Emerging Trends of Metal Organic Framework in Pharmaceuticals : A Brief Review

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Abstract:- Metal–organic frameworks (MOFs) have emerged as a versatile class of materials with enormous potential in several fields, including the pharmaceutical industry. This review provides an overview of the recent progress and applications of MOFs in drug research and development. It underscored the unique properties of MOFs, such as high surface area, tunable pore size, and versatile functionalities, which make them promising candidates for drug delivery, imaging, catalysis, gas storage, and antimicrobial applications. In addition, it highlights the challenges and future directions in the use of MOFs for medical purposes, including stability, biocompatibility, scalable synthesis, and regulatory considerations.

Keywords:- *Metal-Organic Frameworks, Mofs, Pharmaceuticals, Drug Delivery, Imaging, Catalysis, Gas Storage, Antimicrobial, Challenges, Future Perspectives.*

I. INTRODUCTION

Metal-organic frameworks (MOF) represent a class of porous materials composed of metal ions or clusters linked by organic bonds. The tunable nature of MOFs allows precise control of their structure and properties, making them very versatile for a variety of applications. In recent years, there has been a growing interest in exploring the potential of MOFs in the pharmaceutical industry due to their unique properties and functions. Metal-organic frameworks (MOFs) represent an interesting class of porous materials that have attracted considerable attention in the pharmaceutical industry[1]. These materials are made of metal ions or clusters bound together by organic binders, resulting in a highly porous structure with tunable properties. The unique properties of MOFs, such as their large surface area, large pore volume, and tunable framework composition, make them a versatile platform for various pharmaceutical applications. The use of MOFs in medicine has expanded rapidly in recent years due to their ability to solve key problems in drug delivery, imaging, diagnosis and therapy. The tunable nature of MOFs enables precise control of their physicochemical properties, enabling tailored solutions for specific biomedical needs. In addition, the modular structure of MOFs facilitates the incorporation of functional moieties such as targeting ligands, imaging agents and therapeutic payloads, making them ideal candidates for advanced drug delivery systems[2].Looking for innovative solutions to the challenges of drug delivery, diagnosis and therapy in the pharmaceutical industry, researchers are increasingly turning to unusual materials with unique properties. One such class of materials that has pioneered this effort is metal-organic frameworks (MOFs). MOFs, often called "crystal sponges", are a family of porous materials built from metal ions or clusters coordinated to organic ligands[3,4].

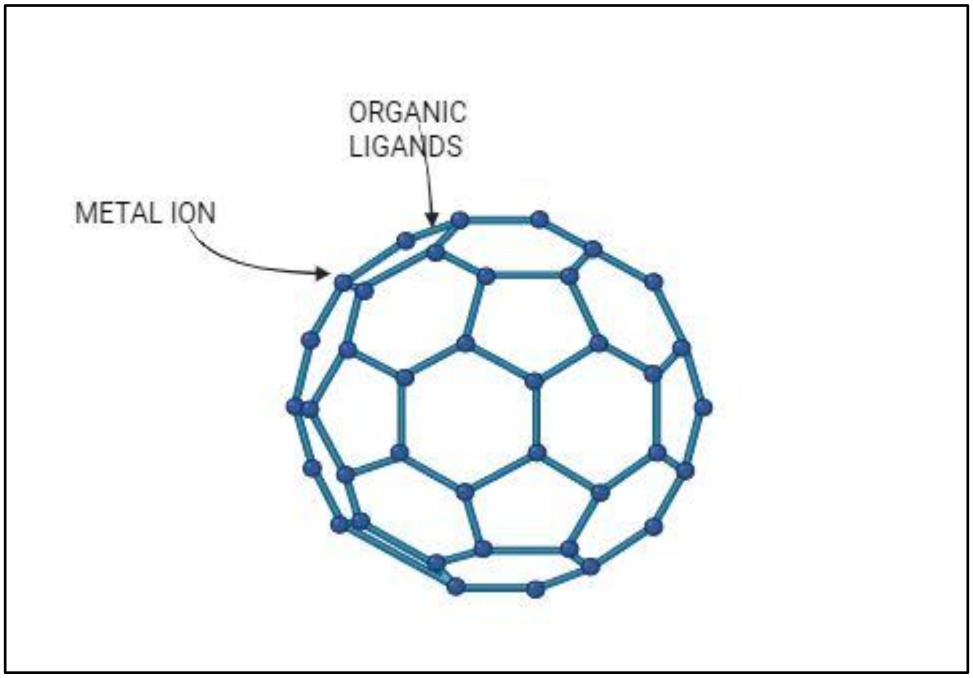

Fig No. 1 Metal Organic Framework

This versatile architecture results in countless pores and channels similar to a molecular scaffold, which can be precisely adapted for different applications[5]. The pharmaceutical arena offers particularly fertile ground for the study of MOFs, as there is an urgent need for improved drug delivery systems, advanced imaging techniques and personalized therapies. MOFs offer several distinct advantages that make them promising candidates in this field[6]. Their exceptionally large surface area, tunable pore size, and versatile chemical functionality allow researchers to design tailored materials with properties that precisely match the requirements of specific pharmaceutical applications. The integration of MOFs into pharmaceuticals has enormous potential for various applications. From improving the solubility and bioavailability of poorly water-soluble drugs to enabling targeted delivery to diseased tissues, MOFs provide a versatile platform to revolutionize drug delivery. In addition, their ability to encapsulate and protect sensitive substances such as proteins and nucleic acids opens up new opportunities for the development of biopharmaceutical products and gene therapies. In addition to drug delivery, MOFs show promise in biomedical imaging and diagnostics. Certain MOFs have intrinsic luminescent properties, making them excellent candidates for contrast agents in various imaging modalities, including magnetic resonance imaging (MRI), computed tomography (CT), and fluorescence imaging. By functionalizing MOFs with targeting ligands or imaging probes, researchers can achieve precise localization and imaging of diseased tissues, facilitating early detection and personalized treatment strategies. Furthermore, the versatility of MOFs lends itself to the concept of theranostics, where a single MOF-based platform can simultaneously deliver therapeutic agents while real-time monitoring of therapy efficacy. This convergence of diagnosis and treatment enables a revolution in precision medicine, enabling personalized treatment programs based on individual patient profiles[7,8].

II. PROPERTIES OF MOFS

The fundamental properties of MOFs, including their high surface area, tunable pore size, and modifiable functionality. Properties of Metal-Organic Frameworks (MOFs):

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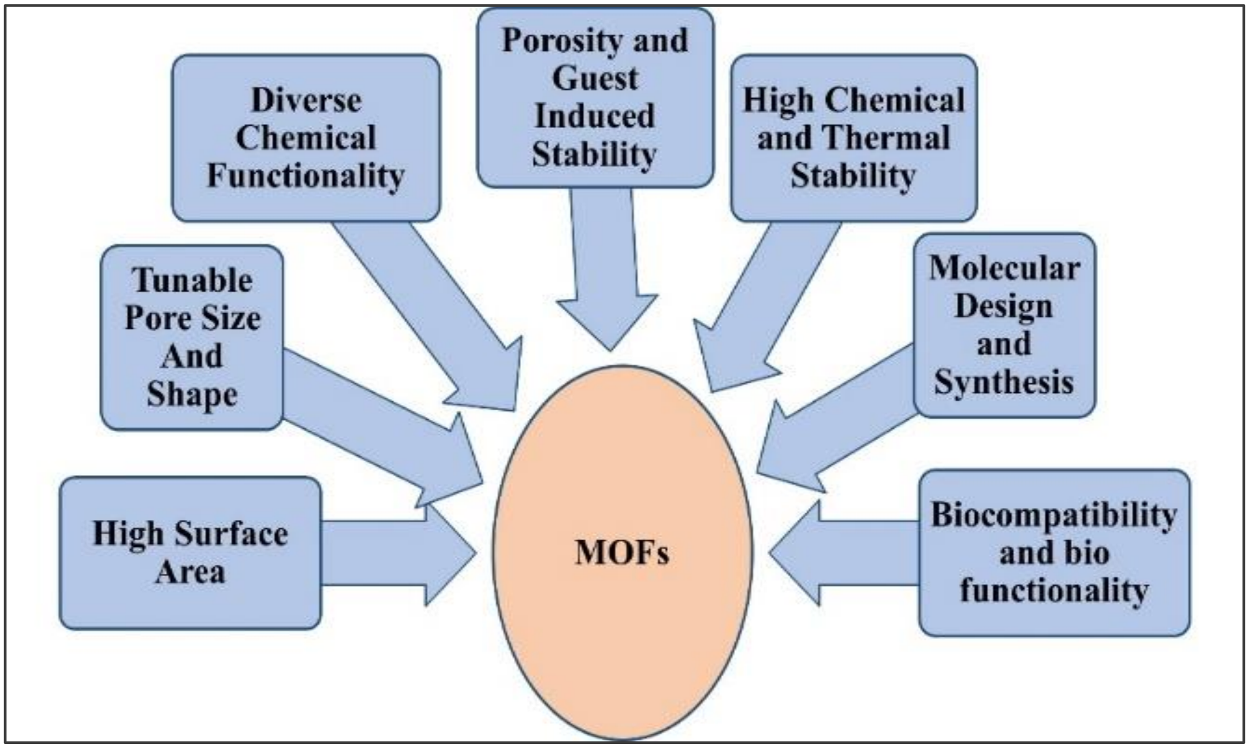

Fig No. 2 Properties of Metal Organic Framework

A. High Surface Area:

MOFs have exceptionally large surface areas, often surpassing traditional porous materials such as and activated carbon. This large surface area is due to their crystal structure, which consists of interconnected pores and channels. The large surface area enables a high loading capacity of foreign molecules, making MOFs promising candidates for drug delivery and gas storage.

B. Tunable Pore Size and Shape:

One of the most interesting features of MOFs is their tunable pore size and shape. By choosing specific metal ions and organic linkers, researchers can tailor the size of the pores in the MOF framework. This tunability enables precise control of the adsorption and diffusion properties of MOFs, allowing them to selectively capture and release molecules of interest. In drug delivery, the ability to adjust the pore size ensures efficient encapsulation and controlled release of therapeutic agents[09,10].

C. Diverse Chemical Functionality:

MOFs offer a different cluster of chemical functionalities due to the flexibility of both metal particles and natural ligands. Analysts can consolidate different useful bunches into the MOF structure, such as hydroxyl, carboxyl, amino, or fragrant moieties. This chemical flexibility empowers the plan of MOFs with custom fitted properties, counting upgraded solidness, biocompatibility, and reactivity. Functionalized MOFs can be built to associated specifically with particular biomolecules or to catalyze wanted chemical responses, growing their utility in pharmaceutical applications.

D. Porosity and Guest-Induced Flexibility:

The permeable nature of MOFs invests them with momentous adaptability, permitting the system to experience auxiliary changes in reaction to outside jolts or visitor atom adsorption. This guest-induced adaptability can be misused to plan energetic MOFs that show reversible auxiliary changes, such as gate-opening wonders or breathing behavior. These energetic properties empower MOFs to adjust their pore measure and shape in reaction to natural conditions, advertising openings for controlled discharge and particular adsorption of visitor particles in sedate conveyance and partition forms[11,12].

E. High Chemical and Thermal Stability:

MOFs are for the most part steady beneath a wide extend of chemical and warm conditions, making them strong materials for different applications. The steadiness of MOFs stems from the solid coordination bonds between metal particles and natural ligands, which bestow basic keenness to the system. This soundness is significant for pharmaceutical applications, guaranteeing the judgment of drug-loaded MOFs amid capacity, transportation, and organization[13].

F. Modular Design and Synthesis:

MOFs are agreeable to measured plan standards, permitting for the precise get together of complex structures from straightforward building squares. The union of MOFs can be custom fitted to attain exact control over the composition, morphology, and crystallinity of the coming about materials. Different engineered approaches, counting solvothermal,

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aqueous, microwave-assisted, and mechanochemical strategies, offer adaptability in tuning the properties of MOFs to meet particular application necessities.

G. Biocompatibility and Biofunctionality:

MOFs display amazing biocompatibility and compatibility with organic frameworks, making them promising candidates for biomedical applications. Biocompatible MOFs can be designed to associated with organic atoms, such as proteins, proteins, and nucleic acids, without inspiring unfavorable resistant reactions or cytotoxic impacts. Besides, the consolidation of bio functional ligands into the MOF structure empowers focused on intuitive with particular cell sorts or tissues, improving their utility in sedate conveyance, imaging, and restorative mediations[14,15].

III. SYNTHESIS OF MOFS

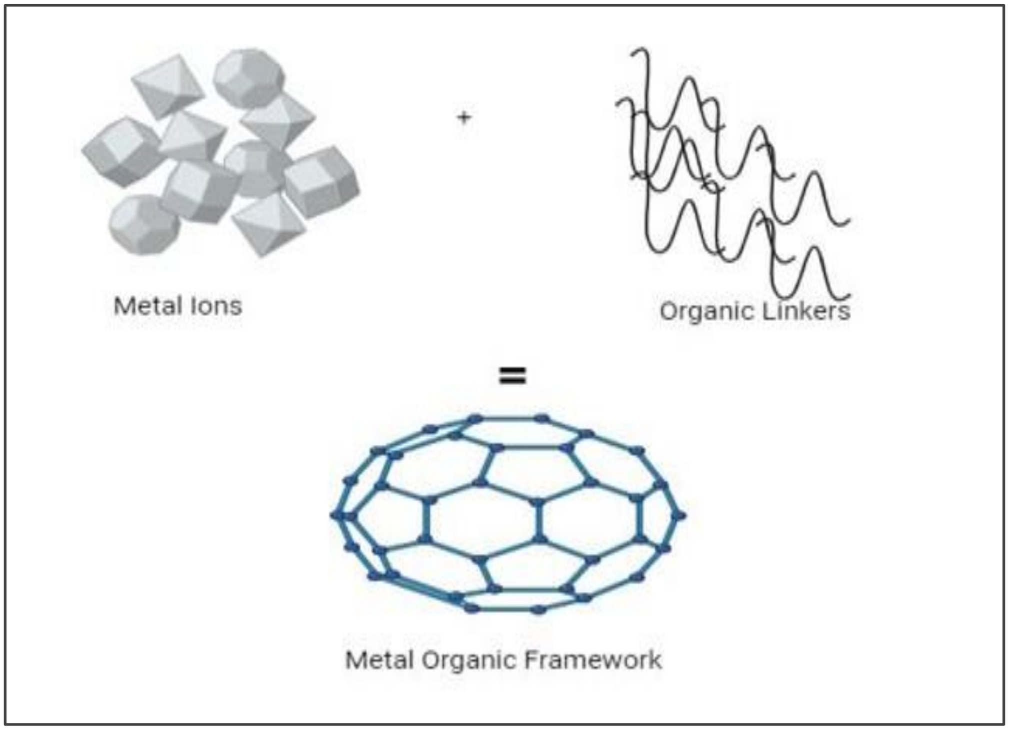

Fig. No. 3 Illustration of Method of MoF Formation.

The blend of MOFs includes the controlled get together of metal particles or clusters with natural ligands to make crystalline systems with well-defined structures and properties. A few synthetic approaches have been created to manufacture MOFs with differing compositions, morphologies, and functionalities. The choice of union strategy depends on components such as the specified MOF structure, pore estimate, and application prerequisites. Here are a few common union methodologies for MOFs:

A. Solvothermal and Hydrothermal Methods:

Solvothermal and aqueous union strategies include the response of metal salts with natural ligands in a high-pressure, high-temperature dissolvable environment. Regularly, the metal antecedent and natural linker are broken down in a reasonable dissolvable, such as water or natural solvents, and warmed beneath autogenous weight. The response conditions are carefully controlled to advance nucleation and precious stone development, driving to the arrangement of MOF precious stones. Solvothermal and aqueous strategies offer amazing control over the crystallinity, morphology, and measure dispersion of the coming about MOFs [16].

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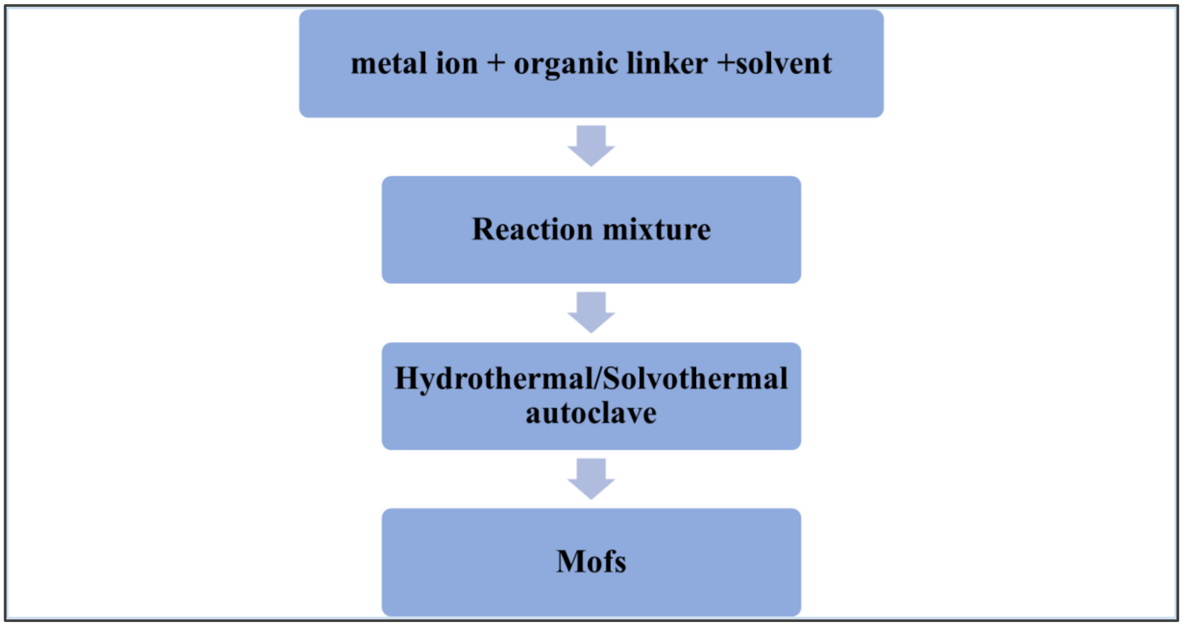

Fig. No. 4 Steps Involved in Solvothermal and Hydrothermal Methods

B. Microwave-Assisted Synthesis:

Microwave-assisted blend has risen as a quick and productive strategy for the creation of MOFs. In this approach, the metal forerunner and natural linker are blended in a dissolvable and subjected to microwave illumination. The microwave vitality quickens the response energy, driving to quicker nucleation and precious stone development compared to customary warming strategies. Microwave-assisted amalgamation offers focal points such as shorter response times, higher yields, and improved reproducibility, making it an appealing choice for large-scale generation of MOFs [17,18].

C. Mechanochemical Synthesis:

Mechanochemical blend, moreover known as ball processing or pounding, includes the coordinate response of strong metal antecedents with natural ligands within the nonattendance of dissolvable. The reactants are put in a ball process or mortar and ground together beneath mechanical drive. The mechanical vitality produced amid processing advances bond breaking and arrangement, driving to the arrangement of MOF nanoparticles or crystalline powders. Mechanochemical amalgamation offers a few points of interest, counting effortlessness, versatility, and decreased dissolvable utilization. Also, it permits for the synthesis of MOFs which will be blocked off utilizing conventional solution-based strategies[19].

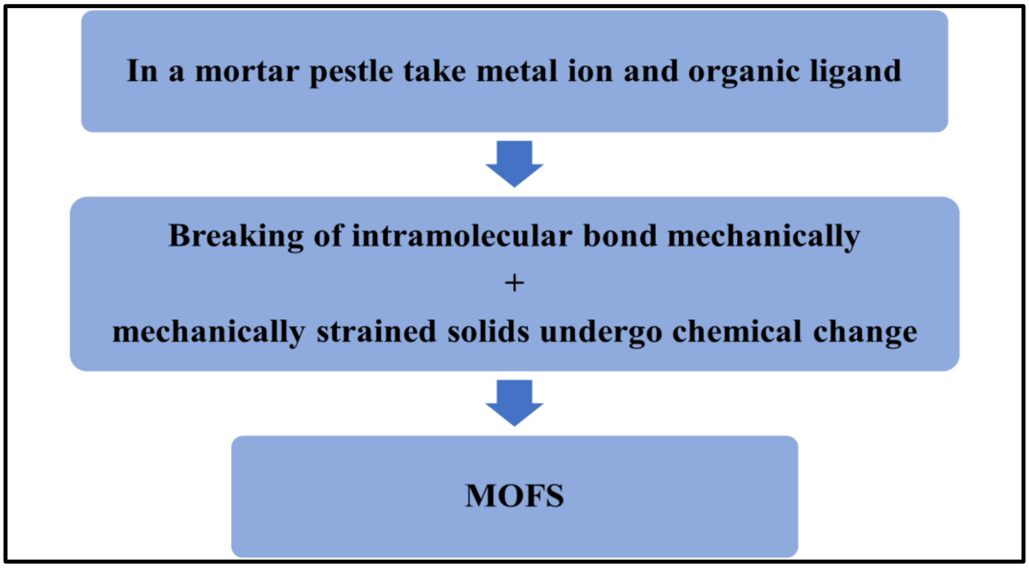

Fig. No. 5 Steps Involved in Mechanochemical Synthesis.

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D. Layer-by-Layer (LBL) Assembly:

Layer-by-layer gathering may be a flexible method for the creation of thin-film MOF coatings on different substrates. In this approach, rotating layers of metal particles and natural ligands are consecutively stored onto the substrate surface through drenching or spin-coating techniques. The substrate-bound layers experience coordination-driven self-assembly to make a nonstop MOF film. LBL gathering empowers exact control over film thickness, composition, and introduction, making it appropriate for applications such as gas division layers, catalytic reactors, and sensors[20].

E. Post-Synthetic Modification (PSM):

Post-synthetic adjustment includes the functionalization of pre-formed MOF precious stones with extra natural or inorganic moieties. PSM permits for the presentation of unused functionalities, such as useful bunches for improved reactivity, visitor particles for specific adsorption, or surface modifiers for moved forward soundness. Common PSM procedures incorporate ligand trade, metal particle trade, surface joining, and visitor atom epitome. PSM offers an adaptable and measured approach to tailor the properties of MOFs for particular applications, without modifying the center structure of the system[21].

In general, the choice of union strategy depends on components such as the required MOF structure, adaptability, immaculateness, and application prerequisites. By leveraging these different union techniques, analysts can create MOFs with custom-made properties and functionalities for a wide extend of pharmaceutical applications, counting sedate conveyance, imaging, theragnostic, catalysis, and antimicrobial intercessions[22].

IV. APPLICATIONS OF MOFS IN PHARMACEUTICALS

A. Drug Delivery:

The utilize of MOFs as carriers for medicated particles, examining their capacity to upgrade medicate solvency, solidness, and focused on conveyance. Illustrations of drug-loaded MOFs and their applications are as in in cancer treatment, antimicrobial treatment, and other infection medicines[23,24].

B. Biomedical Imaging

The utilization of luminescent MOFs as differentiate operators for different imaging modalities, counting MRI, CT, and fluorescence imaging. This highlights the significance of functionalizing MOFs for focused on imaging and determination of illnesses[25,26].

C. Theranostics

The concept of theranostic MOFs coordinating restorative and symptomatic functionalities in a single framework. Cases of theranostic MOFs and their applications in personalized medication and focused on treatment[27,28].

D. Catalysis

The catalytic properties of certain MOFs and their applications in pharmaceutical union forms are inspected. The points of interest of MOF-based catalysts, counting tall catalytic movement, selectivity, and recyclability [29-30].

E. Gas Storage and Delivery

The potential of MOFs for putting away and conveying restorative gasses in restorative applications, such as in respiratory treatments and anesthesia[31].

V. CHALLENGES

This area addresses the challenges and future headings in saddling MOFs for pharmaceutical applications. We talk about issues related to MOF steadiness, biocompatibility, scale-up blend, and administrative endorsement. Methodologies for overcoming these challenges and opening the complete potential of MOFs in pharmaceuticals are proposed. Challenges and Future Viewpoints in Metal-Organic Systems (MOFs) for Pharmaceuticals[32,33]:

A. Stability and Biocompatibility:

One of the essential challenges confronting the utilization of MOFs in pharmaceuticals is guaranteeing their solidness and biocompatibility in physiological situations. A few MOFs may experience debasement or filtering of metal particles, compromising their basic astuteness and possibly causing unfavorable impacts in natural frameworks. Tending to these challenges requires the improvement of MOFs with upgraded steadiness and biocompatibility profiles through levelheaded plan and surface alterations[34].

B. Scalability and Reproducibility:

Another jump within the interpretation of MOFs from laboratory-scale blend to industrial-scale generation is versatility and reproducibility. Numerous MOF blend strategies are optimized for small-scale amalgamation and may not be effectively adaptable to meet the requests of large-scale fabricating. Additionally, guaranteeing batch-to-batch reproducibility and quality control postures noteworthy challenges. Overcoming these impediments requires the improvement of vigorous and versatile amalgamation procedures that can be executed in mechanical settings[35,36].

C. Controlled Drug Release

Whereas MOFs offer the potential for controlled sedate conveyance, accomplishing exact control over medicate discharge energy remains a challenge. Variables such as pore measure, surface chemistry, and guest-host intelligent impact medicate discharge behavior, but anticipating and balancing these variables to attain craved discharge profiles can be complex. Future inquire about endeavors ought to center on explaining the instruments overseeing sedate discharge from MOFs and creating procedures for fine-tuning discharge energy to optimize helpful results[37,38].

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D. Regulatory Approval and Commercialization

The administrative scene encompassing MOFs in pharmaceuticals is still advancing, posturing challenges for their broad selection in clinical settings. Administrative offices require strong prove of security, viability, and quality control some time recently endorsing MOF-based therapeutics for human utilize. Also, the commercialization of MOF-based items may confront obstructions related to mental property security, fabricating costs, and showcase acknowledgment. Overcoming these challenges will require near collaboration between analysts, administrative organizations, and industry accomplices to streamline the administrative endorsement handle and encourage the commercialization of MOF-based pharmaceuticals[39,40].

E. Multifunctionality and Integration

Growing the utility of MOFs in pharmaceuticals requires saddling their multifunctional capabilities and coordination them into comprehensive helpful stages. This involves planning MOFs that can at the same time provide drugs, give demonstrative data, and screen treatment reactions in real-time. Accomplishing consistent integration of these functionalities inside a single MOF-based stage presents both specialized and conceptual challenges but holds gigantic guarantee for progressing personalized medication and accuracy therapeutics[41,42,43].

F. Beyond Traditional Applications

Whereas MOFs have appeared guarantee in sedate conveyance, imaging, and diagnostics, investigating their potential in novel applications such as immunotherapy, regenerative medication, and bioelectronics speaks to an energizing wilderness. Saddling the interesting properties of MOFs to balance resistant reactions, back tissue recovery, or interface with organic frameworks may open up unused roads for tending to neglected restorative needs and revolutionizing healthcare conveyance[44,45].

VI. CONCLUSION

In conclusion, MOFs hold awesome guarantee in revolutionizing different viewpoints of pharmaceutical inquire about and advancement. Their one-of-a-kind properties and functionalities make them flexible materials for medicate conveyance, imaging, , catalysis, gas capacity, and antimicrobial applications. In spite of challenges, progressing investigate endeavors are clearing the way for the interpretation of MOF-based innovations into clinical applications, proclaiming an unused time in pharmaceutical innovation. While MOFs hold colossal potential in pharmaceuticals, a few challenges ought to be tended to realize their full affect. Overcoming these challenges will require intrigue collaboration, inventive inquire about, and concerted endeavors from academia, industry, and administrative offices. In spite of the impediments, long-standing time viewpoint for MOFs in pharmaceuticals is promising, with openings for transformative progressions in sedate conveyance, diagnostics, and personalized medication.

Conflict of Interest

The authors have no conflict of interest regarding this investigation

REFERENCES

[1]. Yang Q, Liu S, Ma X, et al., editors. Metal-Organic Frameworks for Drug Delivery: Current State-of-the-Art and Future Perspectives. Advanced Materials. 2017;29(15):1604903.

[2]. Li Y, Zhang Y, Sun X, et al., editors. Metal-Organic Frameworks for Biomedical Applications: Advances and Challenges. Coordination Chemistry Reviews. 2019;387:17-37.

[3]. Wang X, Gong X, Zhu C, et al., editors. Metal-Organic Frameworks for Biomedical Applications. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology. 2020;12(2)

[4]. Li Y, Li B, Li H, et al., editors. MOF Nanoparticles: From Design to Applications in Biomedicine. Small. 2017;13(15):1603004.

[7]. Li Y, Zhang Y, Sun X, et al., editors. Metal-Organic Frameworks for Biomedical Applications: Advances and Challenges. Coordination Chemistry Reviews. 2019;387:17-37.

[8]. Horcajada P, Gref R, Baati T, et al., editors. Metal-Organic Frameworks in Biomedicine. Chemical Reviews. 2012;112(2):1232-1268.

[9]. Zhang Z, Yao Z, Zheng H, Zhu Y, Wang H. Metal-Organic Frameworks for Applications in Drug Delivery, Biomedical Imaging, and Sensing. ACS Appl Mater Interfaces. 2020 Mar 11;12(10):1248-1265.

[10]. Chen H, Zhao Q, Liu S, Wang Y, Zhang Z. Functionalized Metal-Organic Frameworks for Targeted Imaging and Theranostics. Adv Healthc Mater. 2021 May 25;10(10)

[11]. Li J, Sculley J, Zhou HC. Metal-Organic Frameworks for Separations. Chem Rev. 2012 Feb 8;112(2):869-932.

[12]. Férey G, Serre C. Large breathing effects in three-dimensional porous hybrid matter: facts, analyses, rules and consequences. Chem Soc Rev. 2009 Mar;38(5):1380-99.

[13]. Liu Y, Wang ZU, Zhou HC. Recent advances in carbon dioxide capture with metal-organic frameworks. Greenhouse Gases: Sci Technol. 2012 Jun;2(4):239-259.

[14]. Horcajada P, Gref R, Baati T, Allan PK, Maurin G, Couvreur P, et al. Metal-organic frameworks in biomedicine. Chem Rev. 2012 Feb 8;112(2):1232-68.

[15]. Kreno LE, Leong K, Farha OK, Allendorf M, Van Duyne RP, Hupp JT. Metal-organic framework materials as chemical sensors. Chem Rev. 2012 Feb 8;112(2):1105-25.

[16]. Wang Z, Cohen SM. Postsynthetic modification of metal-organic frameworks. Chem Soc Rev. 2009 Apr;38(5):1315-1329.

[17]. Chen Y, Zhang J, Zhang W, Chen G, Li S. Metal-organic frameworks (MOFs) and their biomedical applications. Chem Soc Rev. 2015 Jun 21;44(6):2099-123.
[18]. Li JR, Sculley J, Zhou HC. Metal-organic frameworks for separations. Chem Rev. 2012 Feb 8;112(2):869-932.
[19]. Férey G, Mellot-Draznieks C, Serre C, Millange F, Dutour J, Surblé S, Margiolaki I. A chromium terephthalate-based solid with unusually large pore volumes and surface area. Science. 2005 Feb 18;307(5712):327-30.
[20]. Horike S, Shimomura S, Kitagawa S. Soft porous crystals. Nat Chem. 2009 Mar;1(2):695-704.
[21]. James SL, Adams CJ, Bolm C, Braga D, Collier P, Friščić T, et al. Mechanochemistry: opportunities for new and cleaner synthesis. Chem Soc Rev. 2012 Feb 8;41(1):413-47.
[22]. Denny MS Jr, Moreton JC, Benz L, Cohen SM. Metal–organic frameworks for membrane-based separations. Nat Rev Mater. 2016 Feb 2;1(2):16078.
[23]. Cohen SM. Postsynthetic methods for the functionalization of metal–organic frameworks. Chem Rev. 2012 Feb 8;112(2):970-1000.
[24]. Rowsell JL, Yaghi OM. Metal-organic frameworks: a new class of porous materials. Microporous Mesoporous Mater. 2004 Jun 25;73(1-2):3-14.
[25]. Horcajada P, Chalati T, Serre C, Gillet B, Sebrie C, Baati T, et al. Porous metal-organic-framework nanoscale carriers as a potential platform for drug delivery and imaging. Nat Mater. 2010 Sep;9(2):172-8.
[26]. Wu MX, Yang YW. Metal–organic framework (MOF)-based drug/cargo delivery and cancer therapy. Adv Mater. 2017 Mar;29(23):1606134.
[27]. Chen Y, Lykourinou V, Hoang T, Ming LJ, Ma S. Luminescent metal-organic frameworks as potential multifunctional bioimaging platforms. Chem Commun (Camb). 2012 Mar;48(10):3279-81.
[28]. Kreno LE, Leong K, Farha OK, Allendorf M, Van Duyne RP, Hupp JT. Metal-organic framework materials as chemical sensors. Chem Rev. 2012 Feb 8;112(2):1105-25.
[29]. Lin W, Rieter WJ, Taylor KML. Modular synthesis of functionalized metal-organic frameworks for imaging and drug delivery. J Am Chem Soc. 2008 May 21;130(36):1158-9.
[30]. He C, Liu D, Lin W. Nanomedicine applications of hybrid nanomaterials built from metal–ligand coordination bonds: nanoscale metal–organic frameworks and nanoscale coordination polymers. Chem Rev. 2015 Sep 9;115(19):11079-108.
[31]. Lee J, Farha OK, Roberts J, Scheidt KA, Nguyen ST, Hupp JT. Metal-organic framework materials as catalysts. Chem Soc Rev. 2009 Feb;38(5):1450-9.
[32]. Corma A, García H, Llabrés i Xamena FX. Engineering metal organic frameworks for heterogeneous catalysis. Chem Rev. 2010 Apr 14;110(8):4606-55.
[33]. Rowsell JL, Yaghi OM. Metal-organic frameworks: a new class of porous materials for gas storage. Microporous Mesoporous Mater. 2004 Jun 25;73(1-2):3-14.
[34]. Horcajada P, Gref R, Baati T, Allan PK, Maurin G, Couvreur P, et al. Metal-organic frameworks in biomedicine. Chem Rev. 2012 Feb 8;112(2):1232-68.
[35]. Farha OK, Hupp JT. Rational design, synthesis, purification, and activation of metal-organic framework materials. Acc Chem Res. 2010 Mar 16;43(8):1166-75.
[36]. Li JR, Sculley J, Zhou HC. Metal-organic frameworks for separations. Chem Rev. 2012 Feb 8;112(2):869-932.
[37]. Furukawa H, Cordova KE, O'Keeffe M, Yaghi OM. The chemistry and applications of metal-organic frameworks. Science. 2013 Apr 12;341(6149):1230444.
[38]. Li JR, Sculley J, Zhou HC. Metal-organic frameworks for separations. Chem Rev. 2012 Feb 8;112(2):869-932.
[39]. Horcajada P, Gref R, Baati T, Allan PK, Maurin G, Couvreur P, et al. Metal-organic frameworks in biomedicine. Chem Rev. 2012 Feb 8;112(2):1232-68.
[40]. Férey G, Mellot-Draznieks C, Serre C, Millange F, Dutour J, Surblé S, et al. A chromium terephthalate-based solid with unusually large pore volumes and surface area. Science. 2005 Feb 18;307(5712):327-30.
[41]. Zhou HC, Kitagawa S. Metal-organic frameworks (MOFs). Chem Soc Rev. 2014 Jan 7;43(16):5415-8.
[42]. Gándara F, Furukawa H, Lee S, Yaghi OM. Solid-state characterization of crystalline metal-organic frameworks. Chem Soc Rev. 2014 Jan 7;43(16):5632-45.
[43]. Horcajada P, Serre C, Vallet-Regí M, Sebban M, Taulelle F, Férey G. Metal-organic frameworks as efficient materials for drug delivery. Angew Chem Int Ed Engl. 2006 Sep 18;45(36):5974-8.
[44]. He C, Liu D, Lin W. Nanomedicine applications of hybrid nanomaterials built from metal-ligand coordination bonds: nanoscale metal-organic frameworks and nanoscale coordination polymers. Chem Rev. 2015 Sep 9;115(19):11079-108.
[45]. Huo J, Aguilera-Sigalat J, El-Hankari S, Bradshaw D. Magnetic MOF microreactors for recyclable size-selective biocatalysis. Angew Chem Int Ed Engl. 2014 Mar 31;53(22):5815-9.
[46]. Della Rocca J, Liu D, Lin W. Nanoscale metal-organic frameworks for biomedical imaging and drug delivery. Acc Chem Res. 2011 Jul 19;44(10):957-68.
[47]. Horcajada P, Gref R, Baati T, Allan PK, Maurin G, Couvreur P, et al. Metal-organic frameworks in biomedicine. Chem Rev. 2012 Feb 8;112(2):1232-68.