Commercialization Strategy for INL's VOC Sensor

Executive Summary

The monitoring of Volatile Organic Compounds (VOCs), particularly high-molecular-weight VOCs (HMW-VOCs), is crucial for industries due to their environmental and health impacts. Traditional methods like Gas Chromatography–Mass Spectrometry (GC-MS) offer precise compound identification but are unsuitable for real-time, continuous monitoring. In contrast, Photoionization Detection (PID) systems enable quick detection but lack the specificity needed for compound-level analysis. Addressing this challenge, researchers at INL have developed a novel photoionization-based sensor capable of real-time monitoring and selective identification of HMW-VOCs such as benzene, toluene, ethylbenzene, and xylene (BTEX), bridging the gap between existing technologies. This innovation offers a scalable, efficient, and industry-focused solution to meet the growing demand for precise VOC monitoring in various sectors.

1.1 Recommendations

Based on the technological advancements and market opportunities, this report argues that adopting an integrated strategy that combines four critical features—**shortened sampling cycles**, **automated data analysis**, **portable device design**, and **humidity resistance**—into a unified solution to address cross-industry demands and challenges in both wine production and medical diagnostics. By reducing the sensor sampling intervals to under five minutes, real-time insights can be delivered to support dynamic decision-making. This applies to optimizing fermentation processes in wineries through monitoring terpenes and lignin-derived compounds, as well as enabling rapid breath analysis for early detection of biomarkers such as hexanal and nonanal in medical settings. Equally important is the automated data analysis capability. Whether through detachable computing modules or integrated cloud platforms, AI-driven algorithms for automated VOC pattern recognition can significantly reduce reliance on manual interpretation and specialized personnel, lowering operational costs. This allows industries to transform raw data into actionable insights with unprecedented efficiency—for example, adjusting brewing environments and parameters in real time to achieve desired wine flavor profiles or swiftly identifying disease risks.

Third, to ensure operational versatility, the sensor's compact and portable design must prioritize seamless integration into diverse environments, from cramped wine cellars to point-of-care clinics, enabling deployment in resource-limited or space-constrained settings while facilitating ease of use. We recommend encapsulating the sensor core module and adopting a modular design for other components to eliminate unnecessary parts and enhance integration. Simultaneously, addressing humidity interference through advanced hydrophobic coatings or modular architectures is critical for maintaining accuracy in moisture-heavy environments common to both industries, such as barrel aging rooms or breath-collection settings. By incorporating these four features, reliability is enhanced, and downtime is minimized—a vital consideration for industries where precision and compliance are non-negotiable.

From a commercialization perspective, we propose positioning the sensor as a multi-functional platform capable of addressing high-value use cases in wine quality optimization and rapid medical diagnostics. Establishing strategic partnerships with wine analytics companies and medical device manufacturers could accelerate adoption by embedding the technology into existing workflows. Tiered pricing models—premium versions for R&D-driven applications and standardized units for regulatory compliance—would cater to diverse budgetary needs. Proactive collaboration with regulatory bodies to align the sensor's capabilities with evolving standards, such as EU emissions directives or FDA diagnostic guidelines, would further solidify INL's leadership in VOC monitoring. By unifying these features into a cohesive offering, INL can establish its sensor as an indispensable tool that bridges precision, scalability, and adaptability across industries poised for exponential growth.

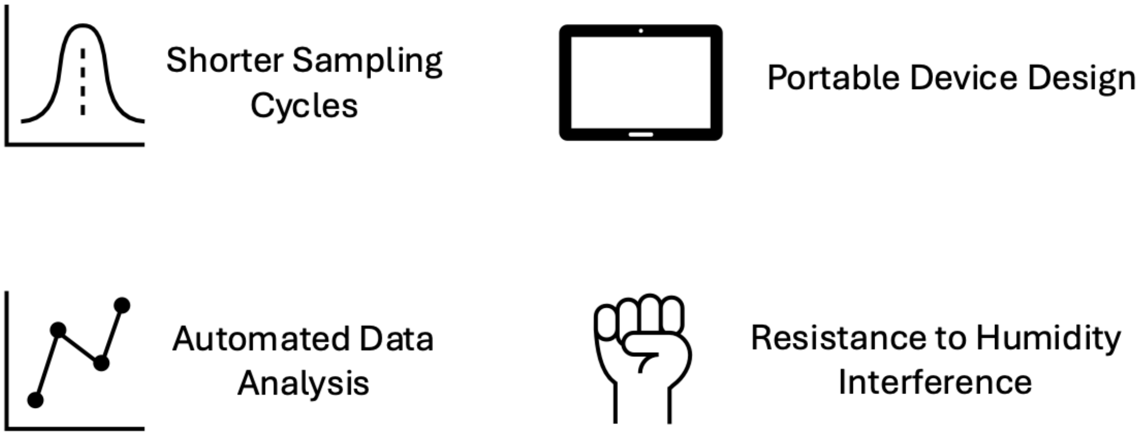


Fig. Key features of INL's VOC sensor: shorter sampling cycles, portable device design, automated data analysis, and resistance to humidity interference.

Introduction and Background

The ubiquity of VOCs, especially heavier hydrocarbons and aromatic compounds, in diverse industrial operations—from petrochemicals and adhesives to the printing, pesticide, and pharmaceutical sectors—underscores the vital importance of accurate and timely detection[8] Traditionally, organizations have relied on GC-MS for thorough compound-level analysis, yet the inherent time delays and the necessity for skilled laboratory operations often make this method impractical for continuous monitoring on production lines[9]. Conversely, simpler PID devices, while more user-friendly and suited to real-time measurement, generally lack the resolution needed to identify specific compounds and focus instead on total VOC loads [10].

This dichotomy has generated a demand for a single, consolidated tool that can detect a broad range of HMW-VOCs in real time, ensuring that operators receive immediate warnings when critical thresholds are approached or exceeded[11].
While this technology excels in selectivity and accuracy, its inherent time delays and the requirement for skilled laboratory operations make it unsuitable for continuous monitoring on production lines [12][13]. In contrast, PID devices offer the advantage of real-time measurement but lack the resolution needed to identify specific compounds and focus instead

on total VOC concentrations [14].
The need for real-time, compound-specific monitoring has become increasingly urgent in industrial environments. Timely detection of high-molecular-weight VOCs not only helps industries comply with stringent environmental regulations but also protects worker health and mitigates risks associated with undetected emissions [15].

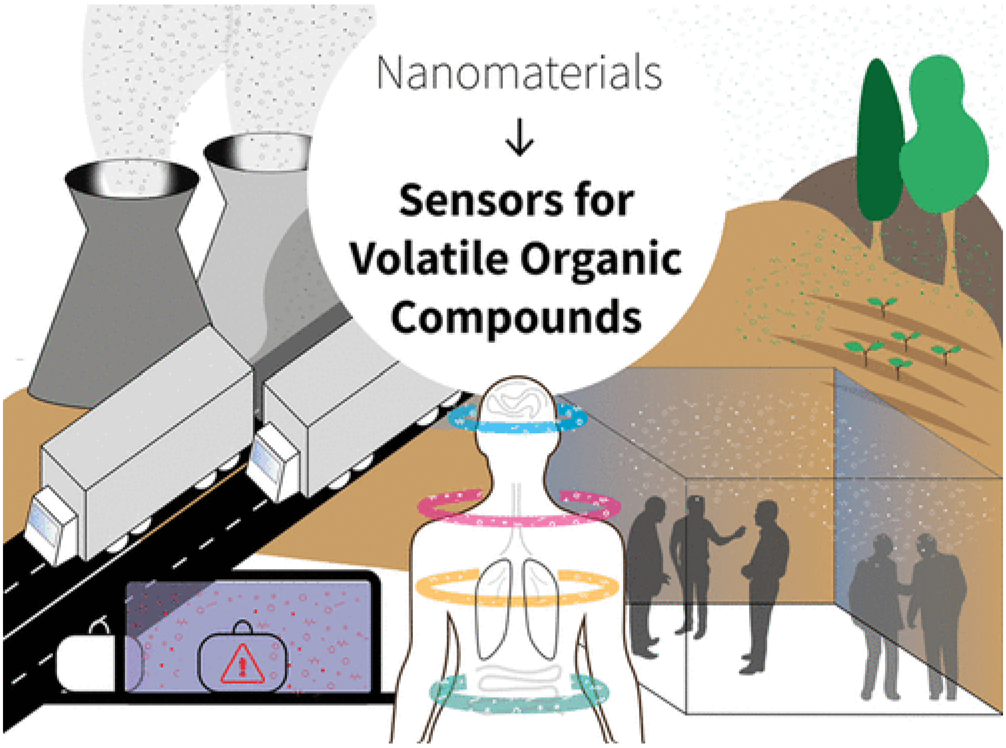


Figure 1. Visual Representation of Volatile Organic Compounds [16]

INL's solution combines a specialized photoionization source, and a proprietary detection module designed to identify specific HMW-VOCs rather than merely registering total organic content. Housed within a 90 × 60 × 30 cm enclosure weighing approximately 40 kilograms, the system offers a balance between ruggedized construction for industrial environments and manageable dimensions that allow for semi-mobile or fixed-site monitoring.
In response to INL researchers' request for *identifying high-value industry applications and strategic development priorities for their novel VOC sensor technology*, this report *analyzes market opportunities, evaluates sector-specific requirements, and provides actionable recommendations to align the device's capabilities with the needs of the medical diagnostics and food & beverage industries. The following sections offer:*

1. **Analysis of Industry Applicability**: A focus on wine production and medical diagnostics as the most promising sectors.
2. **Competitive Differentiation**: A comparison of INL's sensor with existing technologies (e.g., GC-MS, PID) in terms of speed, selectivity, and operational adaptability.
3. **Technical and Design Requirements**: Key features such as rapid sampling cycles, humidity resistance, portability, and automated analytics.
4. **Commercialization Strategies**: Partnerships, pricing models, and regulatory alignment to accelerate market adoption.

Market Analysis

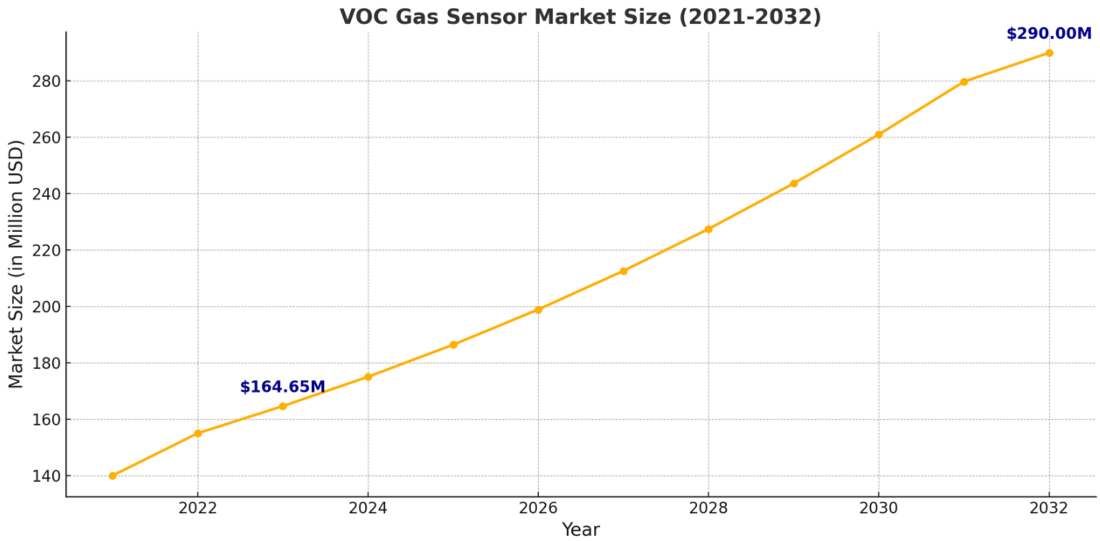


Fig. Projected growth of the VOC gas sensor market

1.2 Market Growth and Industry Demand for VOC Sensors

The global market for VOC gas sensors is experiencing significant growth, driven by stringent environmental regulations, rising awareness of air quality, and advancements in sensor technologies [17][18][19]. VOC detection tools, particularly those capable of identifying high-molecular-weight compounds such as benzene, acetone, and ethanol, are increasingly adopted across industries like oil and gas, automotive, and manufacturing to ensure safety, monitor emissions, and comply with environmental standards [20][21]. According to market reports, the VOC gas sensor industry was valued at approximately USD 141.7 million in 2018 and is projected to grow at a compound annual growth rate (CAGR) of 4–7% through 2030, reaching an estimated USD 290 million by 2030[22][23][24].

Considering the rising momentum for real-time emissions tracking—driven by stronger worker protection mandates and tight environmental standards—the addressable market for advanced VOC detection tools spans diverse sectors ranging from chemical manufacturing and petrochemicals to automotive painting, printing processes, adhesive formulation, food processing, pharmaceutical production, and pesticide development [25][26][27]. Each of these sectors increasingly demands specialized instrumentation that can both rapidly identify hazardous emissions and provide ongoing compliance assurances.

INL researchers have designed their system with a focus on industrial usability, combining a robust photoionization source with a proprietary detection module to enable compound-specific analysis in real time. The system's modular design ensures adaptability to a range of industrial environments, from petrochemical plants to pharmaceutical facilities, where high selectivity and rapid detection are essential.

Fig. Comparative Advantages of INL's VOC Sensor Device

Reports on the global gas sensor market, including data from Transparency Market Research, forecast substantial growth as regulatory scrutiny intensifies worldwide [28]. Within this competitive landscape, high-end offerings such as Proton Transfer Reaction–Time of Flight (PTR-TOF) and Selected Ion Flow Tube Mass Spectrometry (SIFT-MS) command significant acquisition and operational costs, often exceeding 200,000 euros, and frequently require trained personnel for complex data interpretation [29][30]. Meanwhile, less expensive PID devices cannot match the selectivity required in many industrial or research contexts, notably when specific, regulated compounds must be tracked individually [31].

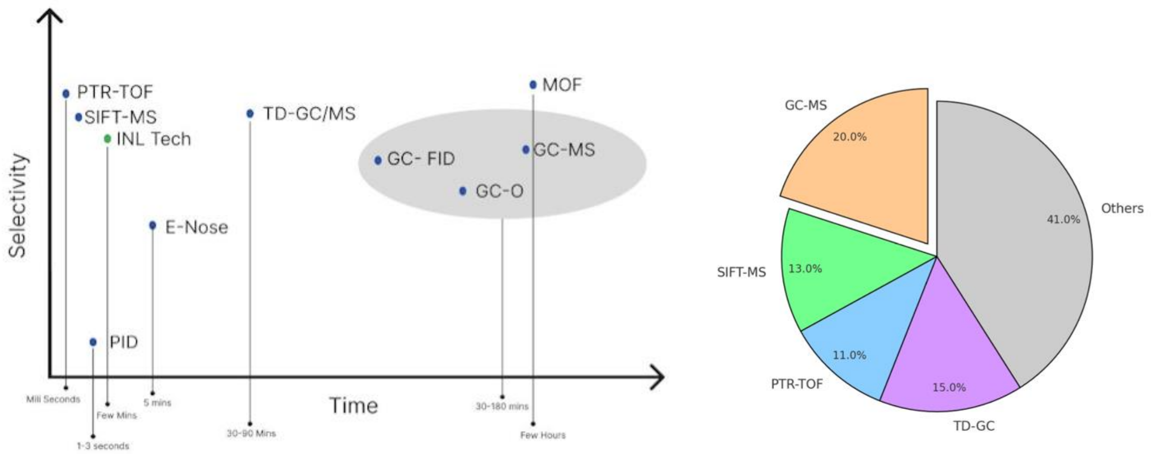
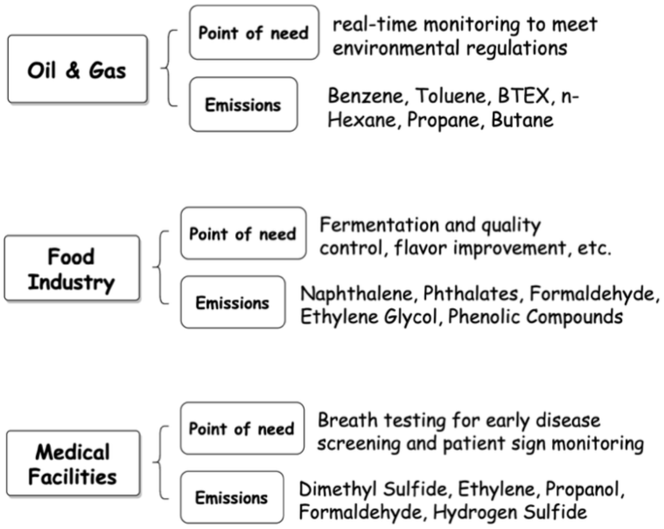


Fig. Left: Selectivity vs. time comparison of VOC detection technologies; Right: Market share distribution of VOC detection methods.

INL's new sensor differentiates itself by delivering compound-level resolution in a continuous, real-time format at a price point that, while not trivial, remains sufficiently competitive to attract industrial users who have struggled to find a middle ground between expensive mass spectrometers and generic PIDs. As businesses face potential fines, operational shutdowns, and reputational damage from non-compliance, a device that promises targeted, rapid detection of HMW-VOCs stands to be adopted by both large corporations and mid-sized enterprises that require precise, timely VOC data to safeguard processes and fulfill regulatory responsibilities.

1.3 Market Segmentation



This report continues by dividing the potential market into two primary segments. The first segment consists of industries that directly produce VOCs during their manufacturing processes. These industries, such as petrochemical refineries, pesticide production facilities, adhesive manufacturing plants, and certain pharmaceutical operations, inherently generate large volumes of volatile organic compounds and therefore require rigorous detection and monitoring mechanisms to ensure operational safety and regulatory compliance. Facilities in this segment often deal with high-molecular-weight VOCs that pose significant risks to both worker health and the surrounding environment, underscoring the need for real-time and selective sensors capable of pinpointing specific compounds (e.g., benzene, toluene, xylene) at critical thresholds.

The second segment is composed of industries that do not produce VOCs per se, but that nonetheless use them extensively in their processes, whether as solvents, reactants, cleaning agents, or additives [32]. These include a broad range of sectors—automotive assembly lines that rely on paints and coatings containing VOCs, printing and packaging enterprises that handle large quantities of inks and thinners, and food processing or pharmaceutical packaging lines that utilize specialized chemicals during sterilization or formulation stages [33][34][35]. Although these industries may not generate VOCs in the same fundamental way as refineries or chemical manufacturers, they face substantial risks related to leakage, accumulation in confined spaces, or contamination of final products [36].

Consequently, the demand for precise and continuous monitoring, particularly of high-molecular-weight VOCs that can linger in the environment and exhibit more pronounced health or safety hazards, is growing [37]. As tighter regulations come into force worldwide—targeting emissions limits, permissible exposure levels, and workplace safety standards—this second segment increasingly seeks cost-effective, user-friendly, and real-time detection solutions to avoid potential liabilities and to maintain consistent product quality [38]. By providing both segments with a single device that merges the benefits of real-time data acquisition and chemical specificity, the novel photoionization-based sensor can position itself as a strategic investment that helps industries uphold stringent safety requirements, enhance process efficiency, and ultimately protect workers and the environment from the adverse effects of uncontrolled VOC emissions[39].

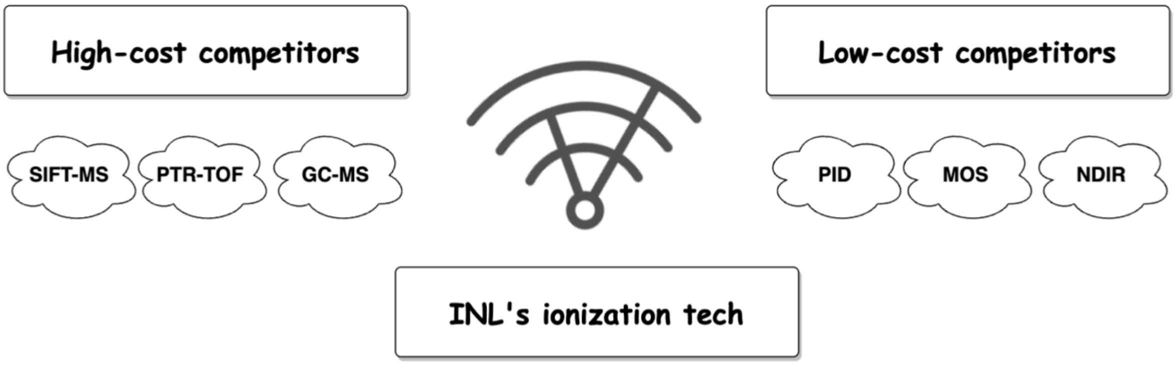


Fig. INL’s ionization tech utilizes a specialized photoionization source and proprietary detection module to enable real-time, compound-specific monitoring of high-molecular weight VOCs like BTEX in industrial environments.

In surveying various industrial sectors, it becomes evident that real-time and selective detection of high-molecular-weight VOCs is not merely a matter of compliance with environmental regulations, but also a means of improving operational efficiency and product quality. For instancTofwerk Technologies, leveraging SIFT-MS (Selected Ion Flow Tube Mass Spectrometry), has demonstrated real-time VOC analysis solutions for chemical industry companies and Contract Development and Manufacturing Organizations (CDMOs)[40]. Similarly, Tofwerk proven effective in residual solvent analysis, impurity detection, and cleaning/sterilization monitoring. Through the Tofwerkpment of the Syft Tracer Pharm11, they achieved 21 CFR Part 11 compliance and improved the pharmaceutical production capacity of their customers [41]. Similarly, Tofwerk has employed Proton Transfer Reaction–Time of Flight Mass Spectrometry (PTR-TOF) to detect and analyze siloxanes, benzene derivatives, and other high-molecular-weight VOCs (HMW-VOCs) released during chemical and automotive manufacturing, offering high-sensitivity results that help end users evaluate environmental performance and material quality in real time[42].

1.4 Medical Market

1.4.1 Overview

Technologies for breath tests related to gastrointestinal microbiota metabolic disorders are still in the market cultivation phase. Additionally, breath testing technologies for NH3, H2S, and VOCs-based early cancer screening are currently in clinical trial stages or awaiting regulatory approval.

These detection techniques vary in speed and precision, and INL's sensor technology stands out with its potential to address critical needs in the medical industry. Designed for rapid and precise analysis, the sensor can support real-time decisions, such as detecting volatile organic compounds (VOCs) linked to inflammation or other biomarkers. While breath-testing technologies for medical diagnostics have been under active development for only a decade, INL’s advanced capabilities position it to accelerate progress in this area. By providing accurate and timely results, the sensor offers a significant opportunity to improve diagnostic methods and expand the use of VOC analysis in medical applications. Technologies for breath tests related to gastrointestinal microbiota metabolic disorders are still in the market cultivation phase. Additionally, breath testing technologies for NH3, H2S, and VOCs-based early cancer screening are currently in clinical trial stages or awaiting regulatory approval.

Traditional breath tests for inorganic molecules are a subset of emerging POCT (point-of-care testing) technologies and have seen extensive clinical application [43]. According to Frost & Sullivan, the market size for breath testing in China was approximately RMB 1.9 billion in 2018, and by 2020, the market size had grown to around RMB 3 billion, calculated at factory prices [44]. Urea breath tests for Helicobacter pylori detection constitute 90% of the overall breath testing market, with an annual growth rate of approximately 20% [45]. Breath NO detection, however, has an even higher compound annual growth rate, exceeding 40% [46].

1.4.2 Key Factors for the Commercialization of Breath VOCs Detection Products

Due to the lack of portable breath VOCs detection products, the market currently relies on professional laboratories to provide VOCs breath metabolomics analysis services. Existing metabolomics detection instruments are mostly large analytical devices used primarily in professional laboratories to analyze breath samples collected from patients using breath bags or tubes. These large analytical instruments are expensive, time-consuming, and not portable.

The emergence of ultra-sensitive, high-resolution miniature gas analyzers, gas sensors, and pre-concentration technologies can significantly accelerate the development of breath metabolomics. These advancements make point-of-care testing (POCT) possible by integrating sampling and analysis into a single device. Such systems could enable breath sampling in just a few seconds and analysis results in tens of seconds. Portable breath VOCs detection and disease identification hold tremendous application potential and commercial prospects.

Currently, research and development in breath VOCs detection focus on three primary directions. First, improving sensor capabilities to accurately measure the concentrations of disease-related VOCs, often by combining solid-phase extraction preprocessing with advanced mass sensor technologies [47]. Second, leveraging sensor arrays and sophisticated data analysis methods to identify diseases through VOC pattern recognition, which requires robust hardware and reliable algorithms [48]. Third, addressing challenges in high-humidity environments, such as enhancing sensor materials and structures to improve detection limits, sensitivity, and selectivity [49]. These advancements are expected to significantly enhance the performance and applicability of breath VOC detection technologies in clinical and industrial settings [50].

For breath VOCs sensors, critical challenges include improving sensor performance in terms of detection limits, sensitivity, species selectivity, and anti-interference capabilities [51]. Given the high humidity of human breath, the performance of sensors in high-humidity environments is particularly important [52].

The performance of sensors is closely related to their materials, structures, sizes, active sites, and physicochemical properties [53]. Research directions for improving sensor performance

include:
1. Doping with other materials to increase active sites, optimize structures, and enhance sensor performance [54].
2. Screening coatings or thin films with high specificity for adsorption to improve the species selectivity of mass sensors [55].
3. Developing stable and reliable methods for mass production of sensors to reduce preparation difficulty and cost [56].

1.4.3 Market Landscape of Breath VOCs Detection

In recent years, an increasing number of world-leading professional medical institutions, such as the Mayo Clinic and Cleveland Clinic in the United States[57], as well as multinational instrument giants like Thermo Fisher[58] and Markes International[59], along with numerous emerging technology companies, have been rapidly advancing the development and application of breath VOCs detection products.
Globally, high-tech metabolomics analysis of breath is transitioning from top-tier research institutions to broader public access through industrialization and marketization. Breath VOCs detection is on the verge of a significant breakthrough, with its applications in early cancer screening drawing considerable attention[60]. Its industrialization and commercialization prospects are gradually emerging.

1.5 Food Industry (Winery)

1.5.1 Overview

A study evaluated VOCs compound released at various stages of the winemaking process. Preliminary findings highlighted differences in emissions of five wine varieties which assessed the effect of indoor air and composition of VOCs and its effects on wine and the air quality experienced by winery workers. The Versatile, Easy, and Rapid Atmospheric Monitor (VERAM) sampler uses low-density polyethylene (LDPE) lay-flat tubes filled with solid-phase adsorbents. The technologies (VERAM and HS-GC-MS) effectively detected both BTEX and terpenes in wineries while simultaneously monitoring various stages of the winemaking process. The use of HS enabled eco-friendly analysis within just 12 minutes, requiring no sample preparation or solvents.
The European wine industry generated $166.7 billion in total revenue, with $73.9 billion from domestic consumption and $92.8 billion from exports. Despite its low compound annual growth rate (CAGR) of 0.15%, the sheer size of the industry ensures significant year-on-year growth. Consumers are willing to pay a premium when their olfactory senses are stimulated correctly, making the detection and monitoring of gases that influence the taste and smell of wines a valuable investment for companies in the sector [61].

1.5.2 Applications of VOC Detection Across Various Industries

(1) **Compliance with work environment regulations:**
A real-time, selective gas sensor can be used to monitor the indoor air quality of a winery using VERAM passive samplers to sample VOCs and pesticides in various workplaces, effectively capturing a wide range of compounds with different physicochemical properties. Doing so ensures compliance with the European REACH policies for worker safety, strict

controls on chemical substances in workplaces to protect worker safety, including exposure limits for VOCs [62]. Testing indoor air quality in a winery is ideally suited for the INL sensor due to its real-time, selective capabilities, enabling it to accurately detect gases and their concentrations. This allows for immediate action and triggers the necessary protocols accordingly. If the INL device can achieve the required accuracy, it has the potential to make a significant impact in the market by ensuring the safety of winery workers and optimizing air quality during the winemaking process.

(2) Fermentation and Process

Monitoring volatile organic compounds (VOCs) and terpenes during the winemaking processes provides valuable insights into controlling fermentation and ensuring wine quality. The volatile fraction of wine consists of over 800 compounds, including terpenes, hydrocarbons, ketones, alcohols, esters, ethers, and fatty acids, with concentrations varying widely from 100 mg/L to µg/mL or even ng/L. This vast array of volatile compounds presents a unique opportunity for our real-time, selective gas sensor to detect and monitor VOCs throughout the winemaking process. By continuously tracking these compounds, the sensor not only helps maintain air quality for workers but also provides critical insights into the aroma profile of the wine. This dual benefit enhances the overall winemaking process, ensuring both a safe working environment and an optimized product, making our sensor a highly valuable tool in the industry [63].

For example, VERAM samplers identified compounds like limonene and toluene, with concentrations increasing through winemaking stages, peaking during ageing. Limone, for instance, appeared only in advanced fermentation as it transitioned from liquid to gas. This highlights the value of real-time monitoring, where a selective gas sensor could track and adjust volatile compound levels, ensuring optimal concentrations of aroma compounds. Such technology would enhance wine consistency, flavor, and quality while maintaining a controlled work environment [64].

(3) **Simplifying Detection Processes and Reducing Costs:**

Compared with traditional VOC detection methods, VERAM samplers combined with HS-GC-MS technology have the advantages of simple operation, speed, no need for sample pretreatment and use of solvents (making the detection processes greener), greatly simplifying the detection process and reducing detection costs and time. When compared to the VERAM sampler, the INL device offers significantly faster sampling times, which can be determined through necessary testing or by using the 8-hour sampling period established in school environment testing, compared to 2 days sampling of VERAM (Citation). Additionally, the INL device provides quicker testing times (~5 minutes) compared to the 12 minutes required by HS-GC/MS. Exploring the integration of both active and passive sampling methods could further enhance the utility and functionality of the INL device. Wineries can carry out VOC detection more frequently, timely grasp the changes of air quality in the production process, and thus more effectively carry out production management and quality control, improving production efficiency and economic benefits [65].

1.5.3 Conclusion

In Conclusion, integration of a real-time, selective gas sensor offers a promising solution to the challenges faced by traditional sampling methods in the winemaking process. Unlike passive samplers, which provide reliable, long-term data but lack real-time monitoring capabilities, a real-time sensor can continuously track VOCs and terpenes during critical stages like fermentation and aging. This real-time capability allows winemakers to make immediate adjustments, enhancing the wine's aroma and quality. Additionally, addressing the limitations of active sampling, such as the complexity, high cost, and the need for noisy pumps, electricity, and frequent maintenance, real-time sensor would eliminate these drawbacks, making continuous, cost-effective monitoring of volatile compounds more feasible and practical in the winemaking industry.

The results highlight that VOC concentrations increase during successive winemaking stages, peaking in the ageing process, with variations influenced by factors like fermentation phases and oak barrels. These findings underscore the potential of terpene profiling to identify wine varieties and the importance of precise monitoring to optimize fermentation conditions. By maintaining ideal levels of aroma compounds, winemakers can enhance the consistency, flavor, and overall quality of the wine, supporting both product differentiation and improved production practices.

1.6 Risk Assessment and Mitigation

1.6.1 Introduction:

The commercialization of INL's VOC sensor technology represents a transformative step forward in addressing the demand for real-time, compound-specific monitoring of high-molecular-weight Volatile Organic Compounds (HMW-VOCs). This novel technology, combining advanced photoionization and AI-driven analytics, is poised to serve diverse industries such as wineries, medical diagnostics, and industrial manufacturing. However, despite its potential, the path to commercialization is fraught with challenges.

This report identifies the critical risks associated with the sensor's market adoption, competition, regulatory compliance, technical performance, financial viability, and intellectual property security. By understanding these risks, INL can proactively address potential obstacles and position its sensor as a valuable tool across industries. Comprehensive mitigation strategies are also proposed to ensure a successful market launch while maximizing operational efficiency and customer trust.

1.6.2 Market Adoption Risks

One of the main challenges lies in limited awareness or trust among potential adopters in industries such as wineries and medical diagnostics. This lack of familiarity could slow the adoption process and hinder the sensor's ability to penetrate the market effectively. The likelihood of this occurring is moderate due to the resistance industries often exhibit toward replacing established technologies with novel solutions. To mitigate these risks, INL could establish strategic partnerships with recognized industry leaders, conduct pilot projects to demonstrate the sensor's real-world value, and leverage case studies or testimonials in marketing campaigns to build credibility and trust [1] [2].

1.6.3 Competitive Landscape Risks

The VOC sensor market is dominated by established technologies such as GC-MS, PTR-TOF, and SIFT-MS. Competing against these mature solutions poses a significant challenge, particularly in terms of differentiation. The impact of this competitive pressure is substantial, and the likelihood of encountering stiff competition is high due to the strong foothold these technologies have in the industry. To address this, INL must emphasize its sensor's unique benefits, such as cost-effectiveness, real-time capabilities, and portability. Additionally, developing tiered pricing models to cater to different customer segments and highlighting the AI-driven automated analysis feature can further strengthen its competitive position [3] [4].

1.6.4 Regulatory and Compliance Risks

Navigating stringent regulatory requirements in environmental and medical industries is another key challenge. This could result in delays in product certification and, subsequently, market entry. The likelihood of encountering such regulatory hurdles is moderate, especially for applications requiring FDA and EU certifications. To mitigate these risks, INL should engage with regulatory authorities during the development phase, partner with certification organizations to ensure compliance, and incorporate flexibility in the sensor's design to adapt to evolving standards [5].

1.6.5 Technical and Operational Risks

The sensor may face technical challenges in high-humidity environments or resource-limited conditions, potentially reducing its reliability and accuracy. The impact of such issues could harm the product's reputation, and the likelihood of these problems occurring is moderate given the diverse conditions under which the sensor is intended to operate. To address these concerns, INL should invest in rigorous testing across different environmental conditions, utilize advanced hydrophobic coatings and modular designs to counter these challenges, and establish a robust warranty and maintenance program to reassure customers [3] [6].

1.6.6 Financial Risks

High upfront costs for research and development, as well as production, represent a significant financial risk. This could strain INL's resources and delay the scalability of the sensor. The impact of these financial constraints is considerable, and the likelihood of such challenges is moderate to high, depending on the availability of funding. To mitigate this, INL should seek government grants or explore industry-specific funding opportunities, pursue joint ventures to share development costs, and implement a phased commercialization strategy that prioritizes high-revenue markets initially [4].

1.6.7 Intellectual Property (IP) Risks

The potential for patent disputes or IP theft poses a risk to the sensor's commercialization. Such legal challenges could delay market entry or result in additional costs. While the likelihood of such risks is low to moderate, it is critical to secure comprehensive patents across multiple jurisdictions. Regular monitoring of the market for potential IP infringements and maintaining confidentiality during collaboration agreements are also essential steps to minimize these risks [7].

1.6.8 Conclusion:

The successful commercialization of INL's VOC sensor hinges on a clear understanding and proactive mitigation of key risks. Market adoption barriers, regulatory complexities, competitive pressures, and technical challenges can significantly impact the sensor's trajectory. However, by leveraging strategic partnerships, investing in product innovation, aligning with regulatory standards, and ensuring robust financial planning, INL can position its sensor as a market leader.

This risk assessment underscores the need for early-stage collaboration with industry stakeholders, customer education, and continuous refinement of the product to address diverse operational needs. By implementing the proposed mitigation strategies, INL not only ensures the sensor's commercial success but also establishes itself as a pioneering force in the real-time VOC monitoring space. The outlined approach offers a roadmap for bridging the gap between innovation and market readiness, enabling INL to unlock new opportunities across industries poised for exponential growth.

Appendices:
Appendix A: Decision Framework and Strategy

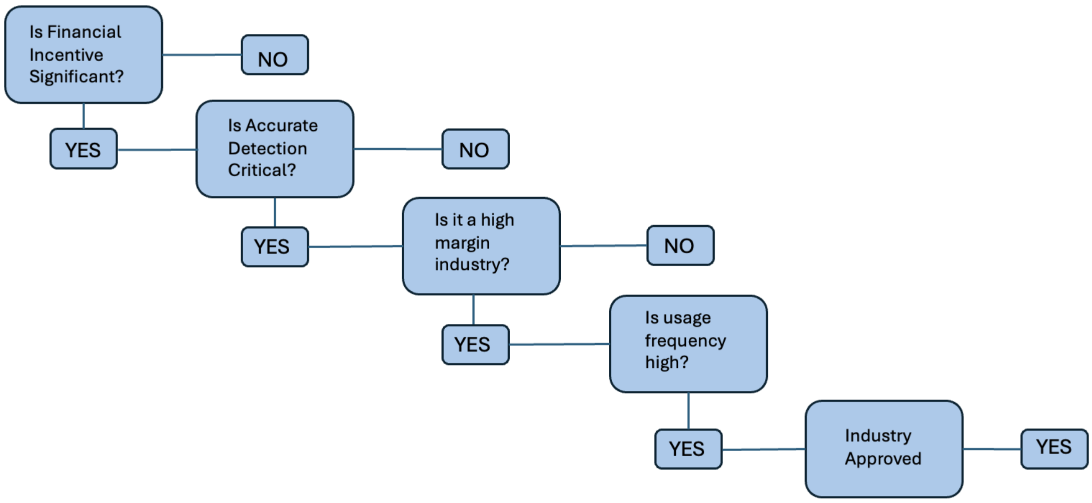


Fig.

This decision framework was designed to evaluate the potential of INL's VOC detection technology across various applications within 11 industries by analyzing key factors: financial incentive, the criticality of accurate detection, industry profit margins, and usage frequency. By systematically applying these criteria, the framework identified which applications and industries were most suitable for commercialization. After careful evaluation, the **Wine Industry** and **Medical Diagnostic Industry** emerged as the target industries due to their significant financial incentives, accuracy requirements, profitable market margins, and frequent usage of detection of VOCs. These industries represent the best alignment between INL's technological capabilities and market needs.

The Various Industries and Their applications are listed in the table below:

Industry	Application area
Agriculture	crop protection harvest timing & storage meat, seafood, & fish products plant production pre- & post-harvest diseases
Airline transportation	public safety & welfare passenger & personnel security
Cosmetics	personal application products

	fragrance additives
Environmental	air & water quality monitoring indoor air quality control pollution abatement regulations
Food & Beverage	consumer fraud prevention quality control assessments ripeness, food contamination taste, smell characteristics
Manufacturing	processing controls product uniformity safety, security, work conditions
Medical & clinical	pathogen identification pathogen or disease detection physiological conditions
Military	personnel & population security civilian & military safety
Pharmaceutical	contamination, product purity variations in product mixtures
Regulatory	consumer protection environmental protection
Scientific Research	botany, ecological studies engineering, material properties microbiology, pathology

Appendix B: Heat Map

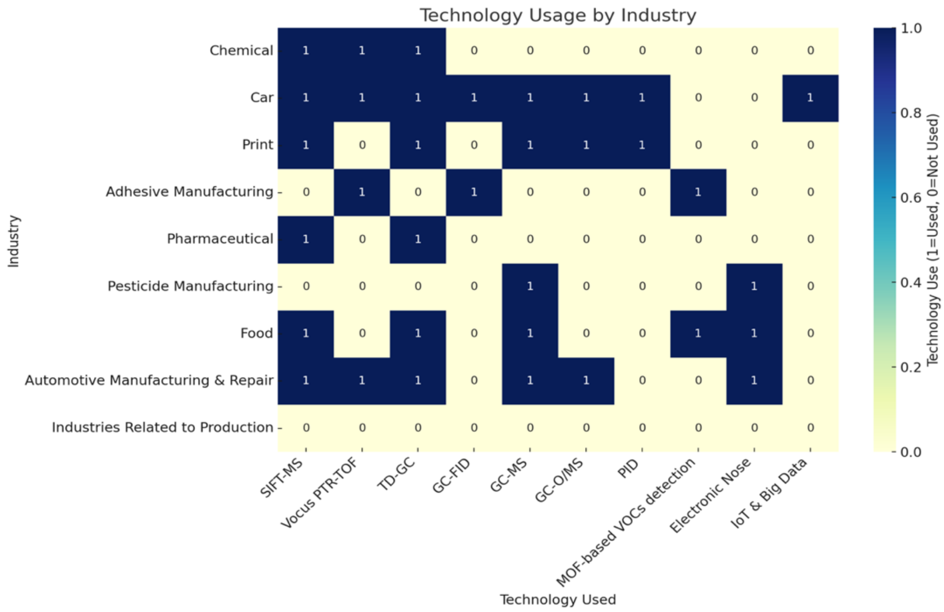


Fig.

The heat map above shows how different industries are using VOC detection technologies. Each cell represents whether a technology is being used (1 = used, shown in dark blue) or not (0 = not used, shown in light yellow). The darker the blue, the more commonly that technology is adopted in a specific industry.

<u>Key Takeaways:</u>

1. **Chemical and Automotive Manufacturing Lead the Way:**
   a. Industries like chemical production and automotive manufacturing have the highest adoption of advanced technologies, such as SIFT-MS, GC-MS, and MOF-based VOC detection. These sectors prioritize precise VOC monitoring to meet strict regulations and ensure safety.
   b. Automotive manufacturing makes significant use of Vocus PTR-TOF for real-time VOC monitoring, especially in paint shops and assembly lines.
2. **Moderate Usage in Adhesive and Pharmaceutical Manufacturing:**
   a. GC-FID and PID are popular in adhesive and pharmaceutical manufacturing, where maintaining product quality and meeting emission standards are key concerns.
   b. Emerging technologies like MOF-based VOC detection are gaining traction in adhesive manufacturing, valued for their precision and adaptability.
3. **Low Usage in Food and Pesticide Manufacturing:**
   a. Adoption of VOC detection technologies is less common in industries like food production and pesticide manufacturing. However, select technologies like Electronic Nose and GC-MS are used for quality control and emission monitoring.
4. **IoT and Big Data Are Still Emerging:**
   a. While not widely adopted yet, IoT and Big Data technologies show potential across

multiple industries. These tools could play a significant role in centralizing VOC monitoring and providing predictive insights, especially in larger operations like automotive and chemical manufacturing.

Industry-Specific Insights:

- **Printing Industry:**
  Technologies like TD-GC and PID are frequently used to monitor solvent emissions in printing. This aligns with the need for environmental compliance and safer working conditions in this sector.
- Automotive Repair:
  Automotive repair and related industries rely heavily on GC-MS and PID technologies to detect harmful VOCs in confined spaces, ensuring worker safety.
- Emerging Technologies:
  MOF-based VOC detection and Electronic Nose are starting to make their mark in niche applications, such as adhesive manufacturing and food production, where precision and odor profiling are especially important.

Conclusion:

The heat map highlights how different industries adopt VOC detection technologies based on their specific needs and challenges. While industries like automotive and chemical manufacturing are leading in adoption, there’s significant room for growth in sectors like food and pesticide manufacturing. Emerging technologies and IoT-based solutions also show promise for bridging these gaps and expanding adoption.

Appendix C: Comparative analysis of Technologies

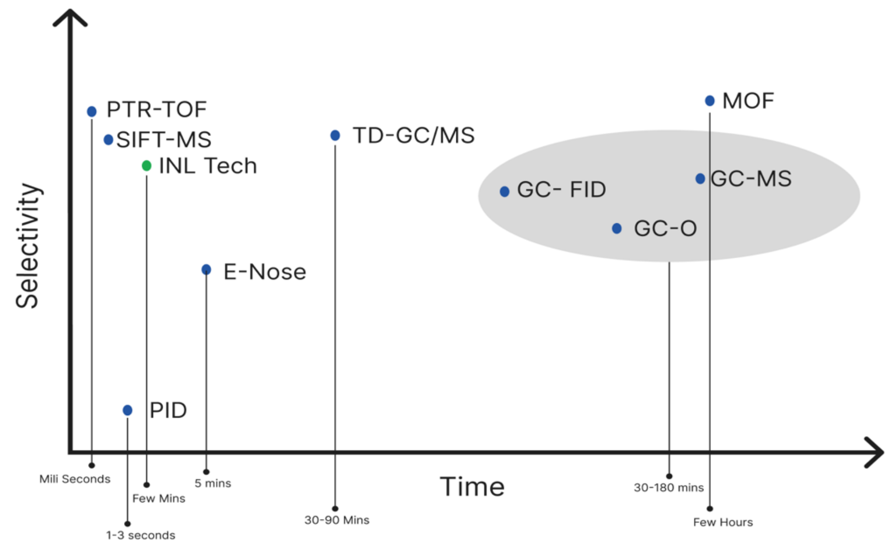


Fig.

The comparative analysis chart above highlights the performance of various VOC detection technologies based on their selectivity (the ability to detect specific compounds) and response time (the speed at which results are delivered). Each technology has its strengths and trade-offs, making them suitable for different industrial applications.

<u>Key Takeaways:</u>

1. Fast and Highly Selective Technologies:
   a. PTR-TOF, SIFT-MS, and INL Technology deliver high selectivity with extremely fast response times measured in milliseconds. These technologies are ideal for industries like automotive and chemical manufacturing, where real-time monitoring and immediate feedback are critical to operations.
2. Balanced Performance for Detailed Analysis:
   a. TD-GC/MS and GC-O strike a balance, offering moderate selectivity with response times ranging from 30 minutes to several hours. These technologies are particularly suited for quality assurance and research applications, where detailed VOC profiling is required but speed is less critical.
3. Specialized Applications:
   a. The Electronic Nose (E-Nose) is designed for odor profiling and is often used in the food and beverage industry. It provides results within a few minutes, making it an effective tool for sensory-related applications.
   b. PID offers a quick and cost-effective solution for general VOC detection. While it has lower selectivity, its rapid response time makes it suitable for preliminary screenings or environments where broad-spectrum VOC detection is sufficient.
4. Emerging Technologies with High Potential:
   a. MOF-based VOC detection is an emerging technology that demonstrates high selectivity. While it requires more time for analysis, its precision makes it highly promising for industries like pharmaceuticals and adhesive

manufacturing, where accuracy is paramount.

5. Traditional and Established Techniques:
    a. Technologies like GC-FID and GC-MS remain trusted industry standards for comprehensive VOC detection. Despite their slower response times (ranging from 30 minutes to several hours), they excel in delivering precise, compound-specific results in controlled environments like laboratories.

Conclusion:

The chart emphasizes the importance of matching technology capabilities with industry needs. For industries requiring real-time, high-precision VOC detection, technologies like PTR-TOF and SIFT-MS are ideal. In contrast, GC-MS and GC-FID remain the gold standard for in-depth analytical work where time is less critical. Emerging technologies such as MOF-based VOC detection are paving the way for more advanced, application-specific solutions. This analysis underlines the need for thoughtful selection of VOC detection systems based on operational priorities and industry demands

Appendix D: VOC Detection Technologies used across Industries

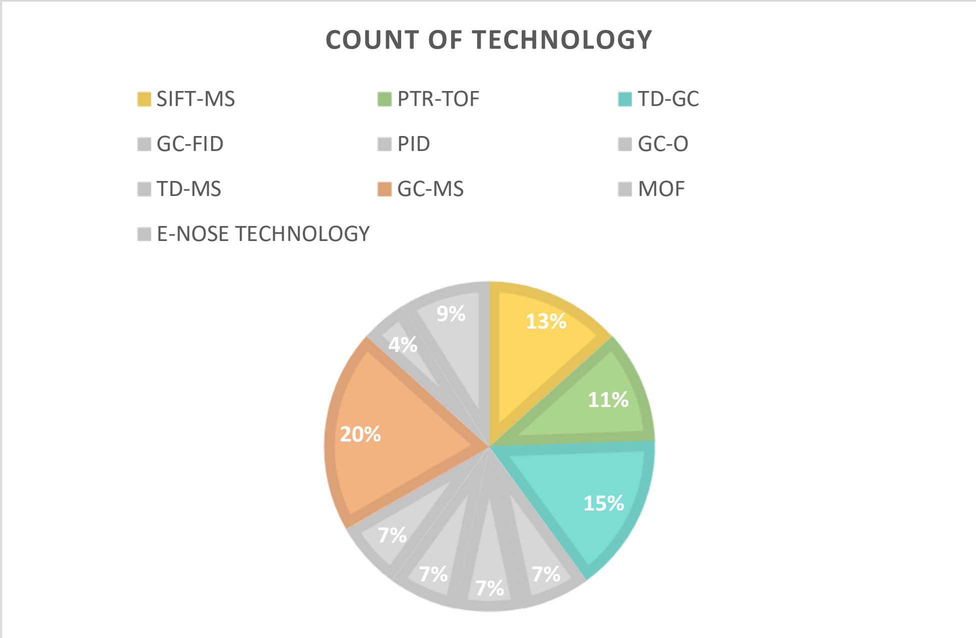


Fig.

The pie chart above shows how various VOC detection technologies are being used across different industries. Each slice of the chart represents the percentage of adoption for a specific technology, giving a clear picture of which tools are leading the way and which are used less frequently.

Key Highlights:

1. **GC-MS Leads the Pack (20%):**
    a. **GC-MS** (Gas Chromatography-Mass Spectrometry) is the most widely used technology, making up 20% of the total. Its high precision and accuracy make it a favorite in industries like chemical manufacturing and pharmaceuticals, where detailed VOC analysis is essential.
2. **TD-GC/MS Sees Strong Growth (15%):**
    a. **TD-GC/MS** is becoming a go-to solution for industries that need a balance between speed and selectivity, such as printing and automotive manufacturing. Its versatility is driving its increasing popularity.

3. **SIFT-MS and PTR-TOF Are Rising Stars (13% and 11%):**
    a. Technologies like **SIFT-MS** (Selected Ion Flow Tube Mass Spectrometry) and **PTR-TOF** (Proton Transfer Reaction Time-of-Flight) are gaining traction for their ability to deliver fast and precise results. These are particularly valuable for real-time monitoring in industries like automotive and adhesives.

4. **Specialized Technologies Hold Steady (7% Each):**
    a. **PID**, **MOF-based sensors**, and **E-Nose** have carved out their niches in areas like food safety and environmental monitoring. While they're not as widely used, their role in these specialized fields is critical.

5. **GC-O Remains Niche (4%):**

a. **GC-O** (Gas Chromatography-Olfactometry) has the smallest share, reflecting its focused use in industries like food production, where understanding odor profiles is key.

Conclusion:

This chart highlights the clear dominance of established technologies like **GC-MS**, while newer tools like **SIFT-MS** and **PTR-TOF** are quickly becoming popular for their speed and precision. Meanwhile, specialized technologies like **MOF-based sensors** and **E-Nose** are proving their value in niche applications, showing there's room for innovation in these areas. Understanding these adoption patterns helps identify opportunities for innovation and growth in underutilized technologies.

Appendix E: Target Companies in Healthcare Industry

Company Name	Technical Approach	Product Pipeline	Number of Collected Samples (Sorted)
Buyue Technology (China)	Single-photon ionization mass spectrometry (SPI-TOF).	Infectious diseases, lung cancer, esophageal cancer diagnosis.	2400 samples collected, 279 clinical trials, 92.83% consistency with LDCT.
Breath Diagnostics (USA)	MEMS processing, silicon microphone sensor to capture gas molecules. Detection using FT-ICR-MS/GC-MS.	Differentiating benign and malignant lesions (lung cancer).	1000<x<10000; Sensitivity 93.6%, Specificity 85.6% (lung cancer).
Owlstone Medical (USA)	(1) Use of breath sampling bags, thermal desorption for GC-MS analysis. (2) Small-scale analysis using non-GC-MS techniques (e.g., ion mobility analysis).	Respiratory diseases, lung cancer, early screening for other diseases.	1000<x<10000; Sensitivity 85%, Specificity 98% (control groups vs. smokers).
Fossil Ion Tech (Spain)	SESI-MS for capturing volatile organic compounds in breath samples.	Lung fibrosis, COPD.	1000<x<10000; Sensitivity 71%, Specificity 86% (COPD lung fibrosis).
NanoScent (Israel)	Nanomaterial-based electronic sensors and artificial intelligence techniques.	Lung cancer.	>1000; Sensitivity >86 %.
G.A.S. GmbH (Germany)	GC combined with ion mobility analysis (GC-IMS) to detect molecular biomarkers.	Disease diagnostics, environmental monitoring, pharmacology studies.	>1000; Early development stage.

Sensigent (USA)	Nanomaterial sensor array.	Chronic respiratory diseases, lung cancer, cough, foodborne diseases.	<100; Preliminary testing phase.
New England Breath Technologies (USA)	Detection of volatile organic compounds using multiple nanomaterial sensor technologies.	Handheld field detection for respiratory diseases.	<100; Early clinical trials for acute detection.
BreathDX (USA)	Use of polymer MEMS array and handheld breath detectors.	Quantitative biomarkers for health screening (e.g., stomach ulcers, liver and kidney function).	<100; Initial testing phase.
Syft Technologies (New Zealand)	Selection of soft ion mass spectrometry (SIFT-MS).	Environmental air monitoring, indoor air quality testing, drug abuse detection.	<100; Early phase of clinical trials.
Alpha Szensor (USA)	VOC detection based on gas-sensitive nanomaterial sensors.	Lung cancer, real-time medical diagnostics.	<1000; Sensitivity 80%.
Shangwo Medical (China)	Nanomaterial sensor technology.	Chronic respiratory diseases, gastrointestinal diseases, lung cancer, and other infectious diseases.	/
Jingzhi Future (China)	MEMS chip integration combined with AI analysis.	Esophageal cancer diagnosis.	/
Mianao Technology (China)	MEMS nanomaterial gas sensors.	Liver cancer, lung cancer, and other infectious diseases.	/

Appendix F: Overview of VOC compounds released in Wineries

The beverage industry represents a viable opportunity for sensors tracking VOC presence and concentration. Wineries are attractive potential partners for this type of device, as research indicates that the winemaking process produces Terpenes (styrene, pinene, p-cymene, limonene) at 3–577 ng/m³, while BTEX compounds (benzene, toluene, ethylbenzene, xylenes) ranged from 13–525 ng/m³ inside containers

Wine Production Stages	VOC	Molecular Weight (g/Mol)	Effect of wine Quality
Fermentation	Terpenes (e.g., Linalool, Geraniol, α-Terpineol) Norisoprenoids (e.g., β-Damascenone)	154.25 190.27	Contribute to floral and citrus aromas. Provide fruity and floral notes
Aging	Lactones (e.g., γ-Nonalactone, γ-Decalactone) Phenols (e.g., Eugenol)	156.27–170.27 164.2	Add creamy, coconut, or peach-like aromas. Impart smoky, spicy, or clove-like aromas, especially in barrel-aged wines
Oak Barrel Aging	Lignin-derived Compounds (e.g., Vanillin) Fatty Acids (e.g., Hexadecanoic acid, Octadecanoic acid)	152.15 256.43–284.48	Add vanilla, caramel, and smoky characteristics. Enhance mouthfeel and contribute to complex aroma profiles
Color Development (Red Wines)	Anthocyanins (e.g., Malvidin-3-glucoside)	493.43	Responsible for vibrant color and stability in red wines

1.6.9 Fermentation:

- **VOC Monitoring in Yeast Performance**:
    - During fermentation, VOCs such as esters, alcohols, and aldehydes are critical in determining the aromatic profile and quality of wine. Monitoring these compounds ensures that the yeast is functioning efficiently, allowing winemakers to control the alcohol-to-ester ratios. For example, VOC measurements can be used to adjust fermentation temperatures or nutrient levels to optimize yeast metabolism.
    - **Relevance**: This phase is critical as it defines the primary characteristics of wine,

such as aroma and initial flavor. Early detection and intervention at this stage reduce the likelihood of errors in downstream processes.

1.6.10 Aging:

- **Tracking Oxygen Ingress**:
  - Oxygen levels influence oxidation, which is a key process in wine aging. Measuring VOCs, such as aldehydes and phenolic compounds, allows winemakers to prevent over-oxidation while ensuring that the wine matures with desirable flavor profiles.
  - **Relevance**: Aging contributes to the wine's body, depth, and character. VOC monitoring ensures that external factors, such as unwanted microbial activity, do not affect the final quality.

1.6.11 Storage and Bottling:

- **Ensuring Contamination-Free Environments**:
  - VOC monitoring during bottling ensures that wine remains uncontaminated by external chemicals or compounds that may alter its flavor, aroma, or safety. Long-term storage can also be monitored for VOC emissions that may indicate spoilage or contamination.
  - **Relevance**: Storage and bottling are the last phases where quality can be compromised. By ensuring stability through VOC analysis, winemakers preserve the product's integrity for consumers.

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