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Comparative Assessment of Chromatographic Methods in the Analysis of Industrial Air Pollutants: Technological Developments and Application Strategies of the Last Decade

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Abstract **–** Industrial activities are indispensable to the economic and technological progress of modern societies; however, they simultaneously generate considerable risks to environmental quality and human health due to the release of atmospheric pollutants. Emissions from power plants, chemical processes, metallurgical operations, petrochemical industries, and waste incineration facilities comprise a broad spectrum of contaminants, including volatile organic compounds, polycyclic aromatic hydrocarbons, pesticide residues, and heavy metal derivatives. These pollutants are well-documented for their toxic, mutagenic, and carcinogenic effects, posing direct threats to public health while also causing persistent disruptions in ecosystem dynamics. Accordingly, the accurate and reliable determination of such substances, even at trace concentrations, is vital for the effective enforcement of environmental regulations and the development of sustainable public health strategies.

Over the last decade, chromatographic techniques have become central to the monitoring and quantification of industrial air pollutants. Gas chromatography (GC) and high-performance liquid chromatography (HPLC) are widely employed for the analysis of volatile and semi-volatile organic compounds. Parallel advancements in sampling techniques (e.g., passive and active sampling, thermal desorption, microextraction approaches) and detector technologies (e.g., MS/MS, FLD, FID) have markedly improved analytical sensitivity, precision, and environmental sustainability.

This review aims to provide a systematic overview of recent progress in chromatographic methods for industrial air pollution monitoring, critically evaluate current applications, and identify emerging research opportunities for future developments.

Keywords – Industrial air pollution, emissions, chromatographic methods, gas chromatography, high-performance liquid chromatography.

I. INTRODUCTION

Atmospheric air, essential for sustaining all life forms, faces increasing degradation due to pollutants generated by human production and consumption activities. These emissions significantly impact Earth's ecosystems and pose substantial risks to global health. When released into the atmosphere, pollutants-whether from natural or anthropogenic sources-undergo complex chemical transformations, become entrained in air currents, and disperse across regional and global scales, making air pollution a pervasive transnational challenge.

The detrimental effects of atmospheric pollution manifest across multiple domains, primarily affecting human health while simultaneously damaging flora, fauna, and infrastructure. The economic consequences are equally substantial, representing a considerable burden on societies worldwide. Industrial establishments constitute major contributors to contemporary air pollution, emitting substantial quantities of gaseous compounds and particulate matter. The persistent chemical contamination observed at numerous decommissioned industrial sites demonstrates the long-term environmental persistence of industrial emissions.

Growing environmental consciousness and strengthened regulatory frameworks have stimulated the development of innovative technologies for monitoring emissions and assessing their potential impacts. In Türkiye, industrial air pollution exhibits significant variation due to differences in raw materials, fuel types, combustion systems, and production processes across facilities [1]. This diversity results in complex pollutant mixtures with varying implications for human health. Rapid urbanization and increased energy consumption associated with industrial development have exacerbated air quality challenges, particularly in major urban centers. Research indicates that synergistic effects between industrial emissions, residential heating sources, and vehicular traffic significantly degrade urban air quality [2]. In metropolitan areas such as Istanbul, this combination produces pollution levels that pose substantial health risks [3].

Comprehensive monitoring of specific pollutants, including sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), is crucial for understanding their health impacts and temporal trends. Investigations in industrial regions like Çerkezköy have demonstrated significant correlations between pollutant concentrations and air quality indices [4]. Such findings underscore the necessity for evidence-based policy and management strategies to improve air quality in industrial zones [5].

The health implications of industrial air pollution are severe, with documented links to respiratory diseases, cardiovascular conditions, and various forms of cancer [6]. In response, international efforts are advancing regulatory measures and technological innovations to mitigate industrial emissions [7]. Addressing industrial air pollution requires a multifaceted approach incorporating stringent regulations, advanced monitoring systems, technological solutions, and public education initiatives. This comprehensive strategy is essential not only for protecting human health but also for ensuring long-term environmental sustainability.

II. RESULTS

In recent years, gas chromatography (GC) has emerged as a pivotal analytical tool for monitoring industrial air pollution and identifying airborne contaminants. This technique allows the separation of complex gas mixtures, facilitating precise quantification of a wide range of pollutants. Gertsiuk demonstrated the application of zeolite-based stationary phases in GC for the determination of carbon dioxide, nitrogen oxides, sulfur oxides, and hydrocarbon gases [8]. Similarly, Toros et al. employed GC to assess the impact of pollutants such as benzene, lead, and other heavy metals on air quality [9]. Specialized GC methodologies have also been developed for the detection of volatile organic compounds, including trichloroethylene and tetrachloroethylene, enabling comprehensive analysis of ambient air samples [10].

Various studies have highlighted the effectiveness of using gas chromatography to measure air quality. For instance, Çukurluoğlu and Besim created an emission inventory based on the loss of raw materials and the formation of air pollutants in the Denizli Organised Industrial Zone. This study demonstrates the critical role of analytical methods, such as gas chromatography, in determining the impact of industrial activities on air pollution (1). Furthermore, Çetin's study, which examined the impact of natural gas use on air quality, detailed the process of improving air quality through the detection of pollutants by gas chromatography [11].

In a 2019 study, Kalıpcı and Başer employed a combination of geographic information systems and gas chromatography to evaluate air pollution in Turkey. Such integrated studies represent a significant advancement in air quality monitoring, supported by the precise measurements provided by gas chromatography [12]. Conversely, integrating data from air quality monitoring stations with gas chromatography data contributes to calculating the air quality index and developing a comprehensive understanding of the effects of industrial air pollution [4]. Li et al.'s study combined gas chromatography and ion mobility spectrometry techniques to detect halogenated airborne pollutants using passive samplers in Hamilton and Sarnia, Ontario, Canada. This study demonstrates an innovative approach to determining harmful air pollutants generated by industrial activities [13]. Similarly, Moura and Vassilenko demonstrated how gas chromatography and ion mobility spectrometry can be used to rapidly assess indoor and outdoor air quality. This study highlights the effectiveness of this technology in detecting various hazardous volatile organic compounds [14].

Moreover, Ratnaningsih et al. utilized air quality monitoring systems in the shoe manufacturing district of Taipei, demonstrating the critical role of gas chromatography in tracking airborne pollutants—especially particulate matter such as $PM_{2.5}$ and PM_{10} [15]. Complementing this, Baur et al. explored the integration of gas chromatography with metal oxide semiconductor gas sensors to achieve selective monitoring of volatile organic compounds in indoor environments [16]. These studies underscore the efficacy of gas chromatography as a robust and versatile tool for industrial air quality assessment and pollutant characterization.

Further advancing this field, several investigations have combined gas chromatography with comprehensive air quality monitoring networks and computational data analysis techniques. For instance, Siregar et al. developed linear models of air quality parameters through such integrated approaches, reinforcing the value of gas chromatography as a reliable method for pollution determination in industrial atmospheres [17].

In parallel, the application of liquid chromatography-particularly when coupled with mass spectrometry-has emerged as a significant methodological focus for the determination of industrial air pollution. This technique enables precise identification and quantification of diverse environmental contaminants derived from industrial emissions. In certain applications, liquid chromatography serves as a complementary analytical strategy. For example, Wang et al. employed graphene-functionalized materials to enhance radical reaction rates, combined with liquid chromatography, for the separation and analysis of peroxyl radicals in air samples [18]. This innovative approach expands the potential for detecting highly reactive pollutant species.

Notably, Sitasuwan et al. focused on refining sample preparation techniques for biopharmaceutical quality control [19]. While aimed at product integrity, their methodologies offer valuable insights for rapid air quality assessment in industrial settings, where timely and accurate monitoring is essential. Similarly, Ghosh et al. conducted an ambient air quality evaluation in an industrial cluster in Paradip, India, employing a suite of analytical methods-likely including liquid chromatography-to measure pollutant levels and compute the Air Quality Index (AQI) [20]. Their findings underscore the correlation between industrial operations and elevated particulate matter, directly linking analytical data to public health outcomes.

Further extending its utility, Evans et al. introduced an innovative multi-attribute monitoring method using liquid chromatography–mass spectrometry to track critical quality attributes in biotherapeutics [21]. Although developed for pharmaceutical applications, this approach is highly relevant for characterizing complex mixtures of airborne pollutants, enabling a more nuanced understanding of their composition and potential impacts.

Additionally, Kuldeep et al. investigated the spatial distribution of criteria pollutants in urban areas and highlighted how liquid chromatography can elucidate the chemical profile of air samples, supporting both source apportionment and impact assessment in densely populated regions [22]. Meanwhile, Liu et al. applied a liquid chromatography-based framework for detailed characterization of monoclonal antibodies [23], suggesting analogous strategies could enhance the resolution of environmental sample analysis.

Collectively, these studies affirm that liquid chromatography-especially when hyphenated with mass spectrometry-constitutes a powerful analytical arsenal for industrial air pollution research. These methodologies not only facilitate accurate identification and quantification of pollutants but also contribute to evidence-based regulatory decisions and targeted public health interventions.

III. CONCLUSION

Over the past decade, chromatographic techniques have become indispensable tools in environmental analysis, particularly for monitoring air pollutants originating from industrial sources, due to their high selectivity and sensitivity. Nonetheless, the practical application of these methods requires careful consideration of both their advantages and inherent limitations.

The primary strengths of chromatographic approaches lie in their ability to detect and quantify pollutants at trace levels, often down to ng/m^3, providing exceptional analytical precision. Modern methodologies enable the simultaneous determination of multiple pollutant classes within a single analytical run. The advent of online chromatography systems and portable devices has further expanded their utility, allowing continuous, real-time monitoring in industrial settings. In addition, advanced sample preparation techniques, including thermal desorption, solid-phase microextraction, and other miniaturized approaches, support environmentally sustainable “green analysis” by minimizing solvent use.

Despite these benefits, several challenges hinder routine implementation. Chromatographic analyses often require extensive sampling and pretreatment steps—such as filtration, extraction, and derivatization—that are time-consuming and may introduce additional errors. The high cost of advanced chromatographic systems limits accessibility, particularly in resource-constrained regions. Moreover, the absence of standardized protocols, including variations in sampling volumes, solvent selection, and chromatographic conditions, reduces comparability across laboratories and studies. While portable and online systems show promise for real-time applications, their sensitivity remains lower than laboratory-based instruments, and complex industrial emissions can produce analytical interferences that complicate data interpretation.

In conclusion, gas and liquid chromatography have been extensively applied for the determination of industrial air pollutants, offering sensitive and reliable data essential for environmental management and emission control. Despite certain limitations, these methods remain critical for assessing industrial air pollution, enhancing our understanding of its environmental and public health impacts. Continued advancements in instrumentation, miniaturization, and method standardization are expected to further improve their applicability and accessibility in the coming years.

REFERENCES

[1] Çukurluoğlu, S., & Besim, T. (2015). Fuel Origin Emission Inventory of Denizli Organized Industrial District. *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi*, *21*(6), 248-253.

[2] Demirel, H., & Ateş, A. (2018). Sapanca Gölü çevresinde karayolu trafiğinden kaynaklanan hava kirleticilerinin emisyon envanteri. *Sakarya University Journal of Science*, *22*(2), 150-158.

[3] Toros, H., & Bağış, S. (2017). Hava kirlilik modellerinde kullanılacak emisyon envanteri oluşturulması için yaklaşımlar ve İstanbul hava kirliliği dağılımı örneği. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, *32*(2), 1-12.

[4] Özel, H., Cihan, P., Özcan, H. K., Aydin, S., & Hanedar, A. (2021). Hava Kirletici Parametrelerinin Hava Kalitesi İndeksine Uzun Zamanlı Etkilerinin İncelenmesi: Çerkezköy Organize Sanayi Bölgesi Örneği. *Kırklareli Üniversitesi Mühendislik ve Fen Bilimleri Dergisi*, *7*(1), 94-106.

[5] Dube, S. (2023). Reducing air pollution through smart energy management in industrial clusters of India. *Environmental Progress & Sustainable Energy*, *42*(4), e14169.

[6] Ashmeet Singh, 1Harsshit Goenka, 1Prakhar Sahu, 1Venkatesh L.,2Dr. Sindhu Sree M., 3Dr. Pavithra G., 4Dr. T.C.Manjunath (2023) Design & development of a air pollution monitoring using smartphone. International Journal of Engineering Technology and Management Sciences, Issue: 3 Volume No.7

[7] Tang DeLiang, T. D., Wang CuiCui, W. C., Nie JieSheng, N. J., Chen RenJie, C. R., Niu Qiao, N. Q., Kan HaiDong, K. H., ... & Perera, F. (2014). Health benefits of improving air quality in Taiyuan, China.

[8] Gertsiuk, M. (2022). Chromatography in Ukraine: Development and Achievements. *Separations*, *9*(5), 114.

[9] Tunç, D. Ç., Dündar, E., İpek, E. A., Toros, H., & Ulubey, A. (2022). Evaluation of Air Quality in Eskisehir. *Journal of Research in Atmospheric Science*, *4*(2), 36-40.

[10] Ulanova, T. S., Nurislamova, T. V., Popova, N. A., & Mal'tseva, O. A. (2020). Working out a procedure for determining potentially hazardous volatile organic compounds (trichloroethylene and tetrachloroethylene) in ambient air. *Health Risk Analysis*, (4), 113-120.

[11] Çetin, M., & Demirci, O. K. (2016). Erzincan'da doğal gaz kullanımının hava kalitesine etkisi. *Erzincan University Journal of Science and Technology*, *9*(1), 8-18.

[12] Kalıpcı, E., & Başer, V. (2019). Coğrafi Bilgi Sistemi (CBS) ve hava kalitesi verileri kullanılarak Türkiye'nin hava kirliliğinin değerlendirilmesi. *Karadeniz Fen Bilimleri Dergisi*, *9*(2), 377-389.

[13] Li, X., Tolefe, E. C., Healy, R. M., Dorman, F. L., Kleywegt, S., Simpson, A. J., ... & Jobst, K. J. (2025). Exposing Halogenated Airborne Pollutants by Non-Targeted Screening of Passive Samplers Using Ion Mobility-Mass Spectrometry. *Environmental Science & Technology*, *59*(21), 10390-10399.

[14] Moura, P. C., & Vassilenko, V. (2022). Gas Chromatography–Ion Mobility Spectrometry as a tool for quick detection of hazardous volatile organic compounds in indoor and ambient air: A university campus case study. *European Journal of Mass Spectrometry*, *28*(5-6), 113-126.

[15] Ratnaningsih, W., Prayogo, W., Hidayahtullah, M. C., Azizah, R. N., Shabrina, H. M., & Fitria, L. (2024). Aır Qualıty Monıtorıng In Footwear Industrıal Areas Usıng Taıwan Aır Qualıty Monıtorıng Network (Taqmn) In Taıpeı Cıty. *Berkala Penelitian Teknologi Kulit, Sepatu, dan Produk Kulit*, *23*(2), 227-238.

[16] Baur, T., Amann, J., Schultealbert, C., & Schütze, A. (2021). Field study of metal oxide semiconductor gas sensors in temperature cycled operation for selective VOC monitoring in indoor air. *Atmosphere*, *12*(5), 647.

[17] Siregar, N. D., Situmorang, M., & Humaidi, S.(2024). Monitoring and Analyzing Air Quality in Several Locations around Medan City Using IoT-Based Integrated Sensors. International Journal of Current Science Research and Review, 7 (6),4301-4314.

[18] Wang, G., Jia, S., Niu, X., Liu, Y., Tian, H., Chen, X., & Shi, G. (2018). Detection of peroxyl radicals from polluted air by free radical reaction combined with liquid chromatography signal amplification technique. *Journal of Separation Science*, *41*(9), 1930-1937.

[19] Sitasuwan, P., Powers, T. W., Medwid, T., Huang, Y., Bare, B., & Lee, L. A. (2021). Enhancing the multi-attribute method through an automated and high-throughput sample preparation. In *MAbs* ,Taylor & Francis, (13,1).

[20] Ghosh, M., Chatterjee, P. N., Pradhan, M. K., & Salony, K. (2022). Assessment of Ambient Air quality in Industrial Cluster at Paradip (India) based on Air Quality Index (AQI). Eco. Env. & Cons. 28 (August Suppl. Issue): 2022; p104-S109

[21] Evans, A. R., Hebert, A. S., Mulholland, J., Lewis, M. J., & Hu, P. (2021). ID–MAM: a validated identity and multi-attribute monitoring method for commercial release and stability testing of a bispecific antibody. *Analytical Chemistry*, *93*(26), 9166-9173.

[22] Kamboj, K., Sisodiya, S., Mathur, A. K., Zare, A., & Verma, P. (2022). Assessment and spatial distribution mapping of criteria pollutants. *Water, Air, & Soil Pollution*, *233*(3), 82.

[23] Liu, P., Zhu, X., Wu, W., Ludwig, R., Song, H., Li, R., ... & Leone, A. M. (2019). Subunit mass analysis for monitoring multiple attributes of monoclonal antibodies. *Rapid Communications in Mass Spectrometry*, *33*(1), 31-40.