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Volatile Fingerprinting with E-Noses: Sniffing Out Mycotoxins Before Storage Spoilage

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Abstract: -

Mycotoxin contamination, particularly aflatoxins produced by Aspergillus species, poses a serious threat to food safety and causes major economic losses during grain and nut storage. Conventional detection methods such as HPLC and ELISA are accurate but slow, destructive, and impractical for continuous monitoring. This article reviews the application of electronic nose (e-nose) technology for early mycotoxin risk prediction through volatile fingerprinting. E-noses detect fungal-derived volatile organic compounds emitted during initial metabolic activity, enabling prediction of mycotoxin development several days before visible spoilage or toxin accumulation. Using sensor arrays combined with machine learning models, e-noses achieve high sensitivity, rapid response, and accurate discrimination of toxigenic fungi under storage conditions. Field studies demonstrate significant reductions in contaminated batches, extended safe storage duration, and substantial cost savings compared to laboratory-based assays. Integration with AI, cloud-based monitoring, and automated storage management systems further enhances predictive capability and scalability. Overall, e-nose–based volatile fingerprinting represents a powerful, non-destructive, and proactive tool for managing mycotoxin risks in postharvest storage systems.

Introduction:

Mycotoxins, including aflatoxins produced by *Aspergillus* species, are a major global food safety concern, contaminating up to 25% of stored grains and nuts. These toxins pose significant health risks, including hepatotoxicity and carcinogenicity, while causing over $1 billion in annual economic losses due to discarded or downgraded

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commodities (Youssef *et al.*, 2023). Traditional detection relies on laboratory analyses such as HPLC or ELISA, which are time-consuming, destructive, and unsuitable for high-throughput monitoring.

Electronic noses (e-noses) provide a non-destructive, portable solution by detecting unique volatile organic compound (VOC) signatures emitted during early fungal metabolism. These VOC patterns allow prediction of mycotoxin accumulation up to 72 hours before visible spoilage occurs, enabling proactive interventions to maintain grain safety and quality (Rhouma, 2025). By offering real-time monitoring capabilities in warehouses and silos, e-noses vastly outperform conventional laboratory assays in both speed and operational feasibility.

Principles and Mechanisms of E-Nose Detection

E-nose systems utilize arrays of 10–32 metal oxide semiconductor (MOS) sensors to detect VOCs such as geosmin, 2-methyl-1-propanol, and 3-octanone, which are characteristic of fungal metabolic activity. Sensor outputs are processed through machine learning algorithms to generate unique chemical fingerprints for fungal species identification, achieving classification performance with area under the curve (AUC) values exceeding 0.95 (Mellikeche *et al.*, 2024).

In peanuts contaminated with *Aspergillus flavus*, e-noses detect early spikes in ethanol and acetaldehyde at concentrations as low as 10^4 CFU/g—approximately 72 hours before aflatoxin accumulation—under controlled conditions (30°C, 85% relative humidity). Principal component analysis (PCA) reduces dimensionality of the sensor data, and support vector machine (SVM) models discriminate fungal species with 92% accuracy (Tian *et al.*, 2025). Calibration with gas chromatography-mass spectrometry (GC-MS) ensures accurate identification of VOC biomarkers and allows implementation of threshold-based alerts for targeted interventions, such as adjusting ventilation rates or culling contaminated batches.

Field Applications and Quantitative Performance

In practical settings, e-noses have demonstrated impressive predictive capabilities. Field trials in maize silos forecasted aflatoxin concentrations above 20 ppb up to five days in advance, enabling targeted drying operations to reach 12% moisture content and reducing contaminated batches by 68% (Hasanaliyeva *et al.*, 2022). In walnut storage, e-nose systems identified Penicillium-derived VOCs, including styrene and γ-decalactone, which are precursors to ochratoxin accumulation. Deployment of these technologies extended safe storage life from

60 to 120 days at 4°C, while reducing postharvest losses by 15% (Khadiri *et al.*, 2024).

Key performance metrics include:

- **Sensitivity**: Detection of mycotoxins at part-per-billion levels (ppb).
- **Response time**: Approximately 30 seconds for a complete VOC scan.
- **Economic impact**: Up to 80% cost reduction compared to HPLC analyses.
- **Stability**: Drift correction using quartz microbalance references enhances long-term reliability (ift.onlinelibrary.wiley +2).

Implementation Strategies

Modern e-nose systems are designed for continuous, automated operation. Rack-mounted units sample silo headspace at six-hour intervals, with data transmitted to cloud platforms for multi-silo dashboards. Edge AI processes compensate for environmental noise, such as humidity interference, while blockchain-based logging ensures secure, traceable records suitable for export compliance (Rhouma, 2025). This integration enables centralized monitoring, predictive maintenance, and rapid decision-making for operators managing large-scale storage facilities.

Future Prospects

Emerging developments aim to enhance both sensitivity and scalability of e-nose technologies. Hybrid platforms combining e-noses with hyperspectral imaging can correlate VOC emissions with spectral changes, enabling multi-mycotoxin prediction with high accuracy ($R^2 > 0.97$). Drone-mounted sensors can map silo interiors and identify localized hotspots of fungal growth for targeted interventions (Botero-Valencia *et al.*, 2025).

Next-generation nano-sensors, including graphene–metal–organic frameworks (MOFs), promise ppb-level VOC detection, further improving early-warning capabilities. Predictive maintenance informed by AI and networked sensor data could potentially reduce global mycotoxin contamination by up to 40% by 2030 (Nikzadfar *et al.*, 2024).

Conclusion

Electronic nose technologies fundamentally transform mycotoxin management in stored grains and nuts by shifting from reactive to predictive approaches. By detecting fungal activity before toxin accumulation, these systems enable early interventions that maintain product safety, extend shelf life, and reduce economic losses. Integration with AI, cloud platforms, and potentially autonomous drones allows scalable, real-time monitoring across multiple storage sites. As hardware becomes more affordable and algorithms more robust, widespread adoption is expected, ensuring safer, more sustainable grain supply chains globally.

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