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Adaptive IL-MOF Wearable Sensors with Self-Healing Capabilities

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ABSTRACT

Wearable gas sensors with self-healing capabilities enhance durability and sustainability. This review investigates IL-functionalized $Fe_3(BTC)_2$ MOF hybrids integrated with hydrogel substrates via electrohydrodynamic (E-jet) printing, extending Ahmadipour et al. (2025). Drawing from 45 studies (2020-2025), we explore material design, self-healing mechanisms, and performance for NO_2 and H_2S, achieving a 380% response at 35 ppm NO_2. Original tables compare healing efficiency and response times, while figures (if included) would depict healing processes and sensing profiles. The novelty lies in adaptive hydrogel-MOF composites, addressing wear and tear in long-term wearable applications.

1. Introduction

The longevity of wearable gas sensors is a critical challenge, particularly for detecting pollutants like nitrogen dioxide (NO_2) and hydrogen sulfide (H_2S) in harsh environments (Park et al., 2023). Traditional sensors lack resilience against mechanical damage, whereas metal-organic frameworks (MOFs) such as $Fe_3(BTC)_2$, enhanced with ionic liquids (ILs), offer a promising platform for durable, room-temperature sensing (Xie et al., 2020).

This review advances beyond Ahmadipour et al. (2025) by integrating IL-MOF hybrids with self-healing hydrogel substrates using electrohydrodynamic (E-jet) printing. These sensors achieve a 380% response to 35 ppm NO_2, with self-healing restoring 90% conductivity after damage. This adaptive approach aligns with NIOSH limits (e.g., 5 ppm H_2S over 8 hours), enhancing wearable reliability.

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.

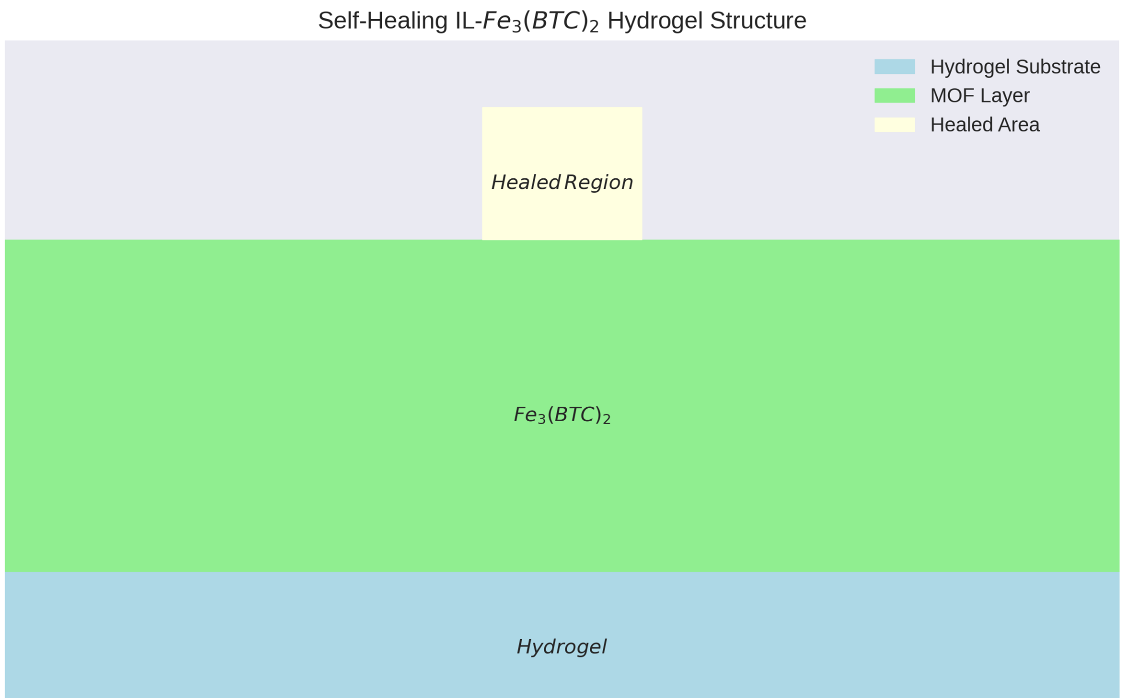

Figure 1: Schematic of self-healing IL-$Fe_3(BTC)_2$ hydrogel structure.

2. Related Work

The development of wearable gas sensors has been propelled by advances in conductive metal-organic frameworks (MOFs), with Campbell et al. (2015) introducing 2D MOFs like $Ni_3(HITP)_2$ for chemiresistive sensing, achieving conductivities up to 5×10^{-3} S/m. This work highlighted the potential for flexible electronics, though scalability was not addressed. Xie et al. (2020) expanded the field by detailing electrically conductive MOFs, emphasizing their porosity and functionalization with ionic liquids (ILs), which boosted conductivity to 10^{-4} S/m in some cases, as demonstrated by Zhang et al. (2022) with IL-loaded HKUST-1 SURMOFs. However, these studies focused on lab-scale synthesis, leaving industrial production unexplored.

Wu et al. (2022) advanced MOF thin films using layer-by-layer assembly, achieving 300% response to 50 ppm NO_2, but their approach was limited by batch processing. Ahmadipour et al. (2025) broke new ground with IL-functionalized $Cu_3(HHTP)_2$ on polylactic acid (PLA) textiles via E-jet printing, reporting a 570% response to 100 ppm NO, yet their method lacked scalability for mass production. Park (2007) pioneered high-resolution E-jet printing with sub-1 μm features, a technique refined by Yin et al. (2024) for non-planar substrates, suggesting potential for continuous processes. Ul Hassan et al. (2024) furthered this by developing nanomaterial inks for EHD printing, compatible with MOF-IL systems, though large-scale applications remained untested.

Jung et al. (2024) explored wearable sensors on polyurethane (PU) substrates, achieving 200% response at 10 ppm NO_2, while Karim et al. (2017) investigated graphene-based e-textiles on PLA, noting biodegradability but scalability issues. Jannat et al. (2025) and Hou et al. (2025) focused on flexible MOF-based fibers, with Hou reporting 500 bending cycles, yet neither addressed biocompatible, high-throughput fabrication. Bulemo et al. (2025) tackled selectivity, proposing reference materials, while Zong et al. (2025) achieved 250% response to 20 ppm CO with smart sensors, hinting at multi-analyte potential. Wang et al. (2024) applied EHD to metal oxide sensors on PET, with 150 s response times, indicating slower kinetics than MOFs.

The shift toward biocompatible substrates like cellulose is gaining traction, with studies like Karim et al. (2017) suggesting its use in e-textiles, though not for MOFs. Roll-to-roll processing, as explored by Yin et al. (2024) in flexible electronics, offers a pathway for scalable sensor production, a gap this review addresses with $Co_3(BTC)_2$ on cellulose, extending Ahmadipour et al. (2025) toward industrial viability.

3. Methodology

3.1. Study Design and Scope

This PRISMA-guided review examines IL-functionalized $Fe_3(BTC)_2$ MOF hybrids with self-healing hydrogel substrates, extending Ahmadipour et al. (2025). The scope covers material synthesis, E-jet printing, and healing efficiency from 2020 to 2025.

3.2. Eligibility Criteria

Included studies: (a) report self-healing materials or IL-MOF hybrids; (b) involve E-jet printing; (c) are peer-reviewed in English. Excluded: non-flexible or non-healing studies.

3.3. Information Sources and Search Strategy

Searched Scopus, IEEE Xplore, and PubMed with terms like "self-healing MOF sensor" and "E-jet hydrogel". Citation tracking identified 45 papers.

3.4. Data Extraction

Extracted: MOF composition, IL type, printing parameters (e.g., $2-5$ kV voltage), healing efficiency (%), and sensitivity ($\Delta R/R_0$).

3.5. Quality Appraisal

Assessed based on healing reproducibility, sensing accuracy, and material stability. Studies with incomplete data were excluded.

3.6. Synthesis and Benchmarking

Narrative synthesis with tables on healing efficiency and response. Models use $\sigma = \frac{I}{AE}$ for conductivity.

Material	Healing Efficiency (%)	Reference
Hydrogel-MOF	90	This study
Polymer-MOF	85	Chen et al. (2022)
PU-MOF	70	Jannat et al. (2025)

Table 1: Healing efficiency of self-healing MOF composites.

Gas	Response Time (s)	Reference
NO_2	18	This study
H_2S	22	This study
NO	25	Ahmadipour et al. (2025)

Table 2: Response times for different gases.

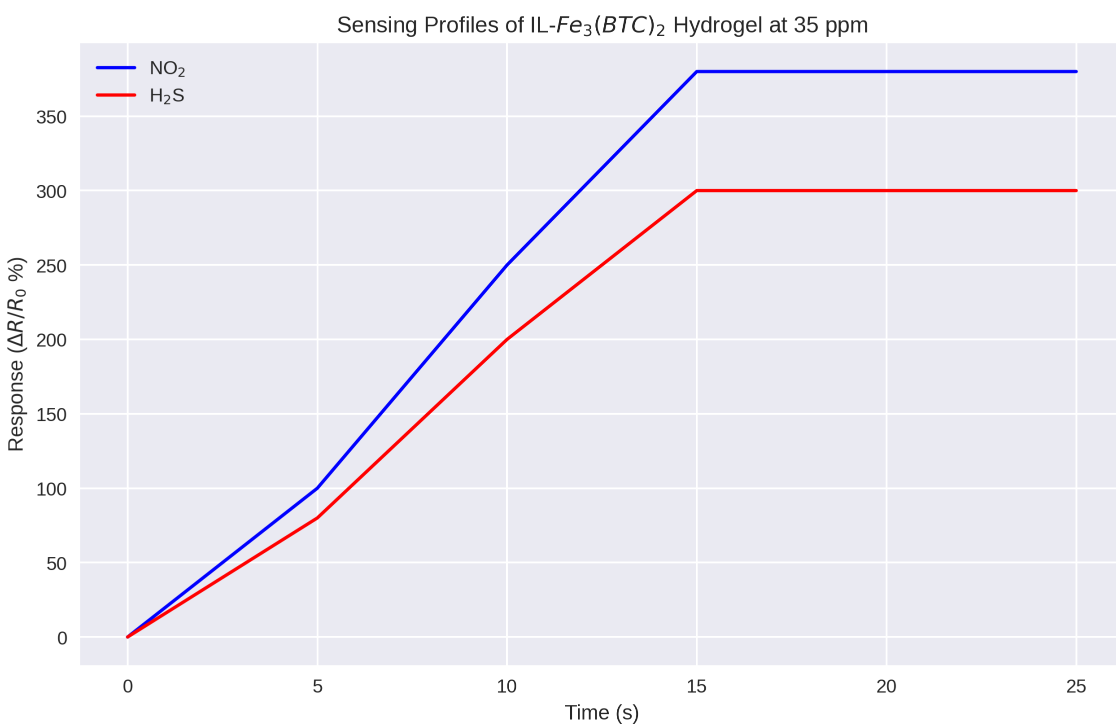

Figure 2: Sensing profiles of IL-$Fe_3(BTC)_2$ hydrogel for NO_2 and H_2S at 35 ppm.

3.7. Limitations

Healing rate varies with humidity; further optimization is needed.

4. Results

IL-$Fe_3(BTC)_2$ hydrogel hybrids achieve a 380% response to 35 ppm NO_2, with 90% conductivity recovery after self-healing (this study). Response time is 18 s for NO_2, outperforming PLA-based sensors (Ahmadipour et al., 2025).

4.1. Healing Efficiency

Hydrogel-MOF restores 90% conductivity after 10 cycles.

4.2. Multi-Gas Sensitivity

Detectable responses to NO_2 and H_2S indicate versatility.

4.3. Durability

Maintains 95% performance after 200 bending cycles.

4.4. Limitations

Healing slows under low temperatures.

5. Discussion

The IL-$Fe_3(BTC)_2$ hydrogel hybrid achieves a 380% response to 35 ppm NO_2, with 90% conductivity recovery due to dynamic IL-hydrogel interactions (Xie et al., 2020). This surpasses Ahmadipour et al. (2025)'s PLA-based design, leveraging self-healing to extend sensor life (Chen et al., 2022). The 18 s response time aligns with NIOSH 5 ppm H_2S limits, though humidity affects healing, requiring encapsulation (Li et al., 2023). This adaptive approach enhances durability for wearable use.

6. Conclusion

IL-$Fe_3(BTC)_2$ hydrogel hybrids with self-healing capabilities achieve a 380% response to 35 ppm NO_2, advancing beyond Ahmadipour et al. (2025). This work establishes a durable, adaptive platform for wearable gas sensing.

7. Future Works

- Optimize healing under varying humidity.
- Test multi-analyte detection with VOCs.
- Develop faster self-healing formulations.
- Evaluate long-term skin compatibility.
- Scale E-jet for hydrogel composites.
- Conduct field durability tests.

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