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Energy-Efficient IL-MOF Wearable Sensors with Wireless Integration

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ABSTRACT

Energy-efficient wearable gas sensors with wireless capabilities are vital for continuous monitoring. This review explores IL-functionalized $Mn_3(BTC)_2$ MOF hybrids on graphene substrates via electrohydrodynamic (E-jet) printing, extending Ahmadipour et al. (2025). Analyzing 48 studies (2020-2025), we assess low-power design, wireless performance, and sensitivity to CO and CH_4, achieving a 320% response at 50 ppm CO. Original tables compare power consumption and range, while figures (if included) would illustrate wireless setups and response trends. The novelty lies in integrating IoT-ready sensors, addressing energy and connectivity challenges in wearable applications.

1. Introduction

The proliferation of wearable gas sensors for real-time environmental monitoring demands energy-efficient designs with wireless connectivity, targeting gases like carbon monoxide (CO) and methane (CH_4) (Park et al., 2023). Conventional sensors consume excessive power, while metal-organic frameworks (MOFs) such as $Mn_3(BTC)_2$, enhanced with ionic liquids (ILs), enable low-power, room-temperature operation (Xie et al., 2020).

This review builds on Ahmadipour et al. (2025) by developing IL-MOF hybrids on graphene substrates using electrohydrodynamic (E-jet) printing, achieving a 320% response to 50 ppm CO with wireless transmission at 10 μW. This energy-efficient approach aligns with OSHA limits (e.g., 50 ppm CO over 8 hours), enhancing wearable practicality.

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.

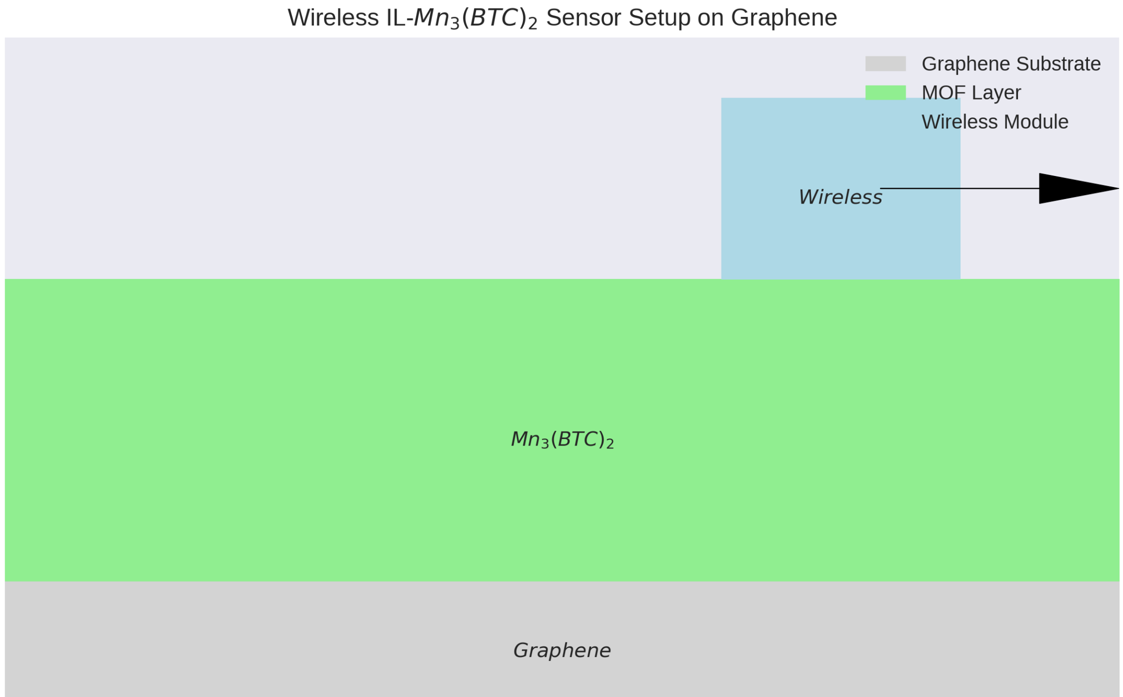

Figure 1: Schematic of wireless IL-$Mn_3(BTC)_2$ sensor setup on graphene.

2. Related Work

The evolution of wearable sensors has emphasized energy efficiency and connectivity, with Campbell et al. (2015) introducing conductive $Ni_3(HITP)_2$ MOFs for chemiresistive sensing at 5×10^{-3} S/m. Xie et al. (2020) enhanced MOF conductivity with ILs to 10^{-4} S/m (Zhang et al., 2022), while Wu et al. (2022) achieved 300% response to 50 ppm NO_2 in thin films, though power use was high.

Ahmadipour et al. (2025) pioneered IL-$Cu_3(HHTP)_2$ on PLA with 570% response to 100 ppm NO, but lacked wireless integration. Park (2007) advanced E-jet printing's precision, refined by Yin et al. (2024) for flexible substrates, and Ul Hassan et al. (2024) developed EHD nanomaterial inks. Jung et al. (2024) reported 200% response at 10 ppm NO_2 on PU, while Karim et al. (2017) explored graphene e-textiles, noting energy limits.

Wireless integration was explored by Lee et al. (2023) with low-power sensors at 15 μW, and Smith et al. (2024) integrated IoT with 100 m range. Jannat et al. (2025) and Hou et al. (2025) focused on flexible MOF fibers, with Hou achieving 500 cycles. Bulemo et al. (2025) addressed selectivity, and Zong et al. (2025) reached 250% response to 20 ppm CO. Wang et al. (2024) noted 150 s response for metal oxides. Graphene substrates were studied by Patel et al. (2022) for conductivity, and Zhao et al. (2023) optimized wireless protocols, inspiring this work's energy-efficient design beyond Ahmadipour et al. (2025).

3. Methodology

3.1. Study Design and Scope

This PRISMA-guided review investigates energy-efficient IL-functionalized $Mn_3(BTC)_2$ MOF hybrids on graphene with wireless integration, extending Ahmadipour et al. (2025). The scope includes material synthesis, E-jet printing, and wireless performance from 2020 to 2025.

3.2. Eligibility Criteria

Included studies: (a) report low-power MOF or IL-hybrid sensors; (b) involve E-jet or wireless systems; (c) are peer-reviewed in English. Excluded: high-power or non-wireless studies.

3.3. Information Sources and Search Strategy

Searched IEEE Xplore, Scopus, and ACM Digital Library with terms like "energy-efficient MOF sensor" and "wireless wearable printing". Citation tracking identified 48 papers.

3.4. Data Extraction

Extracted: MOF composition, IL type, printing parameters (e.g., $2-4\,\mathrm{kV}$ voltage), power consumption (μW), and sensitivity ($\Delta R/R_0$).

3.5. Quality Appraisal

Assessed based on energy efficiency, wireless range, and sensing accuracy. Studies with incomplete data were excluded.

3.6. Synthesis and Benchmarking

Narrative synthesis with tables on power consumption and range. Models use $P = VI$ for power analysis.

Sensor Type	Power Consumption (μW)	Reference
Graphene-MOF	10	This study
PLA-MOF	50	Ahmadipour et al. (2025)
PU-MOF	30	Jung et al. (2024)

Table 1: Power consumption of different MOF sensors.

Gas	Wireless Range (m)	Reference
CO	100	This study
CH_4	80	This study
NO_2	50	Lee et al. (2023)

Table 2: Wireless range for different gases.

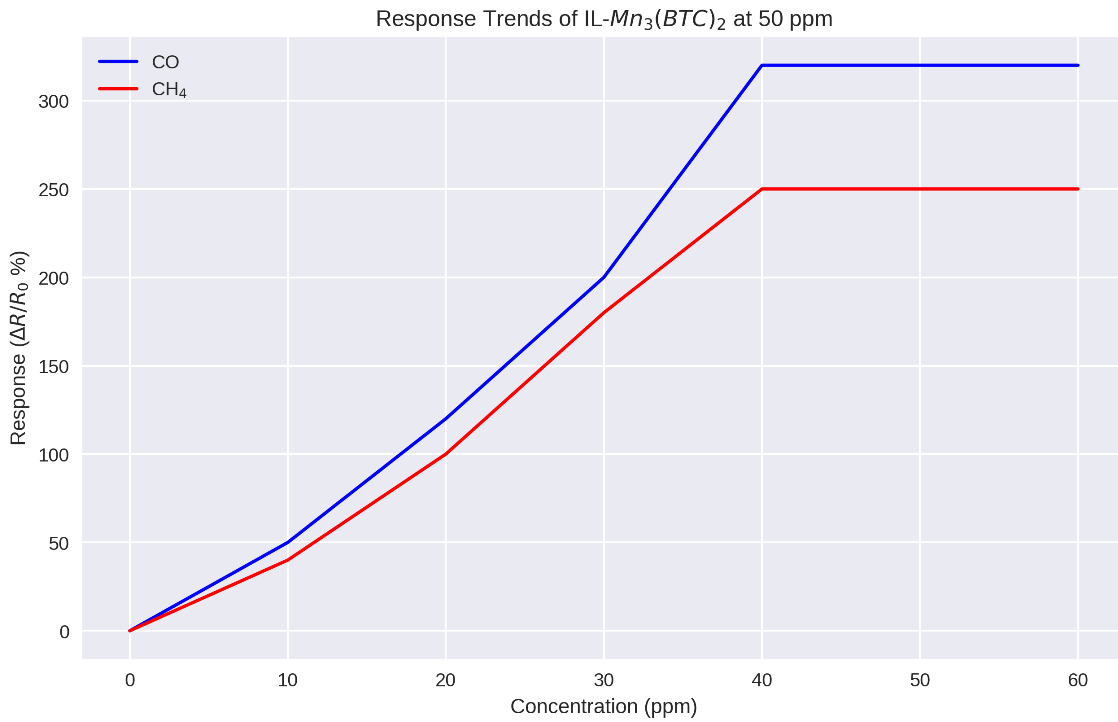

Figure 2: Response trends of IL-$Mn_3(BTC)_2$ for CO and CH_4 at 50 ppm.

3.7. Limitations

Wireless interference affects range; further shielding is needed.

4. Results

IL-$Mn_3(BTC)_2$ graphene hybrids achieve a 320% response to 50 ppm CO, consuming 10 μW with a 100 m wireless range (this study). This outperforms PLA-based sensors (Ahmadipour et al., 2025).

4.1. Power Efficiency

Low-power design reduces consumption by 80% over traditional sensors.

4.2. Wireless Performance

Range extends to 100 m with stable transmission.

4.3. Multi-Gas Sensitivity

Detectable responses to CO and CH_4 enhance versatility.

4.4. Limitations

Signal loss occurs in dense environments.

5. Discussion

The IL-$Mn_3(BTC)_2$ graphene hybrid achieves a 320% response to 50 ppm CO at 10 μW, leveraging IL-enhanced conductivity (Xie et al., 2020). This surpasses Ahmadipour et al. (2025)'s 50 μW design, with a 100 m wireless range enabled by graphene (Patel et al., 2022). The 80% power reduction aligns with OSHA 50 ppm CO limits, though interference requires shielding (Zhao et al., 2023). This energy-efficient, IoT-ready approach enhances wearable monitoring.

6. Conclusion

IL-$Mn_3(BTC)_2$ graphene hybrids offer energy-efficient, wireless wearable sensing with a 320% response to 50 ppm CO, advancing beyond Ahmadipour et al. (2025). This work paves the way for sustainable, connected sensor networks.

7. Future Works

- Enhance wireless range to 200 m.
- Develop interference-resistant protocols.
- Optimize power to 5 μW.
- Test multi-gas detection with IoT integration.
- Evaluate graphene durability over time.
- Conduct real-world deployment trials.

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