Rapid Fungal Typing and Spatial Mapping via VOC Sensing and Machine Learning

Yanbaihui Liu (Duke), Erica Babusci (Duke), Claudia K. Gunsch (Duke), Boyuan Chen (Duke)

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This work is a part of PreMiEr **Project RT1-10 | Measurement of residential built environments** | PI: Noble

Abstract

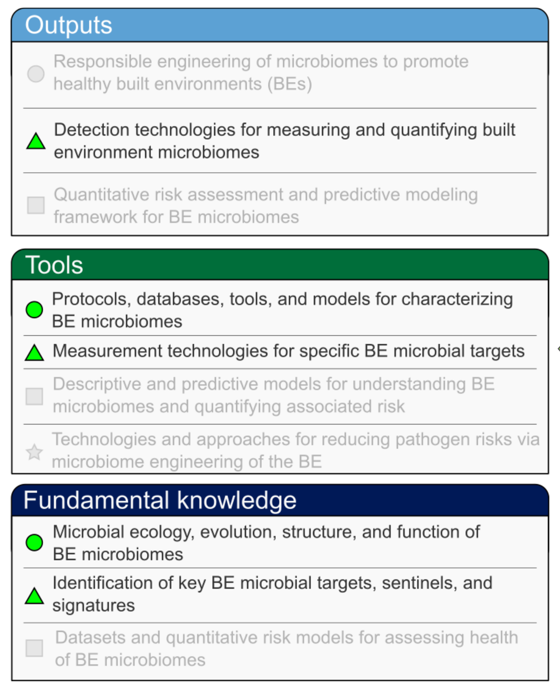
Detecting indoor fungal contamination rapidly, non-invasively, and at scale remains an unmet challenge in environmental monitoring and public health. We introduce a learning-enabled olfactory system that combines a low-cost sensor array with deep neural networks to identify fungal species and infer source location from volatile organic compound (VOC) emissions. Evaluated across five biologically and chemically diverse fungal species including Cladosporium.510 (C.510), Penicillium toxicarium (P. toxicarium), Penicillium.513 (P.513), Trichoderma.508 (T.508), and Bjerkandera adusta (B. adusta), our approach achieves reasonable classification and localization accuracy using only passive, ambient VOC signals. Models trained exclusively in a controlled chamber retain functionality when deployed on a mobile robot in real indoor environments, demonstrating robustness to airflow variation and background noise. By overcoming hardware limitations with machine learning, this work establishes a scalable platform for practical mold detection in buildings, offering a path toward cost-effective air quality diagnostics and autonomous fungal inspection.

Objectives/Aims

- **Detect and localize indoor fungal contamination** rapidly and non-invasively using volatile organic compounds (VOCs).
- **Identify species and infer source location** using only passive sensor data from low-cost arrays.
- **Bridge the gap** between laboratory testbeds and real-world building environments with a scalable platform deployable on robots or as handheld probes.

Novelty/Innovation/Approach

- **Engineering Challenge:** Conventional VOC sensing systems fail at low concentrations, lack chemical specificity, and offer no spatial awareness.
- **Our Innovation**:
  - **Multi-sensor "Olfactory RGB" encoding:** An 8-channel array mimics biological odor coding, using both chemical and spatial diversity.
  - **Deep learning integration**: Neural networks trained on synchronized, temporally structured VOC signals to infer species, source direction (quadrant), and distance—**no airflow control or external localization needed**.
  - **Dual-Mode Sensing:**
    - *Multi-array mode*: Jointly predicts fungal type and coarse location across large environments.
    - *Single-array mode*: Pinpoints species, direction, and distance from a single point, enabling robotic and handheld search.



Alignment of Project RT1-10 with PreMiEr's current 3-plane chart with boxes corresponding to the Knowledge Base (bottom, dark blue), Technology Base (middle, dark green), and Technology Integration (top, light blue).

Species	MAE (mean) [m]	MAE (std) [m]	MSE (mean) [m^2]	MSE (std) [m^2]	RMSE (mean) [m]	RMSE (std) [m]
C.510	0.1644	0.0096	0.0410	0.0047	0.2023	0.0116
P. toxicarium	0.1582	0.0059	0.0389	0.0022	0.1972	0.0055
P.513	0.1744	0.0034	0.0460	0.0012	0.2144	0.0028
T.508	0.1623	0.0096	0.0386	0.0050	0.1960	0.0128
B. adusta	0.1239	0.0062	0.0246	0.0016	0.1566	0.0049

Table 1. Distance regression errors across fungal species. The Smaller the better.

Results

Hardware Design:
We developed a custom PCB-based VOC sensing module tailored for indoor fungal detection. The module includes **eight gas sensors channes** (MQ-3, MQ-9, MQ-135, MQ-136, MQ-138, TGS2602, HCOC, and SHT31) positioned for chemical diversity and spatial encoding. The system supports high-frequency (10 Hz) data streaming and can be mounted on fixed locations, robot arms, or mobile robots for automated sampling.

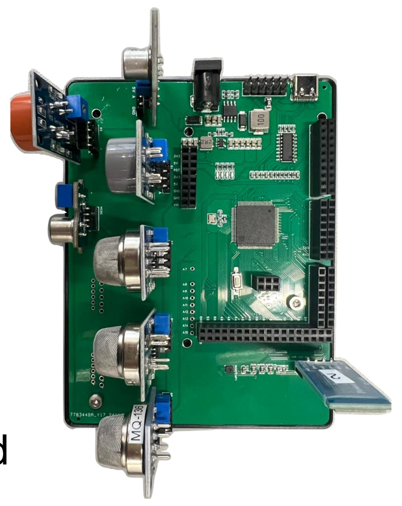


Figure 1. PCB-based VOC sensing module

Task 1 – Environmental monitoring
Setup:
- Six identical VOC sensor arrays are fixed at different locations inside a chamber.
- The robotic arm moves a fungal culture to multiple waypoints; all arrays record simultaneously.

Species Classification:
Model trained on all five target fungi:
Classification accuracy: *85–93%* (highest for *B. adusta*, *P. toxicarium*, *P.513*)
Most confusion: between *T.508* and neighboring classes, likely due to similar VOC profiles.

Coarse Spatial Localization:
Chamber divided into four spatial bins (quadrants).
Localization accuracy: *>96%* correct predictions for all bins.
Even small differences in VOC readings across arrays were sufficient for robust localization.

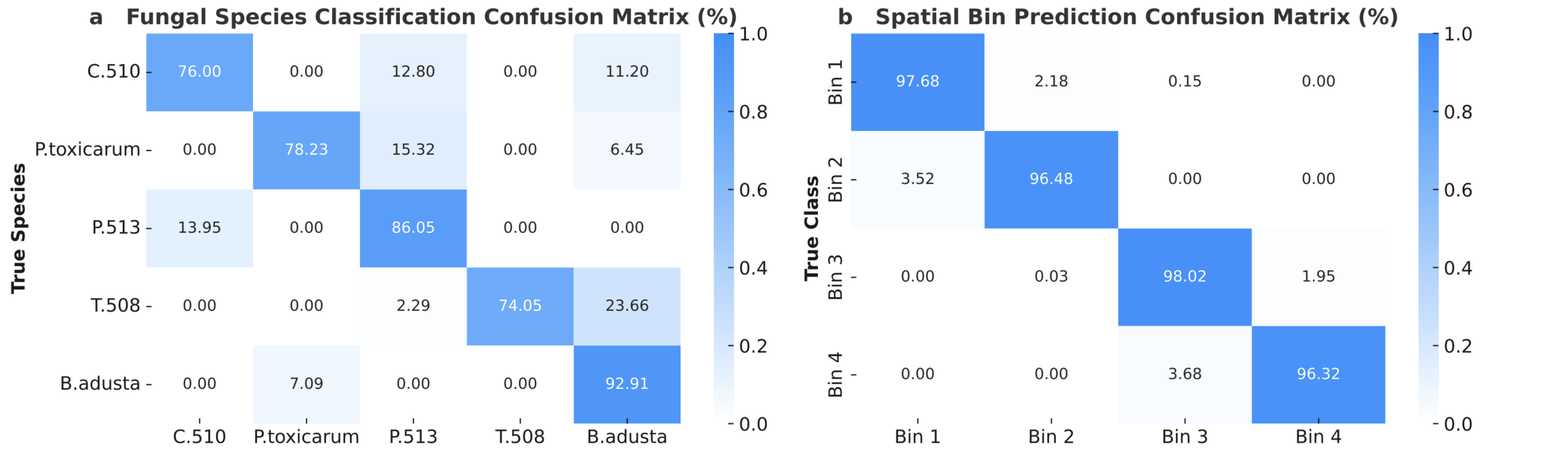


Figure 2. Multi-array model performance for fungal species classification and spatial localization

Task 2 – Single-Array Localized Inference
Setup: Single VOC array placed near a suspected source; reflects mobile robot or handheld usage.

Species Classification:
Classification accuracy: *61–78%*
Most confusion: between *T.508* and other species, reflecting overlapping volatilome signatures.

Direction Prediction:
Source direction divided into four local bins (±x, ±y).
Quadrant prediction accuracy: *43–63%*
Most errors occurred near boundaries between bins.

Distance Regression:
Separate regression model trained for each species.
Best performance:
B. adusta: **MAE = 0.12 m, RMSE = 0.16 m**
Performance varies by species due to plume structure and diffusion

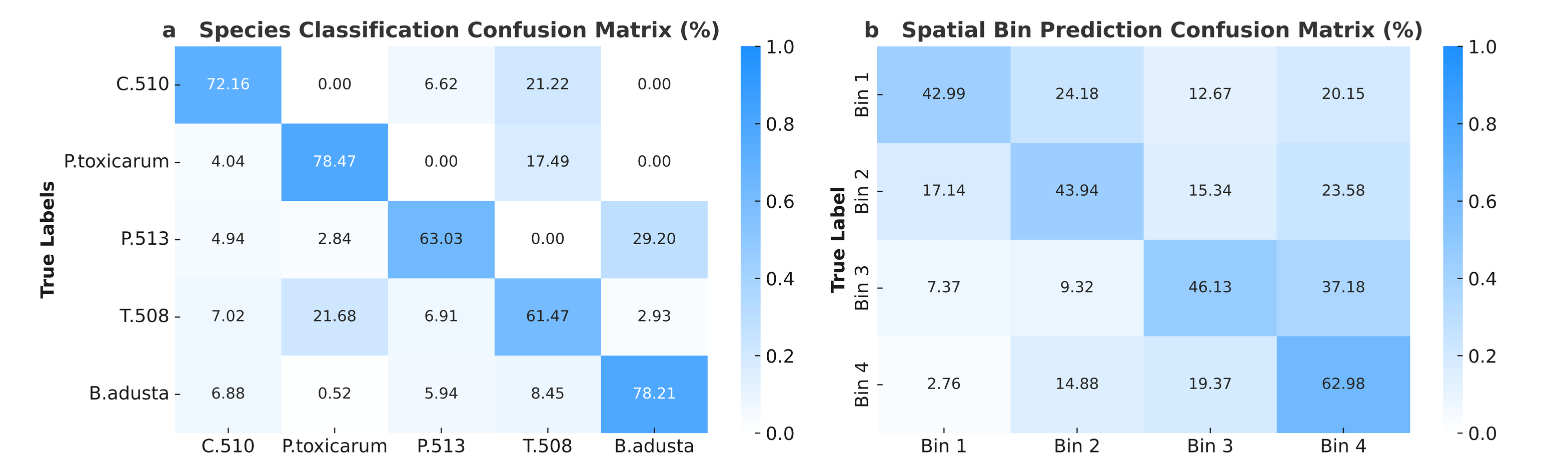


Figure 3. Single-array model performance for fungal species classification and spatial localization.

Real World Demo:
No recalibration needed in real home
Robot navigates to contamination site using VOC predictions

Figure 4. Autonomous VOC-guided localization in a real home. Left: Robot begins at a distant start point. Center: Reaches to Human provided rough region of interest. Right: Robot navigates and pinpoints the hidden fungal source solely using live VOC sensor data and model inference.

Discussion/Conclusions

Conclusions:
- This project delivers a robust, low-cost VOC sensing platform and deep learning pipeline for rapid fungal detection and localization indoors.
- The system accurately identifies species and location in both controlled and real home environments, with no need for external references.

State of the Technology:
- The core sensing and machine learning components are robust and functional for both research and pilot field deployments.
- The platform is currently best suited for use in moderately-sized, enclosed spaces where VOCs can accumulate and passive sensing is effective.

Next Steps:
- Integrate an active air intake mechanism to boost VOC capture and extend performance to larger or ventilated spaces.
- Expand to additional fungal species and broader building types.

Achievements/Accomplishments

- Designed and fabricated a novel 8-channel VOC sensor array, optimized for chemical diversity and spatial encoding.
- Collected a comprehensive dataset from five biologically and chemically diverse fungal species in a controlled chamber.
- Developed multi-task neural network models for species classification, spatial localization, direction, and distance estimation.
- Achieved high classification (>85%) and localization (>96%) accuracy in multi-array mode; robust single-array performance for robotic and handheld deployment.
- Successfully demonstrated real-world transfer: a mobile robot, equipped with the system, autonomously localized hidden fungal sources in an actual home environment—**without retraining or recalibration.**

Outputs

Manuscript:
Scensory: Rapid Fungal Typing and Spatial Mapping via VOC Sensing and Machine Learning (*Under Preparation*)
Yanbaihui Liu, Boyuan Chen, Erica Babusci, Claudia K. Gunsch

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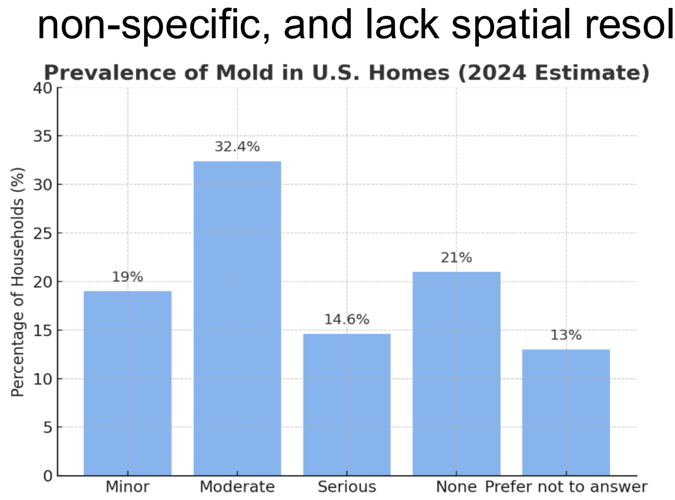
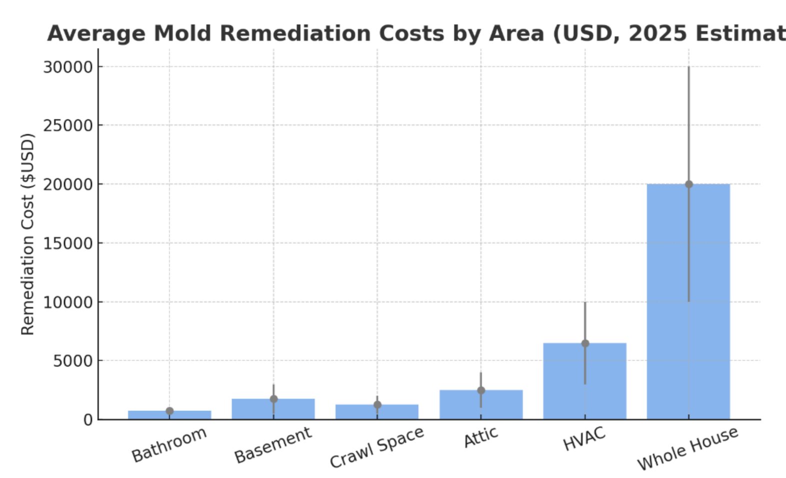
Challenges and Risks

- Mold is frequently missed until it causes significant property loss and impacts occupant health.
- Mold-related issues are widespread and costly, with substantial consequences for both building integrity and public well-being.
- Conventional VOC sensors are often insensitive to early contamination, chemically non-specific, and lack spatial resolution.





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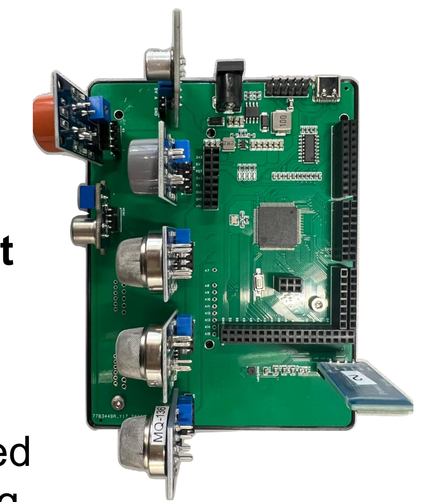

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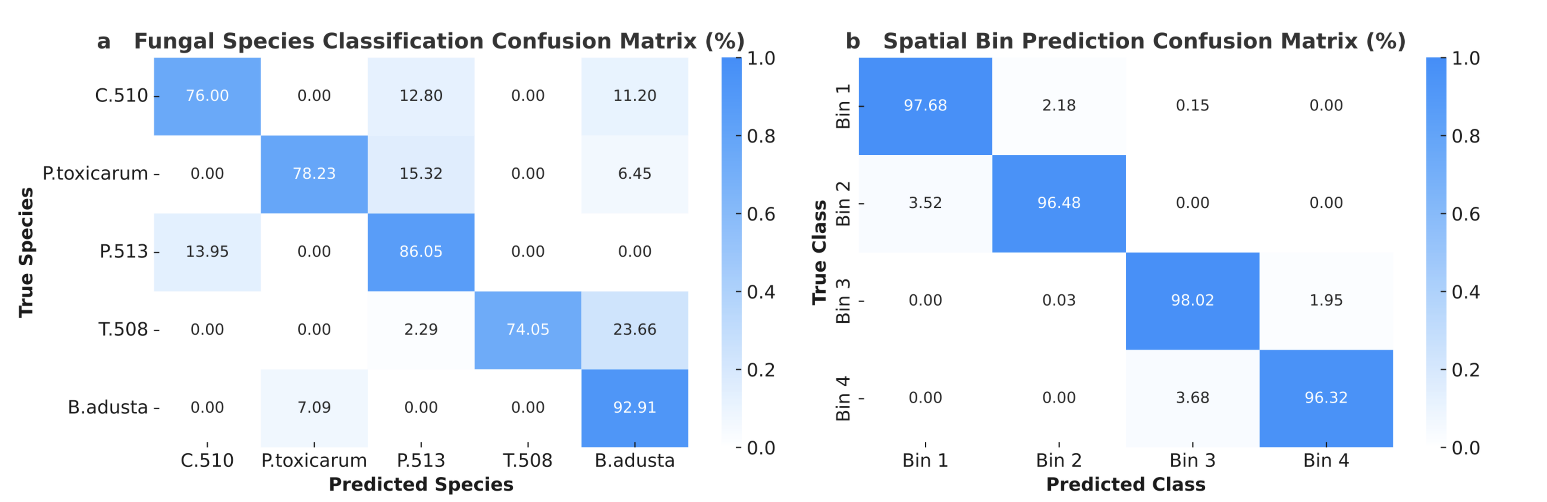

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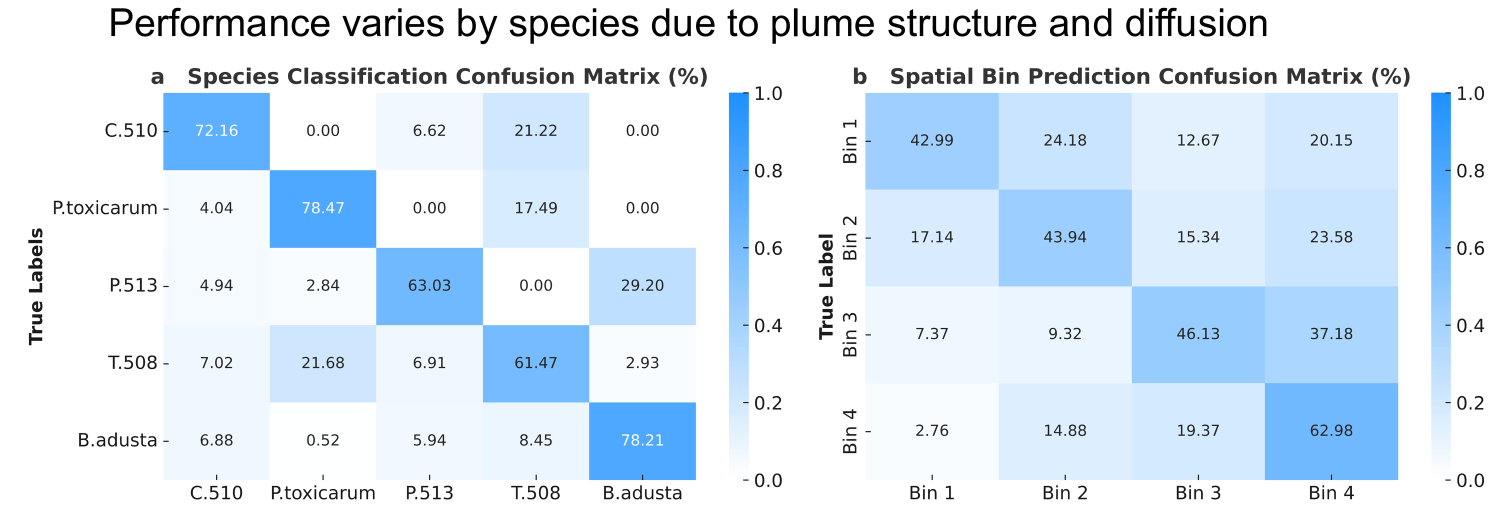

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