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VOC-based sensing for early detection and decision support in postharvest fungal spoilage and storage contamination

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ABSTRACT

Postharvest fungal spoilage and storage contamination remain major causes of quality loss and food safety concern in fresh commodities and stored grains. Early detection is often difficult because infections may remain latent or asymptomatic until deterioration is advanced. Volatile organic compound (VOC)-based sensing offers a rapid and non-destructive tool to monitor infection-related changes in the headspace and to support timely decisions along the postharvest chain. This Scopus-based systematic review synthesises evidence published between 2011 and 2026 on VOC-based sensing and related proxy approaches for early detection, monitoring, screening, and decision support in postharvest fungal spoilage and storage contamination in fruit systems and cereals or grains, with a specific focus on deployment readiness and decision-support applications. The Scopus search identified 192 records. After deduplication, screening, and eligibility assessment, 61 studies were included in the synthesis. The reviewed literature shows that electronic nose systems and sensor arrays are mainly used for rapid screening and triage, while gas chromatography–ion mobility spectrometry (GC-IMS) and headspace gas chromatography–ion mobility spectrometry (HS-GC-IMS) are more often applied to storage monitoring and contamination staging. Headspace solid-phase microextraction gas chromatography–mass spectrometry (HS-SPME-GC-MS) remains central for marker discovery and interpretation, whereas fast mass spectrometry (MS), optical arrays, and biosensor-based approaches address more specific deployment constraints. Across studies, the strongest evidence supports VOC-based sensing as a screening layer rather than a standalone diagnostic method. The main barriers to routine implementation are limited external validation, incomplete control of biological and storage-related confounders, sensor drift, and insufficient standardisation of sampling and reporting. Future research should prioritise multi-lot and multi-site validation, quantitative endpoint anchoring, calibration transfer, and decision thresholds linked to operational consequences. Overall, VOC-based sensing can support food control strategies by enabling earlier risk recognition, lot prioritisation, and targeted confirmatory testing.

1. Introduction

Postharvest fungal diseases and storage contamination remain major drivers of quality loss in fresh commodities and stored grains, causing losses during handling, storage, transport, and marketing (Cerioni & Rapisarda, 2025; Youssef et al., 2022). In many supply chains, infections are recognised only after symptoms become visible or after deterioration is advanced, when options for segregation and mitigation are limited (Youssef et al., 2022). Conventional confirmation methods can be accurate, but they are often slow, destructive, or poorly suited to dense monitoring across lots and time. This limitation supports the need for non-destructive technologies able to monitor larger proportions of stored commodities without generating additional product loss (O'Brien & Alamar, 2025). This creates a practical need for rapid screening tools that can flag suspect units or lots early enough to support timely decisions. The relevance of this issue is not limited to product quality, because postharvest fungal spoilage also affects food availability, trade value, and food safety. Postharvest losses remain particularly critical in supply chains where storage, cooling, sorting, and analytical control capacity are limited, including several fruit- and grain-producing regions in low- and middle-income countries (FAO, 2019; Kader, 2005; Kumar & Kalita, 2017). In stored cereals and grains, fungal

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contamination is associated with mycotoxin-related risks, especially when moisture and temperature conditions favour mould growth during storage (Kumar & Kalita, 2017; Yu & Pedroso, 2023). Mycotoxigenic fungi may also be involved in postharvest fruit rots, as shown for *Fusarium species* associated with banana rot and capable of producing multiple mycotoxins in fruit-based matrices, while *Fusarium* mycotoxins are also well documented in cereal-based matrices (Conti Taguali et al., 2024; Foroud et al., 2019). These constraints make early, rapid, and non-destructive screening tools particularly relevant for food control systems, provided that they can be integrated into realistic operational workflows and supported by appropriate validation.

Volatile organic compound (VOC) signatures provide a plausible route to early detection because infection and host responses can modify headspace composition before extensive tissue breakdown occurs. Recent literature has consolidated fungal volatile biomarkers and their potential role for monitoring and early warning, while also emphasising that operational value depends on validation and transferability rather than proof of concept accuracy alone (Zhu et al., 2025). Across commodities, volatiles are measured either as rich fingerprints or as marker-oriented profiles. In cold stored fruit, combined CO_2 and VOC measurements illustrate how gas phase signals can track fungal growth dynamics under temperature-dependent conditions (Rojas-Flores et al., 2019). Similarly, VOC-based marker discovery in kiwifruit has been proposed for latent postharvest diseases, supporting the use of volatile profiles as early indicators in pathosystems where symptoms can appear only after prolonged cold storage (Di Francesco et al., 2024). In grains, volatile metabolite characterisation and transfer between mass spectrometry (MS) and ion mobility spectrometry (IMS) frameworks illustrate a pathway from analytical profiling toward faster onsite-compatible workflows (Erler et al., 2020). Packaging and constrained headspace environments are increasingly considered, with optical arrays, smartphone-read fluorescent arrays, and biosensor concepts showing that early warning can be implemented without opening units, which is relevant for citrus logistics and retail scenarios (Cavallaro et al., 2024; Chalupowicz et al., 2020; Santonocito et al., 2026).

Platform choice in the last 15 years has diversified toward deployable sensing. In cold chain contexts, handheld electronic nose systems have been developed to detect decay under low-temperature environments, aiming at practical non-destructive screening (Wei et al., 2018). In parallel, toxin-oriented screening has been addressed in grains through electronic nose systems, sensor arrays, and modelling approaches targeting aflatoxin, fumonisin, and other mycotoxin-related endpoints, reinforcing the decision support value of volatile-based signals for lot management (Camardo Leggieri et al., 2021; Jiang et al., 2022; Qu et al., 2024). In cereals and grains, electronic nose and chemometrics have been used for early identification of *Aspergillus* spp. contamination in milled rice (Gu et al., 2021), and volatomic profiling approaches have been proposed for early detection on brown rice with classification and regression outputs (Jiarpinijnun et al., 2020). For fruits, multisensory designs combining sensor arrays and optical readout have been proposed to capture tomato volatile signals (Meléndez et al., 2023), and monitoring strategies have been explored in grapes to address transferability across biological variability (Yang et al., 2025). Mechanistic studies further indicate that host VOCs can interact with pathogen development, supporting the need to control confounders and to interpret early signals beyond purely empirical classification (Neri et al., 2019). In high value chains, early detection frameworks have also been framed around specific process-relevant syndromes such as noble rot in wine grapes, where early recognition is linked to downstream handling choices (Modesti et al., 2023).

The objective of this Scopus-based systematic review is to synthesise evidence published between 2011 and 2026 on early detection of postharvest fungal spoilage and storage contamination based on volatile signals and related sensing outputs, with a specific focus on decision support use cases. In particular, this review frames VOC-based sensing as an operational decision-support layer rather than as a standalone diagnostic approach. The review organises the evidence by sensing platform and operational decision point along the chain, and discusses evidence strength in relation to validation level, endpoint anchoring, confounder control, and transferability. The aim is to clarify what VOC-based sensing can realistically deliver today and what should be standardised to support routine monitoring.

2. Materials and methods

2.1. Database, time window, and search strategy

This Scopus-based systematic review was conducted with reference to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 reporting principles (Page et al., 2021), with adaptations required by the scope of a single-database narrative and descriptive synthesis. A systematic literature search was conducted in Scopus on 12 March 2026 within the 2011 to 2026 publication window. Searches were performed in the Title, Abstract, and Keywords fields. Scopus was selected a priori as the bibliographic source to define a reproducible database-bounded corpus for an interdisciplinary topic that spans food science, postharvest technology, analytical chemistry, sensor development, engineering, and food control. Other databases, such as Web of Science, PubMed, CAB Abstracts, and IEEE Xplore, may contain additional relevant records; however, their inclusion would have changed the scope from a Scopus-based systematic review to a multi-database review. Therefore, the use of Scopus was treated as a methodological boundary of the review rather than as a claim of exhaustive coverage across all bibliographic databases. Search terms were developed to capture three main concept blocks: volatile signals and headspace-based sensing; postharvest or storage context; and fungal spoilage, decay, disease, contamination, or mycotoxin-related risk in fruit systems and cereals or grains. The main query combined VOC-, volatile-, and headspace-related terms with fungal spoilage and postharvest or storage terms. A supplementary query was applied to retrieve relevant sensor-based studies that may not consistently report VOC-related terms in title, abstract, or keywords. Exclusion terms were applied to reduce records focused on molecular diagnostics, field diseases, treatment efficacy without a detection or monitoring objective, aroma or quality without a clear fungal spoilage link, and matrices outside the target scope. The complete search strategies, including query structure, limits and exclusion terms, are reported in Supplementary Table S1 and Supplementary Table S2.

2.2. Eligibility criteria

Studies were eligible when they met all the following criteria: postharvest or storage context; fungal spoilage, decay, or contamination as the target condition; use of VOC-based information, headspace volatile fingerprints, or VOC proxy sensing for early detection, monitoring, screening, or decision support; application to fruit systems or cereals and grains; full text available in English.

Studies were excluded when the main focus was treatment or control without a detection or monitoring objective, or when pathogen identification relied primarily on molecular methods. Studies focused on quality, aroma, or processing without a clear link to fungal spoilage, decay, or contamination were excluded.

In this review, VOC proxy sensing refers to sensing approaches that do not necessarily identify individual volatile compounds, but generate analytical or sensor responses associated with changes in the headspace of infected, contaminated, or deteriorating commodities. This category included electronic nose systems, gas sensor arrays, optical arrays, and biosensor-based approaches when they were explicitly linked to fungal spoilage, decay, contamination, or related decision support.

2.3. Study selection

Records retrieved from the main and supplementary searches were merged and deduplicated. Duplicates were identified using DOI when available. When DOI was not available, records were checked using title, year, and source.

Overall, 192 records were identified, including 167 records from the main query and 25 records from the supplementary query. After merging the two search outputs and removing 17 duplicate records, 175 unique records remained and were screened against the eligibility criteria. Screening was based on title, abstract, and, when required, full-text assessment. Only studies for which the full text was available in English were eligible; records published only in other languages were excluded.

A total of 114 records were excluded because they did not meet one or more eligibility criteria. The main reasons for exclusion were absence of a postharvest or storage context, absence of a fungal spoilage or contamination endpoint, absence of VOC-based information or related headspace proxy sensing, focus on treatment efficacy without a detection or monitoring objective, focus on aroma or quality without a clear fungal spoilage link, molecular identification without a sensing component, application outside fruit systems, cereals, or grains, or lack of full-text availability.

2.4. Data extraction and coding scheme

For each included study, the following information was extracted: commodity; target pathogen or pathogen group; postharvest setting; sensing or analytical platform; type of output; validation approach; and reported performance metrics when available. Data extraction was conducted using a predefined coding scheme. Ambiguous classifications were checked with co-authors and resolved by consensus. Studies were also coded according to their main decision support use case, including storage monitoring, early warning, screening and triage, tracking of contamination, and quality control.

2.5. Assessment of evidence strength

The studies included in this review were highly heterogeneous in terms of commodity, target pathogen, sensing platform, experimental design, endpoint, and validation approach. For this reason, a standard risk-of-bias tool or an aggregate numerical quality score was not applied. Instead, evidence strength was assessed using a structured categorical framework tailored to VOC-based sensing in postharvest and storage systems. The framework considered six predefined criteria: experimental context, validation approach, endpoint anchoring, confounder control or reporting, performance reporting, and deployment relevance. Experimental context distinguished controlled inoculation or laboratory-scale studies from natural contamination, realistic storage conditions, independent lots, or commercial-like settings. Validation approach distinguished internal or model-based validation, such as cross-validation or train-test splitting, from independent validation across lots, cultivars, storage regimes, instruments, or sites. Endpoint anchoring considered whether VOC-based outputs were linked only to class labels or also to quantitative endpoints, such as fungal growth, spoilage degree, lesion development, colony counts, or mycotoxin-related measurements. Confounder control or reporting considered variables such as cultivar, maturity stage, storage temperature, humidity, packaging, wounding, background microbiota, and mixed infections. Performance reporting considered the availability of metrics relevant to decision support, including accuracy, sensitivity, specificity, prediction error, confusion matrices, confidence intervals, or decision thresholds. Deployment relevance considered whether the study addressed portability, non-destructive measurement, packaged or constrained headspace, sensor drift, calibration transfer, user-oriented implementation, or operational decision points.

These criteria were coded descriptively rather than converted into a single score, because the included studies differed substantially in platform, endpoint, and intended use. The framework was used to support the descriptive synthesis of validation quality, transferability, and deployment readiness reported in the Results and Discussion. The resulting evidence-coding matrix is provided as Supplementary Table S4.

3. Results

3.1. Study selection summary

The Scopus searches retrieved 192 records, including 167 records from the main query and 25 records from the supplementary query. After merging the two search outputs and removing 17 duplicate records, 175 unique records were screened against the eligibility criteria. A total of 114 records were excluded because they did not meet one or more inclusion criteria. Finally, 61 studies were included in the synthesis. The PRISMA-guided study selection process is summarised in Fig. 1, including the number of records identified, deduplicated, screened, excluded, and included in the final synthesis.

3.2. Study characteristics

The 61 included studies were published between 2011 and 2026, with most papers appearing in recent years. The evidence covered both fruit systems and cereal or grains. Fruit commodities included apple, citrus, stone fruits, grapes, strawberries, kiwifruit, pear, tomato, and other postharvest commodities, whereas cereal and grain studies mainly focused on maize, rice, wheat, barley, and peanuts, often in storage or warehouse settings. All studies included in the synthesis are listed in Supplementary Table S3.

To facilitate interpretation of the evidence base, a descriptive summary of the geographical distribution, commodity groups, sensing platforms, and main fungal targets or contamination conditions is provided in Table 1. This distribution of commodities, fungal targets, and platform families provides the basis for the following technical comparison, because the type of sensing evidence generated by each study depends strongly on both the biological system and the analytical platform used.

The included studies addressed different but related objectives. Some focused directly on early detection or screening of fungal infection before visible symptoms. Others were designed for storage monitoring, contamination staging, mycotoxin-related risk screening, volatile marker discovery, or interpretation of fungal VOC production. This distinction is important because the included studies differed substantially in operational readiness, deployment context, and validation level.

Studies based on electronic nose systems, sensor arrays, GC-IMS, and HS-GC-IMS were more directly linked to screening or monitoring applications, whereas gas chromatography–mass spectrometry (GC-MS)-based studies more often supported marker identification and biological interpretation.

Most studies relied on controlled inoculation, controlled storage conditions and laboratory-scale experiments, with comparatively limited representation of realistic commercial and supply-chain variability. These designs were useful to isolate infection-associated changes in the headspace, but they also limited direct extrapolation to commercial storage and supply-chain conditions. Natural contamination, independent lots, different storage regimes, and multi-site validation were less frequently represented.

The most common outputs were the classification of sound *versus* infected or contaminated samples, discrimination among contamination stages, and early-warning models during storage. Fewer studies linked VOC-based signals to quantitative endpoints such as conidial counts, spoilage degree, lesion development, fungal growth inhibition, or mycotoxin-related measurements. This limited the possibility of

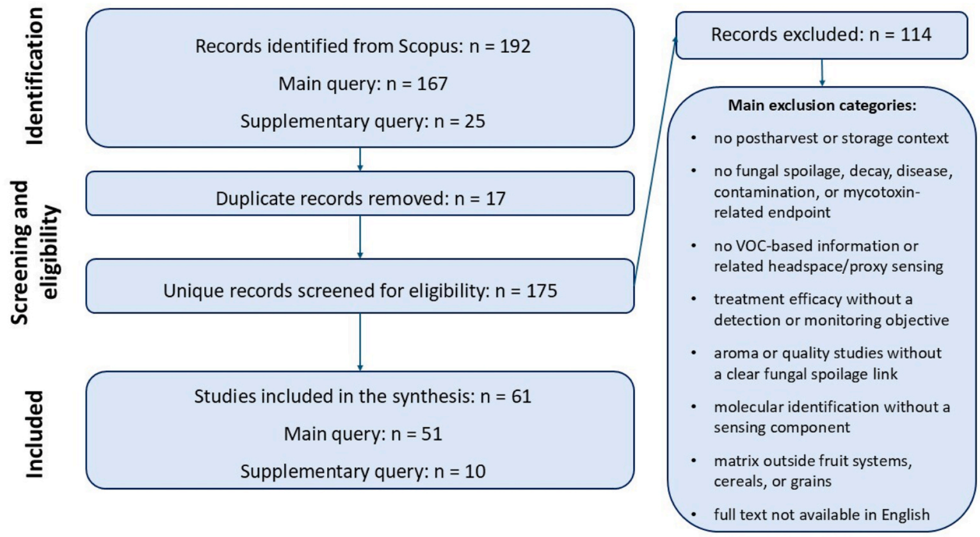

Fig. 1. PRISMA-guided flow diagram of the Scopus-based study selection process. Exclusion categories indicate the main reasons applied during screening and were not treated as mutually exclusive, because some records met more than one exclusion criterion.

Table 1
Descriptive overview of the included evidence base.

Dimension	Summary
Geographical distribution	China was the most represented country or region according to lead/corresponding affiliation or article context (n = 31), followed by Italy (n = 8), Spain (n = 5), Canada (n = 2), and other single-country, international, or multi-country affiliations (n = 15). This classification should not be interpreted as a site-level mapping of validation settings.
Commodity or system type	Fruit systems accounted for 35 primary detection or monitoring records, whereas cereals or grains accounted for 21. One record was classified as a culture or model system, and four records were retained as review or contextual evidence supporting the broader synthesis.
Sensing or analytical platforms	The most represented platforms among the 57 primary detection or monitoring records were electronic noses or gas sensor arrays (n = 27), followed by GC-MS or HS-SPME-GC-MS VOC profiling (n = 12), GC-IMS or HS-GC-IMS (n = 7), hybrid sensor plus GC-MS approaches (n = 3), fast MS or IMS-based profiling (n = 3), optical or colorimetric arrays (n = 3), biosensor or proxy sensing (n = 1), and mixed non-destructive sensing (n = 1).
Main fungal targets or contamination conditions	The reviewed evidence covered *Penicillium* spp. and apple or citrus decay, *Monilinia* spp. in stone fruits, *Botrytis cinerea* in grape and strawberry systems, *Aspergillus* spp. and aflatoxin-related grain contamination, *Fusarium* or mycotoxin-related hazards, and mixed or non-specified mould, mildew, soft rot, sour rot, and general spoilage or contamination endpoints.

defining decision thresholds for routine food control applications.

3.3. VOC-based sensing platforms

Building on the study characteristics described above, the reviewed platforms can be interpreted not only as alternative analytical tools, but also as approaches that differ in chemical specificity, operational complexity, portability, and proximity to routine decision support.

Platform selection was primarily driven by the operational objective, ranging from rapid screening and storage monitoring to marker discovery and deployment-oriented applications. Electronic nose systems and sensor arrays are mainly used to convert complex headspace changes into multivariate patterns for rapid screening. GC-IMS and headspace gas chromatography–ion mobility spectrometry (HS-GC-IMS) provide richer fingerprints and are more often used for storage monitoring and contamination staging. Headspace solid-phase microextraction gas chromatography–mass spectrometry (HS-SPME-GC-MS) and related chromatographic approaches remain central for marker discovery and biological interpretation. Fast MS, optical arrays, and biosensor-based approaches address more specific needs, including non-destructive high-frequency measurements, packaged headspace monitoring, and simplified field-oriented screening. The conceptual workflow linking commodity context, headspace signals, sensing platforms, modelling outputs, and decision support actions is summarised in Fig. 2.

Electronic nose systems and sensor arrays are designed to capture global headspace responses rather than to identify individual compounds. Their main strength lies in the rapid recognition of infection status, spoilage progression, or contamination stage through multivariate headspace patterns. In fruit systems, this approach is repeatedly used for early classification before visible symptoms, especially when the objective is triage or sorting. Stone fruit studies targeting *Monilinia laxa* provide a consistent example, since headspace patterns acquired by electronic nose systems can discriminate incipient infection from controls and support stage classification during storage (Martínez et al., 2025a, Martínez et al., 2025c; 2025d). Similar screening logic has been applied to apple decay caused by *Penicillium expansum* and to broader spoilage classification tasks in stored apples (Guo et al., 2021; Martínez et al., 2025c). In tomato, a multisensor system combining metal oxide semiconductor (MOS) and electrochemical sensors with an optical reader and smartphone interface was used to discriminate ripening and health status and to support early detection of *Botrytis cinerea* (Meléndez et al., 2023). In cereals and grains, sensor arrays are often coupled with feature selection, data fusion, or machine learning to support classification and quantitative monitoring, including toxin-related screening in wheat and maize (Jiang et al., 2022, 2026; Qu et al., 2024). These studies support the use of sensor arrays as rapid screening tools, but they also show that humidity, sensor drift, and calibration domain remain important constraints for transferability in storage environments (Hou et al., 2025, 2026).

GC-IMS and HS-GC-IMS provide rapid volatile fingerprints with higher chemical resolution than conventional sensor arrays. These platforms are strongly represented in cereals and grains, where the

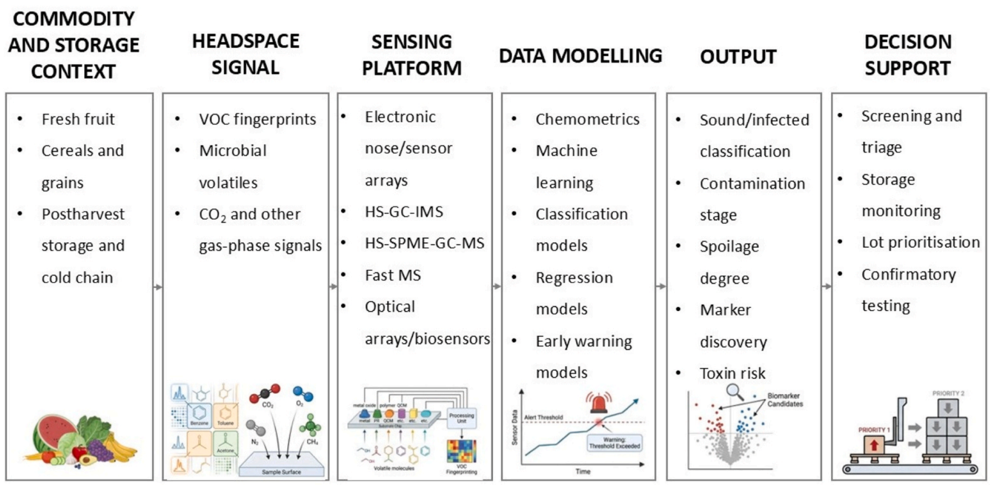

Fig. 2. Conceptual workflow of VOC-based sensing as a decision support layer for early detection of postharvest fungal spoilage and storage contamination. The scheme links commodity and storage context, headspace signals, sensing platforms, data modelling, analytical outputs, and decision support actions along the postharvest chain.

objective is often to detect contamination trajectories at batch or storage level. Rice mildew monitoring by GC-IMS and chemometrics illustrates the use of peak selection and clustering for staging (Chen et al., 2021), while HS-GC-IMS studies in rice demonstrate early discrimination of fungal contamination and growth tracking linked to colony counts through regression modelling (Gu et al., 2022). In maize, HS-GC-IMS has been used for early warning of *Aspergillus* contamination and for exploring associations between VOC fingerprints and aflatoxin-related scenarios (Jiang et al., 2026; Li et al., 2021; Qin et al., 2024). In fruit systems, IMS-based fingerprints are used for early contamination monitoring in selected cases, including kiwifruit soft rot fingerprinting (Gao et al., 2025) and citrus sour rot progression when paired with HS-SPME-GC-MS (Li et al., 2025). The main advantage of IMS in this context is speed and fingerprint richness, while the main limitation is the need for consistent acquisition, alignment, and reporting if fingerprints are to be compared across settings.

HS-SPME-GC-MS and related GC-MS approaches are most useful for interpretation and marker discovery. These methods provide compound-level information that can explain why infected or contaminated samples separate from controls and can guide the selection of candidate markers for targeted sensors or simplified screening rules. This role is clear in citrus sour rot, where HS-SPME-GC-MS was used to profile temporal changes in VOCs while HS-GC-IMS provided rapid fingerprinting (Li et al., 2025). Marker-oriented studies in grape berries infected by *Botrytis cinerea* and peaches infected by *Monilinia fructicola* follow the same logic, with discriminant VOCs proposed as monitoring targets (Fanesi et al., 2023; Nepi et al., 2025). Studies on *P. expansum* further show that fungal VOCs production is affected by biological and environmental conditions. For example, styrene and other volatile compounds produced by *P. expansum* varied with pH and cultivation time, indicating that marker interpretation must account for the conditions under which fungal metabolism occurs (Kim et al., 2019; Wang et al., 2025). Broader GC-MS volatile profiling studies, including those assessing antifungal activity of plant-derived volatile fractions, are useful mainly as contextual evidence for volatile composition and fungal response rather than as direct early detection tools (Falasca et al., 2016). Overall, GC-MS-based designs are essential to avoid purely empirical classification, but they are less suited to routine monitoring when used as standalone platforms.

Fast MS approaches offer a complementary perspective by enabling non-destructive measurements with minimal or no preconcentration. In pears, selected ion flow tube mass spectrometry (SIFT-MS) on intact fruit supports discrimination of infected *versus* control fruit and explicitly shows the trade-off between fingerprint models and reduced marker models (Dizon et al., 2023). Proton transfer reaction mass spectrometry (PTR-MS) based studies in apple systems illustrate how high-frequency volatile monitoring can be used to link VOC dynamics with infection biology and with interaction effects between host volatiles and pathogen development (Neri et al., 2019). These studies are informative for defining what can be measured in real time and for identifying features that could be stabilised for operational monitoring.

Proxy sensing platforms address deployment constraints that are difficult to manage with laboratory instrumentation. Optical arrays can operate directly in packaged headspace and allow monitoring without opening the unit, which is relevant for citrus logistics and retail conditions (Cavallaro et al., 2024; Santonocito et al., 2026). Whole cell biosensors provide another proxy class, where reporter responses to VOC pattern shifts can detect infection before visible symptoms in citrus (Chalupowicz et al., 2020). These systems are relevant for practical integration, but their performance still needs to be tested across packaging formats, atmospheres, humidity levels, storage temperatures, and background microbiota.

3.4. Decision support use cases along the chain

The technical differences among platform families become operationally relevant when they are linked to specific decision points along the postharvest chain, from early sorting and batch prioritisation to storage monitoring and targeted confirmatory testing. Across the included studies, the most consistent and defensible role of VOC-based sensing is as a decision-support and risk-screening layer rather than as a standalone diagnostic system. Its value lies in the earlier recognition of suspect units or lots, the prioritisation of inspection or confirmatory testing, and the monitoring of deterioration trajectories during storage. The main use cases identified in the literature were rapid screening and triage, storage monitoring and early warning, contamination staging, and toxin-related risk prioritisation.

In fruit systems, the most common decision point was early segregation before symptoms became visible. Electronic nose studies on stone fruits infected by *M. laxa* illustrate this use case, since the objective was to discriminate incipient infection from healthy fruit during storage and to support removal or separation of suspect fruit before decay spread (Martínez et al., 2025a, Martínez et al., 2025c; 2025d). A similar logic was used in apple studies, where electronic nose or gas sensor systems were applied to detect early decay, estimate spoilage degree, or provide warning signals during storage. These outputs are directly relevant to sorting, batch inspection, and storage management rather than to definitive pathogen diagnosis (Guo et al., 2021; Martínez et al., 2025c; Yin et al., 2023). Overall, fruit-oriented studies converge on a similar operational objective: enabling earlier identification of suspect fruit or batches before visible decay becomes widespread and management options become more limited. Other fruit studies support the same use case through marker oriented profiling. In peaches infected by *M. fructicola*, VOC markers are proposed as targets for sensors that could flag infection early (Fanesi et al., 2023). In grape berries, VOC markers associated with *B. cinerea* infection on intact fruit support early screening concepts at harvest or prior to processing decisions (Nepi et al., 2025). In kiwifruit, electronic nose and chemometrics have been used to quantify and detect soft rot and *B. cinerea* infection, providing a monitoring-oriented use case linked to storage quality decline (Haghbin et al., 2023; Wang et al., 2023).

Packaging and closed formats introduce additional constraints that shift the decision point from unit sorting to headspace monitoring. Optical arrays operating in packaged citrus headspace support infection detection without opening units, which is compatible with logistics and retail constraints (Cavallaro et al., 2024). Similarly, biosensor approaches that respond to VOC pattern changes provide an operationally simple screening signal for *Penicillium digitatum* infection in citrus, with the aim of early warning before visible symptoms (Chalupowicz et al., 2020). In citrus sour rot, early contamination profiling over short time frames supports rapid warning during storage, with the potential to prioritise lots for intervention or further testing (Li et al., 2025).

Although fully validated commercial deployments were not identified in the reviewed literature, several studies provide prototype-oriented or commercial-like examples of how VOC-based outputs could support operational decisions. In fruit systems, electronic nose and gas sensor studies on apple, kiwifruit, and stone fruits translate headspace patterns into warning signals for early segregation, batch inspection, or storage management (Haghbin et al., 2023; Martínez et al., 2025a, Martínez et al., 2025c, 2025d; Wang et al., 2023; Yin et al., 2023). In packaged citrus, optical and fluorescent arrays illustrate a more logistics-compatible scenario, because measurements can be performed in closed or constrained headspace without opening the unit and can flag atypical fingerprints for confirmatory analysis (Cavallaro et al., 2024; Santonocito et al., 2026). In cereals and grains, GC-IMS, HS-GC-IMS, and sensor-array studies are closer to storage-decision workflows because they link volatile fingerprints to contamination staging, colony counts, or toxin-related risk, which can trigger targeted mycotoxin or microbiological testing (Chen et al., 2021; Gu et al., 2022; Jiang et al., 2022, 2026; Li et al., 2021). Overall, these examples support a triage and prioritisation role rather than autonomous regulatory or commercial release decisions.

In cereals and grains, the dominant use case was storage monitoring at batch, silo, or warehouse level. The operational objective is not only to detect fungal presence, but also to recognise contamination trajectories early enough to trigger actions such as segregation, drying or ventilation adjustment, intensified sampling, or confirmatory microbiological and mycotoxin testing. GC-IMS and HS-GC-IMS studies in rice and maize are representative of this use case, since they use volatile fingerprints to classify contamination stages or to follow fungal growth during storage (Chen et al., 2021; Gu et al., 2022; Liu et al., 2025; Zhang et al., 2022). Several studies further extend the decision support scope by connecting VOC-based signals to toxin-related endpoints. In maize, HS-GC-IMS studies discuss correlations between VOC signatures and aflatoxin B1, supporting a risk screening role for prioritising confirmatory testing (Li et al., 2021). Complementary sensor array approaches provide toxin-oriented prediction models for aflatoxin B1 in wheat and for mycotoxin contaminated maize, illustrating how screening devices can be calibrated to endpoints directly relevant for lot acceptance and segregation (Jiang et al., 2022; Qu et al., 2024). More generally, multimodal frameworks that integrate orthogonal sensing channels and provide explainable outputs strengthen the decision support argument because they map signals to actionable variables rather than only class labels (Jiang et al., 2026).

To clarify the comparative strengths and limitations of the main platform families, Table 2 provides a qualitative comparison of detection capability, analysis time, cost level, portability, ease of operation, sensitivity to environmental factors, and indicative deployment readiness based on the reviewed evidence.

Overall, the most realistic implementation pathway is a tiered workflow. A rapid VOC-based measurement can flag suspect units, packages, or lots, while confirmatory analyses can be applied selectively according to the risk level and the decision point. This framing is consistent with the current evidence base, which is strongest for screening, early warning, and prioritisation, and weaker for standalone diagnosis or species-level attribution. The qualitative relationship between sensing platforms and decision support use cases is summarised in Fig. 3.

3.5. Validation and performance reporting

Across the included studies, performance is mainly reported through supervised classification and, less often, through regression linked to operational endpoints. Reported metrics varied among studies and included accuracy, classification rate, sensitivity, specificity, confusion matrices, correlation coefficients, and prediction errors, depending on the platform and endpoint. Most datasets were generated under controlled inoculation and fixed storage conditions. This design is appropriate to isolate infection-associated signals, but it may overestimate model performance relative to real postharvest and storage variability. According to the evidence-coding matrix reported in Supplementary Tables S4 and 57 records were classified as primary detection or monitoring studies for validation coding. Internal or model-based validation dominated the evidence base: 39 records (68%) used cross-validation, train-test splitting, or prediction-set validation within controlled datasets, and 3 records (5%) reported prototype-oriented internal validation. Fourteen records (25%) were mainly analytical marker-discovery or method-development studies and did not provide predictive deployment validation. Only 1 record (2%) explicitly addressed independent cultivar or variety transferability, while no study clearly demonstrated full external multi-site validation. One additional study tested a realistic packaged or constrained headspace format, but this was not considered external validation. These results support the conclusion that transferability across independent lots, cultivars, storage regimes, instruments, or sites remains the main constraint for decision-support claims.

For sensor arrays and electronic nose systems, the dominant task is classification of sound versus infected samples, sometimes extended to staging by time after inoculation or to prediction of spoilage degree. Linear discriminant analysis and related discriminant methods are common in fruit studies, including *M. laxa* in stone fruits and *P. expansum* in apple (Martínez et al., 2025a, Martínez et al., 2025b; 2025c; 2025d). Neural networks and other machine learning methods are widely used when the goal is early warning at batch level or when multi-sensor inputs are available. This includes apple storage monitoring using gas sensors and chemometrics, and kiwifruit monitoring where odour features are linked to classification and prediction of quality indices (Haghbin et al., 2023; Wang et al., 2023; Yin et al., 2023). These studies illustrate the broader pattern identified in the evidence coding: model performance is often supported by internal validation, whereas transferability across independent batches, cultivars, storage regimes, instruments, or sites remains insufficiently tested.

In grain scenarios, validation frameworks are often closer to decision support because several studies anchor VOC-based outputs to quantitative endpoints. HS-GC-IMS and GC-IMS studies repeatedly link fingerprints to contamination staging, colony counts, or toxin related endpoints. In rice, HS-GC-IMS is used for early discrimination and growth tracking with regression models linked to colony counts, which

Table 2
Comparative overview of VOC-based sensing and analytical platform families reviewed in this study.

Platform family	Main strengths	Main limitations	Portability	Relative cost	Indicative deployment readiness
Electronic noses and gas sensor arrays	Rapid pattern-based screening; suitable for routine monitoring	Sensor drift, humidity and temperature effects, limited chemical specificity	Medium to high	Low to medium	Moderate for screening; limited by calibration transfer and external validation
GC-MS and HS-SPME-GC-MS	High chemical specificity; marker discovery; reference VOC profiling	Laboratory-based; slower; requires trained personnel	Low	High	High for reference analysis; low for onsite routine screening
GC-IMS and HS-GC-IMS	Fast volatile fingerprinting; useful for classification and storage monitoring	Instrument-specific fingerprints; matrix and humidity effects	Low to medium	Medium to high	Moderate; promising but still validation-dependent
Fast MS or IMS-based profiling	Rapid high-throughput fingerprinting	Specialised instrumentation; limited direct chemical interpretation	Low to medium	High	Low to moderate; mainly controlled or laboratory evidence
Optical, colorimetric, and fluorescent arrays	Portable formats; low-cost imaging; non-destructive headspace screening	Prototype-oriented; sensitive to imaging and exposure conditions	Medium to high	Low to medium	Low to moderate; promising for portable screening
Biosensor or proxy-sensing approaches	Targeted or proxy detection; potentially simple formats	Application-specific; needs stronger endpoint validation	Medium to high	Low to medium	Low to moderate; evidence remains limited
Mixed non-destructive sensing approaches	Integration of complementary signals; decision-support potential	Greater modelling complexity; limited external validation	Medium	Medium to high	Low to moderate; promising but still exploratory

Note: Indicative deployment readiness was assigned qualitatively on the basis of the reviewed evidence and should not be interpreted as a formal Technology Readiness Level (TRL). A formal TRL assignment was not possible because most studies did not report harmonised information on field validation, commercial deployment, regulatory use, cost structure, or long-term operational performance.

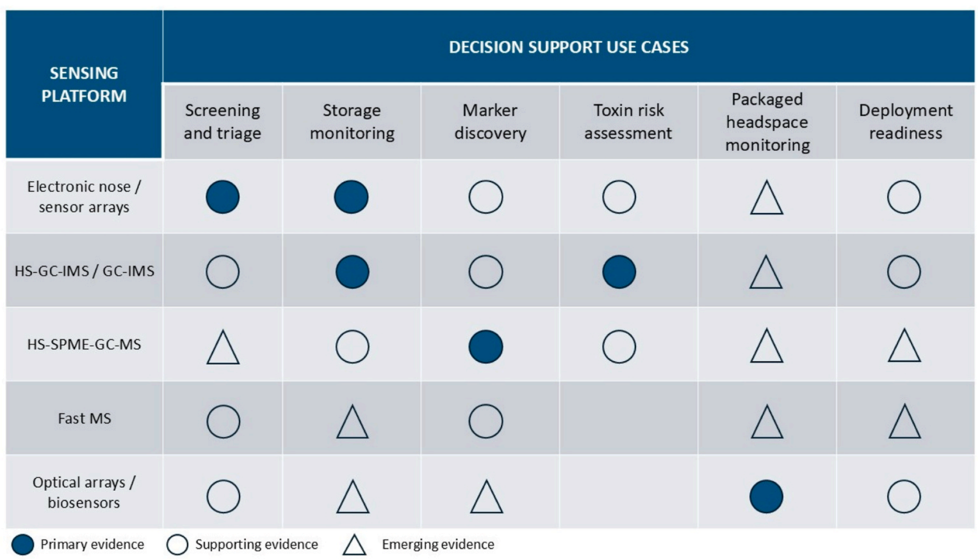

Fig. 3. Platform–use case map for VOC-based sensing in postharvest fungal spoilage and storage contamination. The matrix provides a qualitative synthesis of the main operational roles of each sensing approach across screening, storage monitoring, marker discovery, toxin risk assessment, packaged headspace monitoring, and deployment readiness. Symbols indicate the relative level of support emerging from the reviewed literature and do not represent numerical counts.

provides a stronger basis for operational thresholding than simple classification labels (Gu et al., 2022). In maize, HS-GC-IMS is used for early warning of *Aspergillus* contamination and for exploring correlations between VOC signals and aflatoxin related scenarios, which supports a risk screening role when combined with confirmatory testing strategies (Li et al., 2021; Qin et al., 2024). In wheat and maize, sensor array studies explicitly target aflatoxin or mycotoxin-related outcomes, including colourimetric arrays and artificial olfactory sensors, which makes the validation target directly relevant for lot acceptance and segregation decisions (Jiang et al., 2022, 2026; Qu et al., 2024).

Platform-specific limitations shape how performance should be interpreted. For sensor arrays, humidity and sensor drift are recurrent issues. Studies that address these constraints explicitly, either through sensor design and feature engineering or through modelling strategies, provide a more realistic picture of field feasibility. This is clear in quartz crystal microbalance (QCM)-based approaches designed to discriminate or quantify mouldy wheat while accounting for moisture effects, and in prototype monitoring systems for storage environments where temperature and humidity are integrated with gas sensor arrays (Hou et al., 2025, 2026; Yin et al., 2023). For IMS-based pipelines, reproducibility depends on acquisition settings, alignment procedures, and reporting of pre-processing. Studies using clustering and staging approaches are useful for early warning, but cross-instrument comparability remains a key barrier unless acquisition and reporting are standardised (Chen et al., 2021; Liu et al., 2025; Zhang et al., 2022).

Another important validation issue concerns attribution. Many studies can separate infected from non-infected samples, but fewer demonstrate that the discriminant signal is specific to pathogen activity rather than generic deterioration. This is why studies combining screening platforms with HS-SPME-GC-MS or mechanistic volatile profiling are valuable. They support interpretation, help identify candidate markers, and reduce the risk that models are dominated by confounders such as ripening, wounding, or anaerobic microenvironments. Examples include citrus sour rot where HS-SPME-GC-MS supports temporal profiling alongside IMS fingerprints, and pear infection studies where SIFT-MS is compared with GC-MS and fingerprint models are contrasted with reduced marker panels (Dizon et al., 2023; Li et al., 2025). Marker-oriented studies provide further support for translation, including VOC markers for *B. cinerea* infection in intact grape berries, *M. fructicola* infection in peaches, *Cadophora luteo-olivacea* presence on kiwifruit, and selected marker sets for specific apple rot syndromes (Di Francesco et al., 2024; Fanesi et al., 2023; Holthusen et al., 2025; Nepi et al., 2025). Mechanistic work on apple VOC interactions with latent pathogens adds important context because it links VOC dynamics to infection biology rather than only to classification performance (Neri et al., 2019). This point is particularly relevant for early detection claims, where the discriminant signal may be weaker and more easily affected by ripening, wounding, hypoxia, or storage stress.

Overall, the current evidence supports feasibility under controlled conditions and provides multiple proofs of concept across commodities and platforms. The main limitation is not the absence of measurable VOC signals, but the limited demonstration of transferability across realistic storage and supply-chain variability. Studies that integrate quantitative endpoints, multi-sensor fusion, independent validation, and interpretable outputs provide the strongest basis for deployment-oriented validation (Gu et al., 2022; Guo et al., 2025; Jiang et al., 2026).

4. Discussion

4.1. Strength of evidence and main limitations

Overall, the reviewed literature provides consistent evidence that fungal spoilage and contamination can generate measurable and exploitable changes in volatile profiles across different postharvest systems and storage conditions. Evidence strength varies substantially across platforms and study designs. For clarity, the main limitations can be grouped into methodological limitations, which relate to study design, validation strategy, endpoint definition, and confounder control, and technological limitations, which relate to platform stability, sampling standardisation, calibration transfer, instrument comparability, and operational integration. From a methodological perspective, the dominant study design remains proof of concept. Most datasets are generated under controlled inoculation, fixed storage regimes, and limited cultivar or lot diversity. This is appropriate to isolate infection-associated signals, but it can overestimate performance relative to operational contexts where headspace is influenced by cultivar, maturity stage, mechanical damage, background microbiota, and mixed infections. Multi pathogen designs exist and show feasibility for classification, but they are still typically based on controlled inoculation and short windows (Guo et al., 2021; Pan et al., 2014). A practical implication is that accuracy values reported under controlled conditions cannot be interpreted as readiness for deployment without additional validation across independent lots and conditions.

A related methodological limitation is the risk of confounding infection signatures with general physiological deterioration. In fruit, fermentation related shifts, particularly ethanol and related esters, can appear due to multiple causes, including senescence, anaerobic microenvironments, or wounding. Studies that integrate analytical profiling with sensor outputs help to interpret which chemical changes are infection associated and which are generic spoilage signals (Dizon et al., 2023; Li et al., 2025; Wang et al., 2023). Without this interpretative link, predictive models risk being driven by variables that correlate with ripening, storage stress, or time progression rather than by pathogen-specific activity. This issue becomes more relevant when the decision support target is “incipient infection” rather than “advanced decay,” because the early phase has smaller effect sizes and is more sensitive to background variability.

From a technological perspective, transferability and stability are also central constraints. Sensor arrays are sensitive to humidity, temperature, and drift. Several studies attempt to improve robustness through feature selection, multi-sensor fusion, or device-oriented calibration strategies (Hou et al., 2025, 2026; Yin et al., 2023). However, external validation across batches and environments is still uncommon. For GC-IMS and HS-GC-IMS, fingerprint comparability depends on instrument settings, alignment procedures, and sample handling. When fingerprints are used for staging and clustering, reproducibility across instruments and laboratories becomes a limiting factor unless acquisition and reporting are standardised (Chen et al., 2021; Gu et al., 2022; Liu et al., 2025). This is one reason why studies combining IMS with HS-SPME-GC-MS are valuable. They support interpretability and help define candidate marker features that may generalize better than instrument specific fingerprints (Li et al., 2025).

The strength of evidence increases when VOC-based signals are anchored to quantitative endpoints that relate to risk or decision thresholds. In grains, several studies link volatile fingerprints to colony counts and to aflatoxin-related scenarios, which moves the output closer to actionable risk assessment (Gu et al., 2022; Li et al., 2021). Multimodal designs that predict fungal contamination and aflatoxin B1 simultaneously provide a stronger validation frame because the endpoint is directly relevant to acceptance and segregation decisions (Jiang et al., 2026). In fruit systems, endpoints are more often infection class, time after inoculation, lesion presence, or quality indices, which are useful but do not always translate into explicit operational thresholds. An important gap is that only a minority of studies define decision thresholds aligned with costs of false positives and false negatives in real sorting or storage scenarios.

Finally, proxy sensing systems that operate under packaging constraints are promising, but they introduce additional sources of variability. Closed headspace depends on packaging format, gas exchange, humidity, and temperature. Optical array sensing in packaged citrus illustrates feasibility in a realistic format (Cavallaro et al., 2024), but broader generalisation across packaging types and logistics conditions remains to be demonstrated. Whole-cell biosensors offer early detection potential in citrus, yet performance and stability under variable storage and microbiological backgrounds remain key issues for adoption (Chalupowicz et al., 2020).

A further review-level limitation concerns bibliographic and language coverage. The search was restricted to Scopus, and relevant studies indexed only in other databases may not have been retrieved. Scopus was selected because of its interdisciplinary coverage of food science, postharvest technology, analytical chemistry, sensor development, and engineering. The use of two complementary queries was intended to reduce the risk of missing relevant VOC-based and sensor-based studies within the selected database. In addition, the restriction to English-language full texts may have introduced language bias, particularly because research on postharvest technology, fungal spoilage, and VOC-based sensing is active in several non-English-speaking countries. Therefore, the findings should be interpreted as a structured synthesis of Scopus-indexed, English-language evidence rather than as an exhaustive mapping of all published literature on VOC-based sensing for postharvest fungal spoilage and storage contamination.Taken together, these methodological and technological limitations indicate that the current evidence supports feasibility under controlled conditions and provides multiple proofs of concept across commodities and platforms. The main limitations are limited external validation, incomplete characterisation of confounders, and insufficient reporting of deployment-relevant robustness. These limitations define the main conditions that should be addressed before VOC-based sensing can be transferred from controlled studies to routine monitoring.

4.2. Implications for food control and postharvest decision support

Overall, the reviewed studies support a practical interpretation of VOC-based sensing as an early-warning, screening, and prioritisation layer rather than as a standalone diagnostic tool. A practical workflow is therefore two-stage: a rapid VOC-based screen to flag suspect units or lots, followed by confirmatory testing when required. This structure is consistent with the strongest use cases in both fruit systems and grains, where the key value is earlier risk recognition and prioritisation rather than definitive identification of the causal agent (Chen et al., 2021; Gu et al., 2022; Martínez et al., 2025d; Yin et al., 2023).

Decision points, endpoint anchoring, and confirmatory testing. Studies with the clearest operational framing start from a decision point and then choose the platform accordingly. For fruit, this often means early segregation before visible symptoms, either at sorting or during storage handling, where non-destructive electronic nose systems are appropriate (Martínez et al., 2025c, Martínez et al., 2025c). For grains, the decision point is typically storage monitoring at batch or silo level, where HS-GC-IMS or GC-IMS fingerprints provide rapid warning signals and allow staging of contamination (Chen et al., 2021; Li et al., 2021). For packaged formats, proxy systems such as optical arrays are attractive because they operate without opening units and can be integrated into logistics constraints (Cavallaro et al., 2024).

Decision support becomes more defensible when VOC-based signals are linked to quantitative reference endpoints. In grains, models tied to colony counts and aflatoxin-related scenarios are closer to acceptance and segregation decisions than models that only classify "mouldy *versus* non mouldy" samples (Gu et al., 2022; Jiang et al., 2026; Li et al., 2021). Where mycotoxin measurements are not feasible for every sample, VOC-based tools can be positioned as a risk screen that triggers targeted confirmatory testing. In fruits, pairing sensor outputs with lesion development indices, firmness changes, or quantified decay progression improves the interpretation of early-warning claims and supports thresholding strategies for sorting (Haghbin et al., 2023; Wang et al., 2023).

Fingerprint versus marker strategies and interpretability. From a decision-support perspective, several studies suggest that broad fingerprints often provide more robust discrimination than reduced marker panels, particularly when infection effects overlap with ripening or storage-related processes. In pears, fingerprint-based models built from a wider range of product ions improved discrimination compared with models restricted to a small set of identified compounds (Dizon et al., 2023). In rice and maize, three-dimensional IMS fingerprints support early classification and growth tracking even when individual compounds vary in concentration (Gu et al., 2022; Liu et al., 2025). Marker discovery remains important, but it should be treated as a bridge to future targeted sensors rather than as the default monitoring strategy in complex real-world matrices (Fanesi et al., 2023; Nepi et al., 2025).

Reporting, validation, and integration into routine monitoring. A recurrent limitation across the reviewed literature is the incomplete standardisation and reporting of acquisition and headspace conditions, which directly affects reproducibility and transferability across studies and operational settings. Across platforms, headspace composition is strongly influenced by sample temperature, storage atmosphere, packaging state, headspace volume, incubation time, and humidity. These factors should be controlled when possible and reported systematically. This is particularly critical for sensor arrays, where humidity sensitivity and drift can undermine transferability. Studies that explicitly address humidity interference in sensor design or modelling provide useful examples of deployment-oriented development (Hou et al., 2025, 2026). For IMS-based workflows, reproducibility depends on instrument settings and alignment procedures. Reporting of acquisition parameters and pre-processing steps is therefore essential to allow comparison across studies and to support multi-site validation (Chen et al., 2021; Gu et al., 2022).

Internal validation is informative for proof of concept, but decision support requires evidence that models generalize across batches, cultivars, seasons, and storage conditions. Practical validation should therefore include independent lots and realistic variability in maturity and handling. When this is not feasible, the limitation should be stated and the workflow positioned as screening within the calibration domain. Designs that integrate multiple sensors, fuse data sources, and deploy models on embedded systems are promising because they provide a pathway from laboratory models to operational monitoring prototypes (Guo et al., 2025; Yin et al., 2023).

The most realistic deployment scenario is not the replacement of existing control systems, but their augmentation. VOC-based monitoring can reduce sampling burden by focusing confirmatory testing on flagged units or lots. In fruit systems, this aligns with sorting and storage monitoring workflows. In grains, it aligns with early warning in silos and warehouse environments, where rapid screening can trigger targeted sampling for mycotoxins and microbiology (Jiang et al., 2022, 2026; Li et al., 2021).

This interpretation follows from the validation pattern quantified in Section 3.5 and Supplementary Table S4. Most primary detection or monitoring studies relied on internal or model-based validation, whereas full external multi-site validation was not clearly demonstrated. For this reason, VOC-based sensing is best interpreted at present as a triage, prioritisation, and early-warning layer rather than as a standalone regulatory or commercial release tool.

Economic feasibility will depend on the intended decision point, commodity value, batch size, and the balance between screening costs and the consequences of missed or unnecessary interventions. The main cost drivers include instrument acquisition, consumables, calibration and drift management, maintenance, operator training, data handling, and confirmatory testing after positive screens. Potential benefits include earlier segregation of suspect fruit, reduced spread of decay during storage, targeted rather than routine confirmatory analyses, reduced destructive sampling, improved stock rotation, and better prioritisation of lots for mycotoxin testing. This interpretation is consistent with the broader use of non-destructive technologies and electronic noses as rapid screening tools for food quality and safety applications (El-Mesery et al., 2019; Sanislav et al., 2025). For low-margin or high-throughput chains, low-cost sensor arrays, electronic noses, and optical or smartphone-read formats are more plausible as frontline screening tools, whereas GC-MS remains more appropriate for reference confirmation and marker discovery (Santonocito et al., 2026). From a cost-benefit perspective, the most realistic adoption scenario is therefore not replacement of microbiological or chemical testing, but a two-stage strategy in which rapid VOC-based screening reduces the number of lots requiring confirmatory analysis. The economic balance will depend on contamination prevalence, batch value, the costs of false positives and false negatives, and the ability of the method to maintain sensitivity under operational variability.

4.3. *Research gaps and priorities*

Despite the breadth of the included literature, several gaps limit translation from proof of concept to routine monitoring. Overall, the identified gaps are less related to the absence of detectable VOC signals and more related to robustness, standardisation, transferability, and operational validation under realistic postharvest conditions. These gaps are not uniform across platforms. They reflect recurring issues in study design, reporting, and validation, and they define clear priorities for the next phase of research. To make these priorities actionable, they can be organised into a staged roadmap. In the short term, research should focus on harmonised reporting, clearer definition of decision points, explicit control of confounders, and validation against quantitative endpoints such as colony counts, lesion development, spoilage degree, or mycotoxin-related measurements. In the medium term, priority should be given to independent validation across lots, cultivars, seasons, storage regimes, instruments, and laboratories, together with calibration transfer, drift correction, and decision thresholds linked to false-positive and false-negative consequences. In the long term, VOC-based sensing should be tested in integrated postharvest workflows, including sorting lines, storage facilities, packaged commodities, silos, and warehouse environments, where outputs can be connected to confirmatory testing, regulatory monitoring, stock rotation, and lot destination decisions.

External validation and variability. Most studies rely on controlled inoculation, fixed storage regimes, and limited cultivar or lot diversity. This design is appropriate for signal discovery, but it does not quantify how robust models are under operational variability. The key priority is external validation across independent batches, cultivars, seasons, and storage facilities. For fruit systems, variability in maturity, mechanical damage, mixed infections, and storage atmospheres should be explicitly represented. For grains, variability across warehouses, silos, moisture content, and background microbiota is critical. Without this level of validation, reported accuracies and regression metrics remain strongly context-dependent and may overstate real-word deployment readiness (Gu et al., 2022; Martínez et al., 2025d; Yin et al., 2023).

Confounders and attribution. A major risk is that models discriminate generic physiological deterioration rather than infection. In fruits, fermentation related volatiles can increase due to senescence, hypoxia, or wounding, and may not be pathogen specific. In grains, moisture driven changes can reshape headspace profiles even without active fungal growth. Priority should be given to designs that explicitly separate pathogen effects from time, ripening stage, and storage stress, and that report control experiments addressing these confounders. Studies integrating sensor outputs with chromatographic profiling help address attribution and should be used as a benchmark for more defensible modelling pipelines (Dizon et al., 2023; Li et al., 2025; Wang et al., 2023).

Standardised reporting. Cross study comparison is currently limited by incomplete reporting of sampling conditions and preprocessing. For sensor arrays, humidity management, sensor drift, calibration routines, and headspace sampling protocols are often under described. For IMS-based workflows, acquisition parameters, alignment procedures, and feature selection steps are not always reported in a way that allows replication. A priority is to adopt minimum reporting requirements specific to VOC-based sensing in postharvest contexts, including sample temperature, headspace volume, incubation time, humidity, storage atmosphere, and model training and test partitioning. Reviews in the field repeatedly highlight the need for harmonisation, but implementation remains inconsistent (Ali et al., 2023; Sun et al., 2025).

Decision thresholds and cost sensitive metrics. Many studies report accuracy or correlation coefficients without defining the intended decision threshold and the consequences of false positives and false negatives. This limits operational interpretation. Priority should be given to reporting frameworks that include sensitivity and specificity at defined thresholds, confidence intervals, and performance under class imbalance. For screening applications, high sensitivity may be more valuable than overall accuracy, while for lot acceptance decisions, false positives have direct economic costs. Linking VOC-based outputs to specific decision points and costs will improve the relevance of models for decision support (Chen et al., 2021; Jiang et al., 2026).

Calibration transfer and drift. Sensor arrays can drift, and headspace conditions can vary widely in storage environments. Several studies propose feature selection, multi-sensor fusion, and robust sensor design to mitigate these issues, but systematic long-term stability tests are rare. For IMS and MS based platforms, comparability across instruments and laboratories remains a barrier. Priority should be given to calibration transfer protocols, drift monitoring procedures, and multisite intercomparison studies, with shared reference materials or shared benchmark datasets where feasible (Gu et al., 2022; Hou et al., 2025, 2026).

Packaged and constrained environments. Packaged fruit and closed storage units introduce distinct constraints related to gas exchange, humidity, and headspace dynamics. Optical arrays and biosensors provide promising directions because they can operate in packaged headspace, but broader generalisation across packaging types and logistics conditions is still limited. Priority should be given to studies that test multiple packaging formats and storage atmospheres and that quantify how these factors affect false positive rates and detection windows (Cavallaro et al., 2024; Chalupowicz et al., 2020).

Data availability and comparability. Most datasets are not openly available, and modelling choices vary widely, which slows convergence towards robust pipelines. Priority should be given to sharing curated datasets with clear metadata and to reporting modelling pipelines in sufficient detail to enable reproduction. Where data sharing is not feasible, structured data extraction tables in supplementary materials can still improve comparability across studies (Ali et al., 2023; Sun et al., 2025).

Overall priority framework. Short term, the most impactful steps are standardised reporting, external validation, and explicit linkage between model outputs and decision thresholds. Medium term, calibration transfer, drift management, and multi-site benchmarking will be decisive for deployment. Long term, integration of VOC-based sensing into routine monitoring workflows will require economic assessment, user-oriented interfaces, and validated protocols tailored to specific decision points.

5. Conclusions

The reviewed evidence indicates that VOC-based sensing can support early detection and monitoring of postharvest fungal spoilage and storage contamination in fruit systems and cereals or grains. The reviewed studies show that infection and contamination are often associated with measurable changes in volatile signatures, especially under controlled experimental conditions. Electronic nose systems and sensor arrays are mainly suited to rapid screening and triage, while GC-IMS and HS-GC-IMS provide rapid fingerprints for storage monitoring and contamination staging. HS-SPME-GC-MS remains important for marker discovery and interpretation, whereas fast MS, optical arrays, and biosensor-based approaches address more specific deployment needs.

The most defensible implementation scenario is a tiered workflow. VOC-based screening can flag suspect units, packages, or lots, while confirmatory microbiological, chemical, or mycotoxin analyses can be applied selectively according to the decision point and risk level. In this context, VOC-based sensing should be considered a decision support layer rather than a standalone diagnostic method.

The main barriers to routine implementation are limited external validation, incomplete control of biological and storage-related confounders, sensor drift, and insufficient standardisation of sampling and reporting. Future studies should prioritise multi-lot and multi-site validation, quantitative endpoint anchoring, calibration transfer, and decision thresholds linked to operational food control actions.

From a technology-readiness perspective, the current evidence is strongest for laboratory reference profiling, marker discovery, and prototype-level screening under controlled or semi-controlled conditions. Near-term adoption is therefore most plausible as a complementary screening and triage layer, particularly for prioritising suspect lots, packages, or storage units for confirmatory microbiological or chemical testing. Medium-term progress will require independent validation across lots, cultivars, seasons, storage conditions, instruments, and sites, together with calibration transfer and operational decision thresholds. Routine commercial or regulatory use as a standalone decision tool should be considered a longer-term objective, dependent on robust external validation, standardised workflows, cost-benefit evidence, and integration with existing food control systems.

Overall, these findings link the objectives of the review to three main stakeholder needs. For researchers, the priority is to move from platform-specific proof-of-concept studies toward harmonised validation, transferable models, and quantitative endpoint anchoring. For industry, the near-term value of VOC-based sensing lies in rapid triage, lot prioritisation, storage monitoring, and targeted confirmatory testing rather than replacement of existing control systems. For regulatory and food-control stakeholders, VOC-based sensing may support risk-based sampling and early-warning workflows, but only when outputs are validated against accepted microbiological, chemical, or mycotoxin-related endpoints.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

CRediT authorship contribution statement

Mario Riolo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alessandra Di Francesco:** Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing. **Marco Camardo Leggieri:** Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2026.112459.

Data availability

No data was used for the research described in the article.

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