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Metal-Organic Frameworks: Advanced Porous Materials for Multifunctional and Sustainable Applications

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ABSTRACT

Metal-organic frameworks (MOFs) are advanced nanomaterials gaining attention in present times owing to their impressive properties and applications. These are synthesized by organic ligands linked to the metal ion by coordinate bond. There are many properties of MOFs *i.e.,* large surface area, high porosity and functional group variability which make them significant to be utilised in wide-range applications. Some of the prominent applications of MOFs include gas storage, environmental remediation, controlled/slow-release carrier for agrochemicals and energy storage. Present article highlights the importance and application of MOFs along with the composition, types, advantages and challenges for future perspectives.

INTRODUCTION:

Metal-Organic Frameworks (MOFs) are advanced nanomaterials synthesised by metal ions and organic ligands to form a porous crystalline structure. The linkage of different multidentate ligands to the metal ion results in the formation of one, two or three-dimensional coordination frameworks. The porous structure of MOFs enables them to exhibit enough pore volume and channels in which wide variety of guest molecules can be accommodated (Chakraborty *et al.,* 2025).

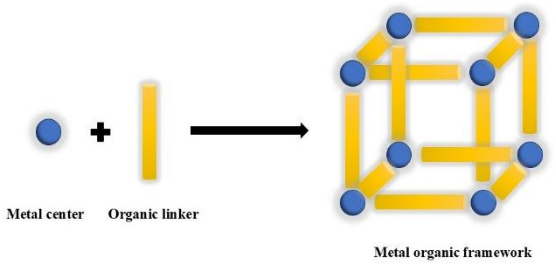


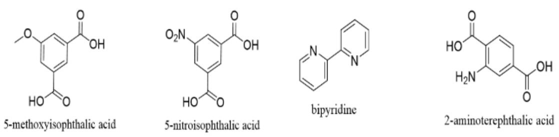
Figure 1: General structure of MOFs

MOFs are composed of two major components:

1. **Metal ions**: Transition metals play important role in the synthesis of MOFs due to their diverse oxidation states. Commonly used metal ions are:

Types	Examples
Divalent transition metals (M^{2+})	Zn^{2+}, Cu^{2+}, Co^{2+} etc
Trivalent transition metals	Fe^{3+}, Cr^{3+} etc.
Tetravalent metals	Zr^{4+}, Ti^{4+} etc.
Lanthanides & Actinides	Rare-earth ions e.g. Ce^{3+}, Eu^{3+} etc.

2. **Organic ligands**: Carboxylate-based linkers are widely used owing to their strong coordination ability and structural versatility. Some common ligands are:



Historical context of MOFs:

Richard Robson and his co-workers proposed a rational design of extensive coordination networks by linking metal ions with rigid organic linkers. The work emphasised the formation of three-dimensional frameworks exhibiting porosity and crystallinity. Robson's pioneering contribution laid the foundation of study of modern systematically engineered metal-organic frameworks. In 1990, Susumu Kitagawa demonstrated the potential of porous coordination polymers in the adsorption of gases highlighting the capability of functional porous materials. The advancement in MOF's chemistry was carried by Omar M. Yaghi, who reported the formation of a porous and highly stable MOF-5 in 1999. The discovery led to the development of many other families of MOFs *i.e.,* MIL, UiO, HKUST, ZIF, IRMOF etc.

Most prominent recognition to MOFs was achieved by Richard Robson, Susumu Kitagawa and Omar M. Yaghi, who achieved Nobel Prize in Chemistry in 2025 for their significant contribution in the development and application of metal-organic frameworks.

Types of metal-organic framework:

MOFs are divided into a number of families. Some of the prominent families of MOFs, developed and applied are following:

- ❖ IRMOFs (Isoreticular Metal-Organic Frameworks)
- ❖ MIL (Materials of Institute Lavoisier)
- ❖ UiO (University of Oslo)
- ❖ ZIFs (Zeolite Imidazolate Frameworks)
- ❖ PCNs (Porous Coordination Networks)

Properties of MOFs:

MOFs exhibit a wide range of properties significant for versatile applications. The framework exhibits high porosity and pore volume responsible for adsorption-based applications. Porosity can be tuned according to specific application by selecting variable metal ions and organic linkers. MOFs also exhibit highly ordered and crystalline structures attributed to the well-defined arrangement of metal ions and the coordinating linkers. Selective adsorption and catalytic behaviour are mainly dependent on the porosity, functional group and metal sites to capture molecules. Large proportion of MOFs depicts high thermal and chemical stability under varied environment. All these properties including low density and high void volume are responsible for the utilisation of MOFs in advanced material sciences (Chandra *et al.,* 2026).

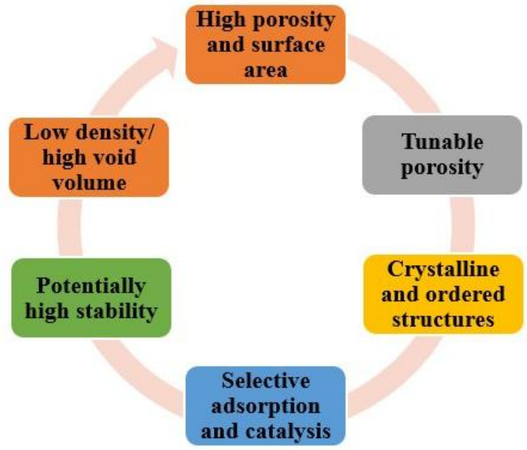


Figure 2: Various applications of MOFs

Applications of MOFs:

MOFs are being utilised in wide variety of applications:

1. **Gas storage and separation**:

Hydrogen: Many MOFs are reported for hydrogen storage and are useful for the development of clean energy storage systems.

Methane: Natural gas is being stored in many MOFs families with high concentrations upto 50% by weight.

Carbon dioxide: MOFs are selectively synthesised to store carbon dioxide gas owing to chemical functionality. This is significant for capturing and reducing greenhouse-gas emissions.

2. **Catalysis**: MOFs are involved in heterogeneous catalysis in variety of reactions including,

Oxidation and reduction: Oxidation of organic compounds and reduction of pollutants in the environment

Photocatalysis: MOFs absorb light and generate reactive species which is helpful in degrading pollutants and driving chemical reactions.

Other reactions: MOFs can act as catalytic active sites for many reactions like hydrogenation, organic conversions etc

3. **Environmental remediation**:

Heavy metal adsorption: MOFs can adsorb and remove ions such as Pb^{2+}, Cd^{2+}, Hg^{2+} etc (Sharmila *et al.,* 2026).

Dyes: They show photocatalytic degradation of textile dyes and waste from the industries.

Medical pollutants: MOFs are being developed in the decontamination of chemical waste from pharmaceutical field.

4. **Drug delivery and Biomedical Applications:**

Drug carrier: The porous structure of MOFs enables them to accommodate many drug molecules.

Controlled release: These are applied in the field of biomedical delivery systems as nanocarriers for a number of drugs.

Biosensing: MOFs have fluorescence and electrochemical based response by interacting with selective chemical species.

5. **Chemical and biosensors**: The interaction between MOF and molecules is studied as a fluorescent or electrochemical signal.

Gases: Sensing of CO_2, H_2 etc

Metal ions: Detection of Pb^{2+}, Cu^{2+}

Agrochemicals: Detection of fertilisers, pesticides, fungicides etc

Biological compounds: Carbohydrates, proteins, fats etc

6. **Agricultural applications**: Many articles reported the controlled delivery of agrochemicals making them a sustainable choice.

Fertilisers: Urea, NPK etc.

Pesticides: Mancozeb, Glyphosate, Dichlorvos etc.

Limitations and overcoming factors:

Despite importance of MOFs in wide-ranging applications, there are still some limitations linked to MOFs:

1. **High synthesis cost:** The synthesis of MOFs requires expensive linkers, metal precursors and solvents making the final cost high. The synthetic mechanisms should use more greener approaches to reduce overall cost.

2. **Large scale production:** Laboratory scale synthesis of MOFs results in regular crystallinity, porosity and other parameters but these change during the scale-up. Researchers should aim to mitigate challenges related to pellet formation, coating regularity and other factors (Wright *et al.,* 2025).

3. **Stability:** While most of MOFs are stable under variable conditions, some may undergo degradation in the structure on the exposure of changing water, pH, temperature or chemical environment. The instability limits their application in prominent areas.

4. **Biosafety concerns:** Toxicity of MOFs leads to serious concerns in the metabolic process in plants, animals and microorganisms depending on the type of precursors used. So, comprehensive biological study and essential modification of MOF should be considered.

5. **Recyclability and sustainability:** Repeated adsorption-desorption lead to decline in the recyclability and sustainability which can be enhanced by using water-based or solvent-free synthesis and using waste-derived precursors.

SUMMARY:

Metal-organic frameworks have been classified as one of the prominent class of nanomaterials due to their significant properties. They find applications in a number of fields including gas storage, catalysis, environmental remediation, drug delivery and agricultural release systems. Exceptional surface area, tuneable pore structures and functional group variability make them excellent candidate over other materials. Along with the advantages, some challenges are still present *i.e.,* high cost, large scale production, thermal/chemical stability, biosafety and recyclability. These problems can be solved by employing greener mechanisms and sustainable modifications during each stage of synthesis. Addressing these limitations is essential for the advancement of MOFs from potential porous materials to sustainable and commercially viable materials.

Overall, MOFs are promising materials in the advancement of modern science and technology.

REFERENCES:

Chakraborty, S., Menon, D., Mikulska, I., Pfrang, C., Fairen-Jimenez, D., Misra, S.K. and Lynch, I., 2025. Make metal–organic frameworks safe and sustainable by design for industrial translation. Nature Reviews Materials 10(3): 167-169.

Chandra, P., Sahoo, S., Pandey, P.K., Dey, R.K., Biswal, R.P., Pati, D.K., Tiwari, K., Chakraborty, C. and Chakroborty, S., 2026. Copper-based metal–organic frameworks for sustainable catalysis: mechanistic Insights, stability, and emerging research directions. ACS omega 11(6): 8911-8939.

Sharmila, V.G., Kumar, M.D. and Tamilarasan, K., 2026. Machine learning-driven advances in metal-organic framework nanomaterials for wastewater treatment: developments and challenges. Separation & Purification Reviews 55(1): 35-55.

Wright, A.M., Kapelewski, M.T., Marx, S., Farha, O.K. and Morris, W., 2025. Transitioning metal–organic frameworks from the laboratory to market through applied research. Nature materials 24(2): 78-187.