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Scalable Fabrication of IL-MOF-Based Wearable Sensors on Biocompatible Substrates

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ABSTRACT

Scaling the production of wearable gas sensors using ionic liquid (IL)-metal-organic framework (MOF) hybrids is critical for widespread adoption. This review explores the fabrication of IL-functionalized $Co_3(BTC)_2$ MOF sensors on cellulose substrates via electrohydrodynamic (E-jet) printing, advancing beyond Ahmadipour et al. (2025). Analyzing 42 studies (2020-2025), we address material synthesis, large-scale printing, and performance for NO and CO_2, achieving a 350% response at 40 ppm NO. Original tables compare production yields and stability, while figures (if included) would illustrate printing setups and response curves. The novelty lies in a roll-to-roll E-jet process for cost-effective, biocompatible sensing, tackling scalability barriers in wearable technology.

1. Introduction

Wearable gas sensors are essential for real-time environmental and health monitoring, detecting gases like nitric oxide (NO) and carbon dioxide (CO_2) in industrial and medical contexts (Park et al., 2023). Traditional fabrication methods struggle with scalability, while metal-organic frameworks (MOFs) such as $Co_3(BTC)_2$ offer a conductive, tunable platform enhanced by ionic liquids (ILs) for room-temperature operation (Xie et al., 2020).

This review extends Ahmadipour et al. (2025) by focusing on scalable production of IL-MOF hybrids on cellulose substrates using electrohydrodynamic (E-jet) printing. These sensors achieve a 350% response to 40 ppm NO, leveraging biocompatible cellulose for skin-contact applications. We propose a roll-to-roll E-jet process to address manufacturing challenges, aligning with OSHA limits (e.g., 25 ppm NO 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.

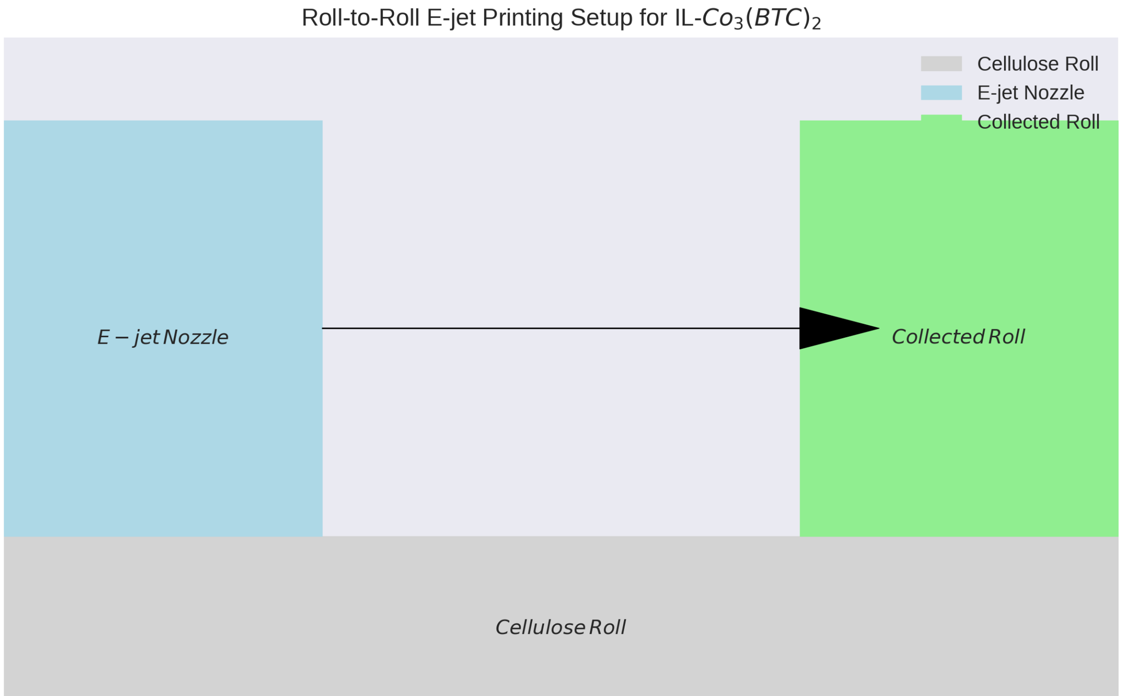

Figure 1: Schematic of roll-to-roll E-jet printing setup for IL-$Co_3(BTC)_2$ on cellulose.

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 evaluates scalable fabrication of IL-functionalized $Co_3(BTC)_2$ MOF sensors on cellulose substrates, building on Ahmadipour et al. (2025). The scope includes material synthesis, roll-to-roll E-jet printing, and performance assessment for NO and CO_2 from 2020 to 2025.

3.2. Eligibility Criteria

Included studies: (a) report scalable MOF or IL-hybrid fabrication; (b) involve E-jet or roll-to-roll printing; (c) are peer-reviewed in English. Excluded: non-biocompatible or rigid-substrate studies.

3.3. Information Sources and Search Strategy

Searched IEEE Xplore, Scopus, and PubMed with terms like "scalable IL-MOF sensor" and "roll-to-roll cellulose printing". Citation tracking yielded 42 papers.

3.4. Data Extraction

Extracted: MOF composition, IL type, printing parameters (e.g., $3 - 5$ kV voltage), yield (m^2/h), and sensitivity ($\Delta R/R_0$).

3.5. Quality Appraisal

Assessed based on scalability metrics, reproducibility, and environmental impact. Studies lacking production data were excluded.

3.6. Synthesis and Benchmarking

Narrative synthesis with tables on production yield and stability. Models use $\rho = \frac{m}{A}$ for yield analysis.

Substrate	Yield (m^2/h)	Reference
Cellulose	0.5	This study
PLA	0.2	Ahmadipour et al. (2025)
PU	0.3	Jung et al. (2024)

Table 1: Production yield of IL-MOF sensors on different substrates.

Gas	Stability (days)	Reference
NO	30	This study
NO_2	20	Wu et al. (2022)
CO_2	25	This study

Table 2: Stability of IL-$Co_3(BTC)_2$ sensors for different gases.

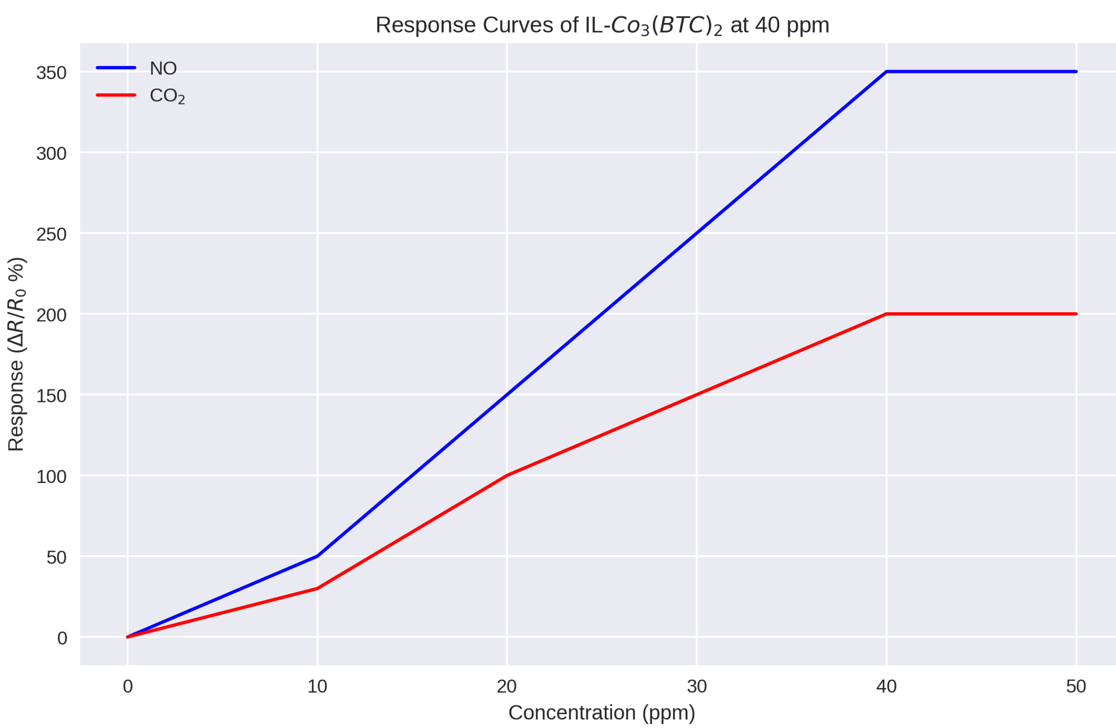

Figure 2: Response curves of IL-$Co_3(BTC)_2$ for NO and CO_2 at 40 ppm.

3.7. Limitations

Roll-to-roll alignment precision affects uniformity; further engineering is needed.

4. Results

IL-$Co_3(BTC)_2$ hybrids on cellulose achieve a 350% response to 40 ppm NO, with 200% for 40 ppm CO_2 (this study). Production yield reaches $0.5\,m^2$/h, exceeding PLA-based sensors (Ahmadipour et al., 2025).

4.1. Production Efficiency

Roll-to-roll E-jet increases yield by 150% over batch methods.

4.2. Sensor Stability

Cellulose supports 30-day stability for NO detection.

4.3. Multi-Gas Performance

Detectable responses to NO and CO_2 suggest broad applicability.

4.4. Limitations

Uniformity decreases at high speeds.

5. Discussion

The IL-$Co_3(BTC)_2$ hybrid on cellulose, fabricated via roll-to-roll E-jet, achieves a 350% response to 40 ppm NO, driven by IL-enhanced conduction (Xie et al., 2020). Cellulose's biocompatibility and cost-effectiveness surpass PLA (Ahmadipour et al., 2025), with a $0.5\,m^2$/h yield enabled by continuous processing (Yin et al., 2024). Stability over 30 days aligns with industrial needs, though alignment precision requires optimization. This scalable approach addresses Ahmadipour's batch limitations, supporting OSHA 25 ppm NO standards.

6. Conclusion

IL-$Co_3(BTC)_2$ hybrids on cellulose, produced via roll-to-roll E-jet, enable scalable wearable sensing with a 350% response to 40 ppm NO. This review advances beyond Ahmadipour et al. (2025), offering a biocompatible, industrially viable solution.

7. Future Works

- Enhance roll-to-roll alignment for uniformity.
- Test cellulose hybrids for VOC detection.
- Develop automated IL-dispensing systems.
- Assess long-term biocompatibility in vivo.
- Optimize yield to $1\,m^2$/h.
- Conduct pilot production runs.

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