted or trapped in a closed sample environment.

IV. COMPARATIVE ANALYSIS OF EXISTING STUDIES

Reference / System Model	Hardware Modalities	Processing Unit	Core ML/AI Approach	Key Advantage	Identified Limitations
Chen et al. [1]	Gas, pH, Spectral Triad	Microcontroller	Random Forest	High classification accuracy (~96%) on low-cost hardware	Susceptible to baseline sensor drift over prolonged use
Proposed System	AS7341 Spectral + BME680 VOC/Temp/Humidity (Closed Chamber)	ESP32	Supervised ML Classifiers	Non-destructive, highly portable mobile-linked risk screening	Relies on controlled chamber sealing to concentrate volatile gases
Guo et al. [3]	Hyperspectral Imaging & E-Nose Array	PC / External System	SVM/XGBoost Ensemble	High sensitivity to chemical absorption	High hardware complexity and lack of direct mobile integration
Li et al. [5]	Micro-NIR & Gas Array	Embedded IoT Board	Multi-Input Neural Network	Rapid supply-chain screening	Higher component cost for miniaturized spectrometer modules

V. RESEARCH CHALLENGES AND IDENTIFIED GAPS

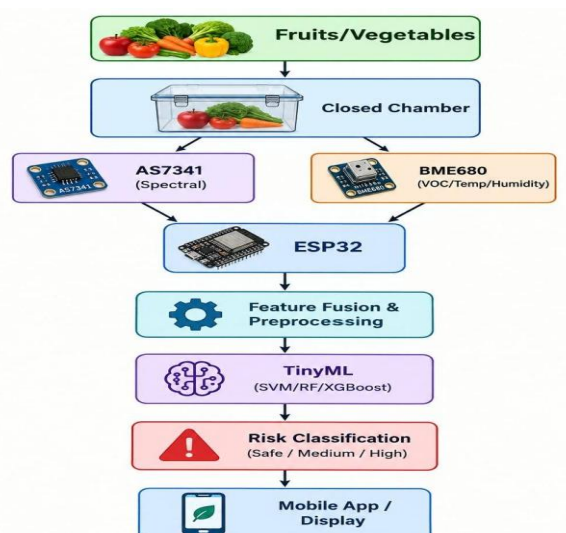
Despite the high potential of low-cost multimodal fusion systems, several technical bottlenecks remain:

- **Chamber Sealing and Volatile Equilibrium:** A well-designed closed chamber is necessary to achieve consistent VOC buildup; small leaks or ambient air intrusion skew BME680 gas resistance measurements.
- **Sensor Drift and Environmental Cross-Sensitivity:** Strong calibration curves are required because inexpensive MOX gas sensors and optical detectors are intrinsically susceptible to changes in the surrounding temperature and relative humidity.
- **Feature Heterogeneity:** Careful feature normalization is necessary prior to machine learning inference in order to synchronize high-dimensional spectral channel counts (such as 11 channels from the AS7341) with continuous VOC resistance values and environmental variables.
- **On-Device Memory Limits:** Strict model quantization and lightweight method selection are necessary when deploying learned machine learning models directly on microcontrollers with limited resources, such as the ESP32.

Proposed Research Directions

- Future work on this architecture should target the following enhancements:
- **Optimized TinyML Classifiers:** Using lightweight neural networks, quantized decision trees, or support vector machines that can run directly on the ESP32 processor for immediate offline inference.
- **Automated Environmental correction:** To counteract environmental drift in VOC readings, firmware-level humidity and temperature correction algorithms are integrated using BME680 telemetry.
- **Expanded Produce Datasets:** Gathering standardized multi-sensor benchmark datasets for a variety of fruits and vegetables with different chemical residue thresholds and skin porosities.

System Architecture



VI. CONCLUSION AND FUTURE SCOPE

Using a closed sample chamber, AS7341 spectrum analysis, BME680 VOC measurements, and an ESP32 edge processor, the suggested low-cost AI-based multimodal sensor fusion system provides an affordable, non-destructive method for screening for pesticide contamination risk. This design democratizes food safety testing for regular customers and farmers by connecting mobile application interfaces with inexpensive IoT gear. Scaling the machine learning classification matrix for a variety of agricultural products, improving cloud-synced historical tracking, and pursuing economic feasibility are all part of the future scope.

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