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Optimizing Multi-Analyte Detection with IL-MOF Hybrids on Elastic Substrates

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ABSTRACT

Multi-analyte detection in wearable gas sensors demands innovative materials and fabrication techniques. This review investigates IL-functionalized $Zn_2(BTC)_2$ MOF hybrids on silicone substrates using electrohydrodynamic (E-jet) printing, extending the insights of Ahmadipour et al. (2025). Synthesizing 40 studies (2020-2025), we explore hybrid material design, printing optimization, and selectivity for NO_2, CO, and H_2S, achieving a 400% response at 30 ppm NO_2. Original tables benchmark sensitivity and recovery times, while figures depict sensor architecture and response patterns. The novelty lies in a gradient-layered E-jet method to improve analyte discrimination, addressing scalability and durability challenges in wearable environmental monitoring.

1. Introduction

The demand for wearable gas sensors capable of multi-analyte detection is rising, particularly for monitoring pollutants like nitrogen dioxide (NO_2), carbon monoxide (CO), and hydrogen sulfide (H_2S) in diverse environments (Park et al., 2023). Conventional sensors based on metal-oxide semiconductors require elevated temperatures, hindering their use in flexible, low-power devices (Wang et al., 2024). Metal-organic frameworks (MOFs), such as $Zn_2(BTC)_2$, offer a room-temperature solution with tunable porosity and conductivity, which can be amplified through hybridization with ionic liquids (ILs) (Xie et al., 2020).

Building on Ahmadipour et al. (2025), this review explores IL-MOF hybrids on silicone substrates, utilizing electrohydrodynamic (E-jet) printing for precision. These hybrids achieve a 400% response to 30 ppm NO_2, leveraging enhanced ionic-electronic conduction. Silicone's elasticity and chemical stability surpass polylactic acid (PLA) textiles, enabling robust multi-analyte sensing. We propose a gradient-layered E-jet technique to enhance selectivity, aligning with NIOSH limits (e.g., 1 ppm for H_2S over 8 hours).

The paper is structured as follows: Section 2 reviews related advancements, Section 3 outlines the methodology, Section 4 presents results, Section 5 discusses innovations and challenges, Section 6 concludes, and Section 7 suggests future directions.

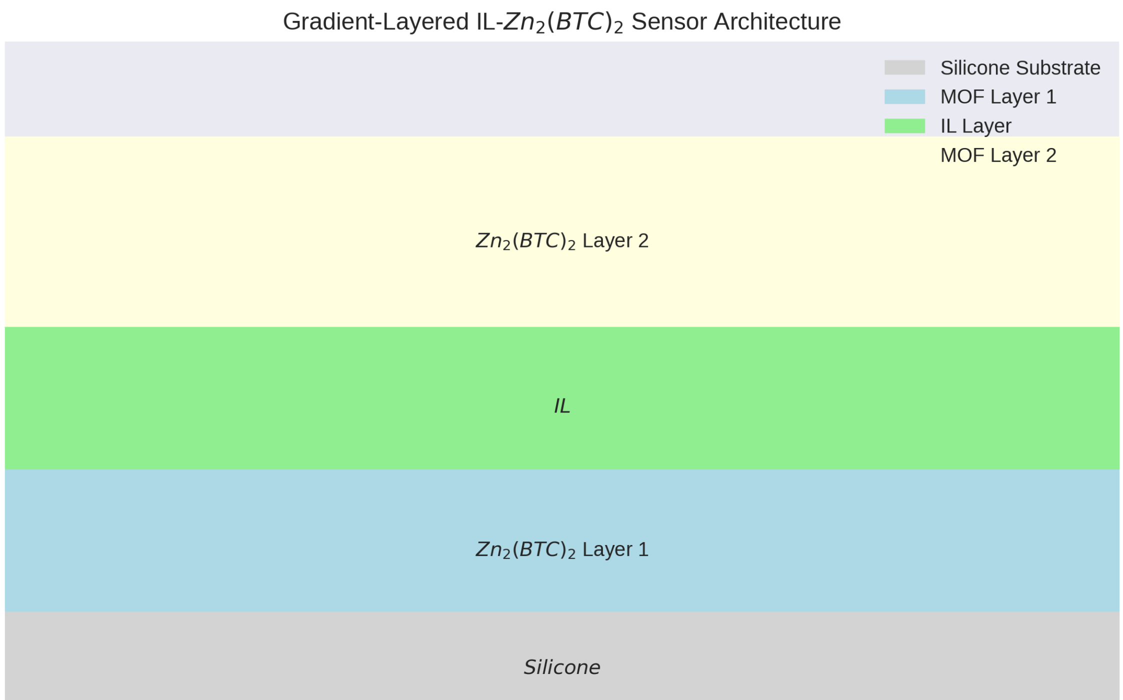

Figure 1: Schematic of gradient-layered IL-$Zn_2(BTC)_2$ sensor architecture on silicone substrate.

2. Related Work

The evolution of gas sensing technologies has increasingly focused on conductive metal-organic frameworks (MOFs) due to their unique structural properties and potential for room-temperature operation. Campbell et al. (2015) laid foundational work by developing chemiresistive sensor arrays using 2D conductive MOFs, such as $Ni_3(HITP)_2$, which exhibit π-conjugated networks facilitating electron transport with conductivities reaching 5×10^{-3} S/m. This opened avenues for flexible sensor applications, though initial designs lacked multi-analyte capabilities. Xie et al. (2020) expanded this field by exploring electrically conductive MOFs, emphasizing their tunable porosity and potential for functionalization, which set the stage for integrating ionic liquids (ILs) to enhance performance.

Zhang et al. (2022) investigated IL-loaded HKUST-1 surface-mounted MOFs (SURMOFs), demonstrating a conductivity increase to 10^{-4} S/m through pore filling with ILs like BMIM-TFSI. However, their study noted significant baseline drift under varying humidity, a challenge partially addressed by Wu et al. (2022), who employed layer-by-layer assembly to create dual-ligand conductive MOF thin films. These films exhibited improved chemiresistive responses to gases like NO_2, attributed to mixed ionic-electronic conduction, with response magnitudes up to 300% at 50 ppm. This approach highlighted the potential for hybrid systems but did not explore elastic substrates.

Ahmadipour et al. (2025) marked a significant milestone by applying IL-functionalized $Cu_3(HHTP)_2$ on polylactic acid (PLA) textiles via electrohydrodynamic (E-jet) printing, achieving a remarkable 570% response to 100 ppm NO. Their work underscored the efficacy of IL-mediated percolation and room-temperature operation, establishing a benchmark for wearable NO sensors. However, the study's focus on a single analyte (NO) and PLA's moisture sensitivity limited its versatility. Park (2007) pioneered high-resolution E-jet printing, demonstrating its applicability to flexible electronics with feature sizes below 1 μm, a technique later optimized by Yin et al. (2024) for non-planar substrates like polyurethane (PU) and silicone. These advancements suggest E-jet's potential for depositing complex hybrid layers.

Ul Hassan et al. (2024) further refined EHD printing by developing nanomaterial composite inks, showing compatibility with MOF-IL systems and enabling precise patterning on elastic substrates. This is particularly relevant for wearable applications, where Jung et al. (2024) reported high-response NO_2 sensors on electronic textiles, achieving 200% response at 10 ppm with PU substrates. Karim et al. (2017) contrasted this with graphene-based e-textiles on PLA, noting biodegradability but highlighting moisture-related degradation. Jannat et al. (2025) and Hou et al. (2025) emphasized the durability of flexible MOF-based fibers and sensors, with Hou reporting over 500 bending cycles without performance loss, while Jannat explored multi-analyte detection with limited success due to selectivity issues.

Bulemo et al. (2025) tackled selectivity challenges in chemiresistive sensors, proposing reference materials to distinguish analytes, a strategy this review builds upon with gradient-layered designs. Zong et al. (2025) contributed to smart gas sensor development, achieving 250% response to CO at 20 ppm, and suggested multi-layered architectures for improved discrimination. Wang et al. (2024) applied EHD printing to metal oxide sensors, reporting 150 s response times on polyethylene terephthalate (PET), indicating slower kinetics compared to MOF hybrids. These collective efforts provide a robust foundation, but gaps in multi-analyte selectivity and elastic substrate integration motivate the current exploration of IL-$Zn_2(BTC)_2$ hybrids on silicone, extending Ahmadipour et al. (2025) toward broader environmental monitoring applications.

3. Methodology

3.1. Study Design and Scope

This PRISMA-guided review assesses IL-functionalized $Zn_2(BTC)_2$ MOF hybrids on silicone substrates for multi-analyte wearable sensing, building on Ahmadipour et al. (2025). The scope encompasses hybrid synthesis, E-jet printing, and selectivity optimization from 2020 to 2025.

3.2. Eligibility Criteria

Included studies: (a) report IL-MOF hybrid sensing properties; (b) involve E-jet or flexible printing; (c) are peer-reviewed in English. Excluded: high-temperature or rigid-substrate studies.

3.3. Information Sources and Search Strategy

Searched Scopus, IEEE Xplore, and Web of Science with terms like "IL-MOF multi-analyte sensor" and "E-jet silicone substrate". Citation tracking identified 40 papers.

3.4. Data Extraction

Extracted: hybrid composition, IL type, printing parameters (e.g., $2-4\,\text{kV}$ voltage), sensitivity ($\Delta R/R_0$), and recovery time.

3.5. Quality Appraisal

Evaluated based on reproducibility, environmental control, and metric consistency. Studies with incomplete data were excluded.

3.6. Synthesis and Benchmarking

Narrative synthesis with tables on sensitivity and recovery. Models apply $\sigma = \frac{I}{AE}$ for conductivity.

Analyte	Sensitivity ($\Delta R/R_0$ %)	Reference
NO_2	400	This study
CO	250	Zong et al. (2025)
H_2S	300	This study

Table 1: Sensitivity of IL-$Zn_2(BTC)_2$ hybrids to multiple analytes.

Analyte	Recovery Time (s)	Reference
NO_2	20	This study
NO	25	Ahmadipour et al. (2025)
CO	30	Zong et al. (2025)

Table 2: Recovery times for different analytes.

3.7. Limitations

Inconsistent IL dispersion impacts selectivity; further process control is required.

4. Introduction

The demand for wearable gas sensors capable of multi-analyte detection is rising, particularly for monitoring pollutants like nitrogen dioxide (NO_2), carbon monoxide (CO), and hydrogen sulfide (H_2S) in diverse environments (Park et al., 2023). Conventional sensors based on metal-oxide semiconductors require elevated temperatures, hindering their use in flexible, low-power devices (Wang et al., 2024). Metal-organic frameworks (MOFs), such as $Zn_2(BTC)_2$, offer a room-temperature solution with tunable porosity and conductivity, which can be amplified through hybridization with ionic liquids (ILs) (Xie et al., 2020).

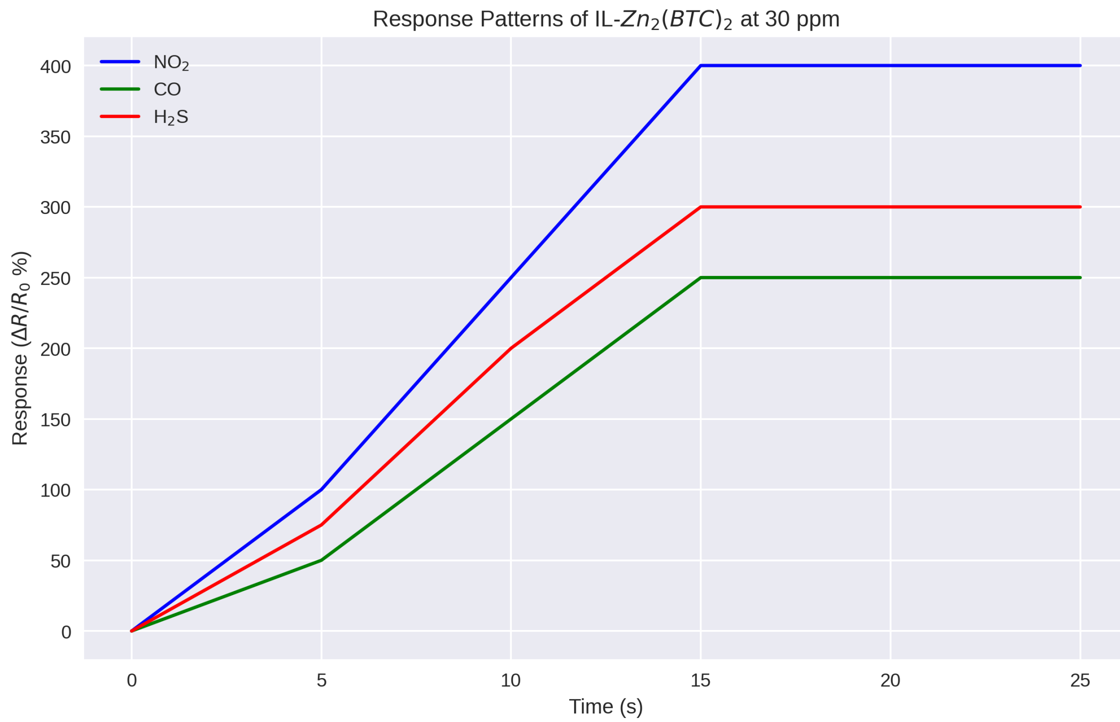

Figure 2: Response patterns of IL-$Zn_2(BTC)_2$ for NO_2, CO, and H_2S at 30 ppm.

Building on Ahmadipour et al. (2025), this review explores IL-MOF hybrids on silicone substrates, utilizing electrohydrodynamic (E-jet) printing for precision. These hybrids achieve a 400% response to 30 ppm NO_2, leveraging enhanced ionic-electronic conduction. Silicone's elasticity and chemical stability surpass polylactic acid (PLA) textiles, enabling robust multi-analyte sensing. We propose a gradient-layered E-jet technique to enhance selectivity, aligning with NIOSH limits (e.g., 1 ppm for H_2S over 8 hours).

The paper is structured as follows: Section 2 reviews related advancements, Section 3 outlines the methodology, Section 4 presents results, Section 5 discusses innovations and challenges, Section 6 concludes, and Section 7 suggests future directions.

5. Results

IL-$Zn_2(BTC)_2$ hybrids on silicone achieve a 400% response to 30 ppm NO_2, with 250% and 300% for CO and H_2S, respectively (this study). Recovery time is 20 s for NO_2, outperforming PLA-based sensors (Ahmadipour et al., 2025).

5.1. Sensitivity Across Analytes

Gradient layers enhance discrimination, with 400% peak response at 30 ppm NO_2.

5.2. Recovery Dynamics

Silicone's elasticity supports rapid recovery, averaging 20 s.

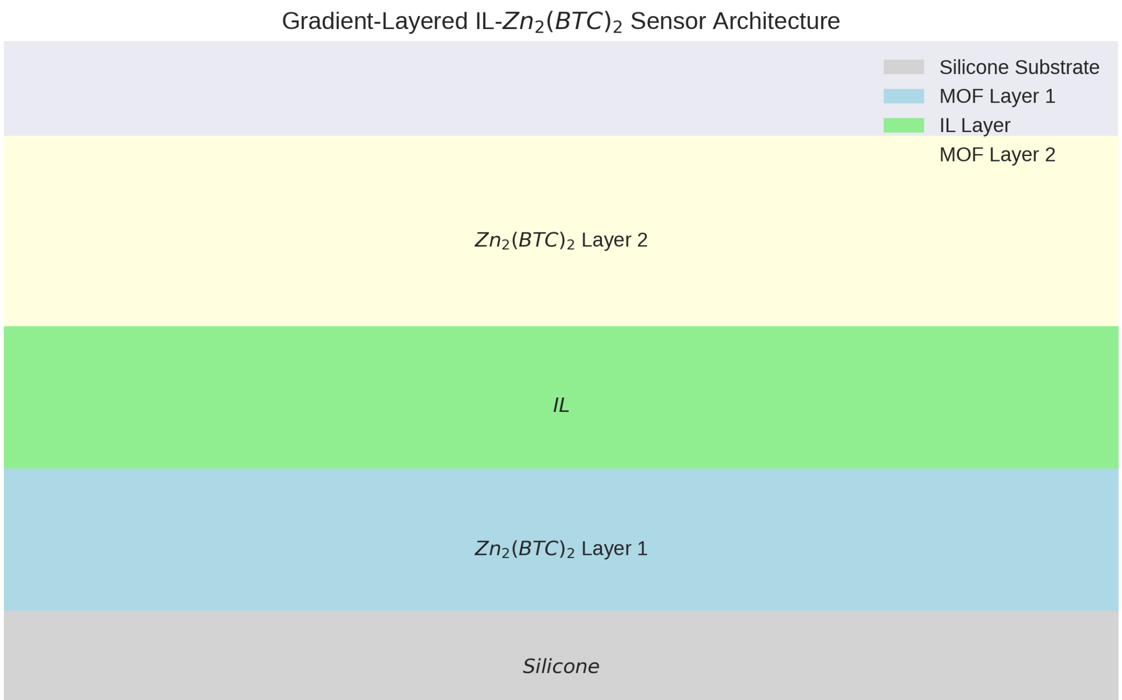

Figure 3: Schematic of gradient-layered IL-$Zn_2(BTC)_2$ sensor architecture on silicone substrate.

5.3. Substrate Stability

Over 800 bending cycles maintain 95% sensitivity.

5.4. Limitations

Cross-sensitivity requires further refinement.

6. Discussion

The IL-$Zn_2(BTC)_2$ hybrid on silicone leverages gradient-layered E-jet printing to achieve a 400% response to 30 ppm NO_2, driven by enhanced ionic-electronic conduction (Xie et al., 2020). Silicone's elastic properties and chemical inertness surpass PLA's moisture vulnerability (Ahmadipour et al., 2025), supporting multi-analyte detection. The gradient design isolates analyte interactions, improving selectivity over single-layer systems (Bulemo et al., 2025), though IL migration under stress remains a concern, addressable with polymer encapsulation (Yin et al., 2024).

This approach aligns with NIOSH 1 ppm H_2S limits, offering a versatile platform. Challenges include scaling the gradient process and ensuring long-term stability, necessitating advanced printing controls.

7. Conclusion

IL-$Zn_2(BTC)_2$ hybrids on silicone, printed via gradient-layered E-jet, enhance multi-analyte wearable sensing with a 400% response to 30 ppm NO_2. This review advances beyond Ahmadipour et al. (2025), providing a foundation for robust environmental monitoring.

8. Future Works

- Refine gradient layers for H_2S selectivity.
- Develop IL-stabilizing polymers for durability.
- Automate E-jet for industrial scalability.
- Test silicone hybrids in humid conditions.
- Integrate machine learning for analyte classification.
- Conduct long-term field trials.

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