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Review Article

An overview of the synthesis, structure and applications of $Cu(NO_3)_2.3H_2O$ in the development of porous structures

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ABSTRACT

Metal-organic frameworks of MOFs with copper metal cores have attracted a lot of attention in various scientific and industrial fields due to their unique features such as high porosity, wide specific surface and structural adjustability. This article provides a comprehensive review of these structures, including the definition and history of development, chemical and physical characteristics of copper metal, synthesis methods with an emphasis on the use of $Cu(NO_3)_2{\cdot}3H_2O$, structural analysis and characterization techniques, and their diverse applications in Catalysis, absorption and separation of gases, drug delivery and sensors. Also, the challenges in the synthesis and stability of these materials and research opportunities to improve their performance have been discussed. Finally, by providing summaries and suggestions for future research, new paths are drawn for the development and future applications of copper metal-based MOFs.

Keywords: structure, application, porous, synthesis, MOF

1. Introduction

In recent decades, metal-organic frameworks (MOFs) have quickly gained the attention of researchers as one of the outstanding achievements of materials science. The porous crystalline structures of these materials, due to their very high specific surface area and the possibility of fine-tuning the structure through changing the composition of metals and ligands, have created a wide potential in various applications including gas storage, molecular separation, catalysis and drug delivery. In addition, the chemical and structural flexibility of

MOFs has made it possible to design functional materials with customized properties suitable for industrial and research needs.

2. Materials and methods

ncreasing specific surface area and porosity: regular and porous structures of MOFs significantly increase the contact surface and provide the possibility of optimal absorption of molecules (gas or liquid); This is very vital in energy storage and gas separation processes [18]

Ability to customize the structure: the possibility of changing the composition of metals and ligands makes the physical and chemical properties of these materials adjustable; In this way, MOFs with unique characteristics can be designed for sensing, drug delivery and catalysis applications (Taddei, [14]

Crystal stability and accurate analysis capability: The structural order and crystallinity of MOFs, in addition to improving performance in the mentioned applications, provide the possibility of detailed study of their structural and electronic properties.

For this reason, MOFs are used as a key tool in the design of new materials, the development of energy storage systems and biomedical applications, and future research in this field can lead to the improvement of the performance of related technologies.

2.1. The role of copper metal in porous structures

Copper metal is recognized as one of the central elements in the synthesis of metal-organic frameworks (MOFs) due to its unique electron characteristics and ability to form diverse chorodination bonds. The use of copper in porous structures allows the creation of crystalline networks with regular and adjustable channels, which, in addition to increasing the specific surface area, also improves thermal and chemical stability. Research shows that combining copper with suitable ligands can lead to the creation of structures that maximize the ability to absorb guest molecules such as gases and drugs; This improves performance in applications such as gas separation, catalysis, and controlled drug release [15]

2.2. Motivation and objectives of the article

The main objective of this review paper is a comprehensive review of synthesis methods, structural characteristics and applications of copper metal-organic frameworks in the development of porous structures. The motivation of the article comes from the need to improve the performance of molecular absorption and release systems; So that by using the unique properties of copper, structures with optimal channels and high stability can be designed. In this regard, with the aim of identifying challenges and providing new solutions to improve the stability and efficiency of copper-based MOFs, the article examines new applications in the fields of catalysis, gas separation and drug delivery [18]

2.3. Theoretical foundations

Metal-organic frameworks are designed as a group of porous crystalline materials, based on the principles of coordination chemistry and crystallography. In these structures, metal ions or metal clusters act as coordination centers and bind together with organic ligands, which usually contain carboxylic groups, through coordination bonds. These connections form regular 3D networks with internal pores and adjustable channels that provide features such as very high specific surface area and controllable porosity[18]. From a theoretical point of view, controlling the number and type of ligands, metal type and synthesis conditions allows researchers to optimize the physical, chemical and functional properties of MOFs for specific applications such as gas storage, catalysis and drug delivery.

3. Research background

Early research in the field of MOFs led to the introduction of simple structures such as MOF-5, which were synthesized using simple ligands such as 1,4-benzene dicarboxylic acid [18] .Next, as synthesis and structure control techniques progressed, extensive studies were conducted on the impact of structural changes on gas absorption properties, thermal stability, and drug delivery applications [14] In addition to improving synthesis, subsequent researches have investigated practical aspects such as the use of MOFs in catalytic systems and sensors. Also, attention to aspects related to the improvement of electrical properties and the use of MOFs in the manufacture of electronic and semiconductor devices has increased in recent years; An area where recent studies show that ligand changes and metal exchange can improve electronic properties and charge transfer [15]

A 2020 study by Mathieu et al. presented a simple method for growing single crystals of copper coordination polymer with the formula $[Cu(C_2O_4)(4\text{-aminopyridine})_2(H_2O)]n$. Research included synthesis, structural identification using X-ray diffraction, and theoretical and physical investigations of the compound. Net showed that this method can produce high quality crystals that are useful for various applications in material chemistry. (arv.org)

A 2021 study by Silva et al.: This study focused on the formation of copper (II) oxide in polymer fibers produced by the solution-blow spinning method. They showed that it is possible to produce nanocomposite fibers containing copper oxide using a simple synthetic route, which are converted into non-woven ramiks after the calcination process. These materials can be used in various applications such as catal and sensors. (arxiv.org)

A 2022 study by Rej et al: They investigated the controlled synthesis of copper oxide (Cu_2O) nanostructures with certain crystal levels and studied the effect of these levels on fafotocatalytics in the production of solar fuels and chemicals. The results showed that the engineering of Cu_2O chrysli surfaces can create a significant improvement in the photocatalytic performance of these materials. (arxiv.org)

A study in 2019 by Iranian researchers: A synthesized copper hydroxide nitrate $(Cu)_3NO_3)$ microsheets using plasma electrolysis method of copper nitrate aqueous solution. This method led to the production of a pale blue-green powder that was identified using XRD and EDS. FESEM images showed that this powder consists of microplates with nanometer thicknesses. This study showed that the production of OH ions and radics in plasma, as well as the breakdown of water molecules due to the collision of high-energy ions in plasma, is the main factor in the synthesis of this powder. (jitf.alzahra.ac.ir)

A 2024 study by Lee et al: They developed copper-based casors for sustainable ammonia production. These catalysts are synthesized using copper (II) oxide and act in a high yield ammonia nitre electrochemical process. The results showed that these catalysts can be effectively used in the production of ammonia with high efficiency and suitable stability. (laboratorydirect.ir)

A 2020 study by Zhang et al: They synthesized a new copper-based metal-organic framework (MOF) using $Cu(NO_3)2\cdot 3H_2O$ and an organic ligand. This MOF had a porous structure with a high specific surface area. The results showed that this material has a high capacity in absorbing CO_2 and CH_4 gases and can be used as an effective adsorbent in separating gases.

A 2021 study by Lee et al.: They synthesized copper oxide nanoparticles using $Cu(NO_3)_2\cdot 3H_2O$ and chemical precipitation method. These nanoparticles had a porous structure with uniform particle size. The results showed that these nanoparticles have high catalytic activity in the CO oxidation reaction and can be used as effective catalysts in environmental applications.

A 2022 study by Kim et al.: They synthesized a porous composite of copper oxide and carbon using $Cu(NO_3)_2\cdot 3H_2O$ and a hydrothermal method. This composite had a three-dimensional structure with high porosity. The results showed that this material has a high capacity in energy storage and can be used as an electrode in supercapacitors.

A 2019 study by Chen et al: They synthesized a porous copper oxide-based catalyst using $Cu(NO_3)_2\cdot 3H_2O$ and sol-gel method. This catalyst had a high specific surface area and a uniform distribution of cavity sizes. The results showed that this catalyst has a high activity in the hydrogenation reaction of nitrobenzene and can be used in the chemical industry.

A 2023 study by Park et al.: They synthesized a gas sensor based on copper oxide nanostructures using $Cu(NO_3)_2{\cdot}3H_2O$ and spray pyrolysis method. These nanostructures had high porosity and nanometer particle size. The results showed that this sensor is highly sensitive to H_2S gas and can be used in the detection of toxic gases.

A 2020 study by Zhang et al: Ha synthesized a new copper-based metal-organic framework (MOF) using $Cu(NO_3)_3{\cdot}3H_2O$ and an organic ligand. The MOF had a porous structure with a high specific surface area. It did not show that this material has a high capacity in absorbing CO_2 and CH_4 gases and can be used as an effective adsorbent in separating gases.

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A 2021 study by Gaa et al.: They synthesized a porous nanocomposite of oxcopper and graphene using $Cu(NO_3)_2{\cdot}3H_2O$ and electrochemical method. This nanocomposite had a special level of suitable electrical conductivity. The results showed that this substance has the activity of electrocatalyzing oxygen reduction reaction and can be used in fuel cells.

A 2022 study by Ahmed Vekaran: They synthesized porous copper oxide nanorods using $Cu(NO_3)_2 \cdot 3H_2O$ and microwave-hydrothermal methods. These nanorods had high porosity and were morpholoconvex. The results showed that these nanorods have a high storage capacity of lithium ions and can be used as anodes in lithium-ion batteries.

These studies represent recent developments in the field of synthesis and applications of copper-based compounds, especially in the development of porous structures and nanostructures that can be used in various areas such as catalysis, sensors and renewable energy.

4. Definition of MOFs and their development history

Metal-organic frameworks (Metal–Organic Frameworks or MOFs) are a class of porous crystalline materials obtained by binding metal ions or metal clusters to organic ligands (binding agents). In these structures, the metals act as chorodination centers and the organic ligands, which typically contain carboxylic groups, form a three-dimensional network with regular and adjustable internal pores by forming chorodination bonds. The distinctive feature of MOFs is the very high specific surface area, high porosity and the possibility of changing the structure as desired through changing the type of metal or ligand, which makes them ideal for applications such as gas storage, molecular separation, catalysis and drug delivery [15]
The development of MOFs began in the late 1990s; The first reported examples, such as MOF-5, were a structure based on zinc ions and the ligand 1,4-benzenedicarboxylic acid, which attracted a lot of attention. Since then, the development of MOFs using various synthesis methods and improved structural control has led to the emergence of different families such as IRMOFs, HKUST-1 and UiO-66. These advances have made it possible to achieve porous structures with precise regulation of pore size, high thermal and chemical stability, and have led to the expansion of MOF applications in various scientific and industrial fields [15]

4.1. Chemical and physical properties of copper metal

Copper metal (Cu) is considered as one of the important elements in coordination chemistry due to several unique chemical and physical properties:

Alteration of oxidation states: Cu is mainly present in Cu(I) and Cu(II) states. The Cu(II) state is characterized by common conformational structures such as flat quadrilateral, octahedral or tetrahedral, which allows the creation of several types of coordination structures. This property makes copper act as a flexible element in the construction of MOF networks [15]

Electron and magnetic properties: Copper has a half-filled electron structure that creates meaningful electron and magnetic activities. These properties are very important in applications such as sensors and catalysis, where electron transfer plays a key role.

Solubility and reactivity: Copper compounds such as $Cu(NO_3)_2{\cdot}3H_2O$ dissolve well in water solvents and some organic solvents due to the presence of an aqueous (hydration) state in their structure. This property is particularly important in the synthesis of MOFs because it allows a rapid and controlled reaction between copper ions and organic ligands [18]

Chemical stability: Copper metal in its compounds, especially in copper (II) forms, exhibits appropriate resistance to oxidation and chemical change, which is essential for the synthesis of high-stability MOFs.

4.2 .Location of $Cu(NO_3)_2{\cdot}3H_2O$ in the synthesis of MOFs

$Cu(NO_3)_2{\cdot}3H_2O$ is known as a common precursor of copper metal in the synthesis of MOFs. This compound is particularly important in the synthesis processes of MOFs for the following reasons:

Reliable source of Cu(II): $Cu(NO_3)_2{\cdot}3H_2O$ acts as a reliable source of Cu(II) ions. The aqueous state of this compound (three water molecules) plays an important role in easy solubilization in conventional solvents such as water and compound solvents, facilitating the provision of metal ions to form chorodination bonds with organic ligands ([13]

Labylated longs and reactivity: Nitrites in this compound are substitutable for organic ligands. During the synthesis of MOFs, these anions are simply replaced by carboxylic groups or other linking groups and converted into regular crystal lattices. This property contributes to better control of synthesis conditions and to obtain high quality crystals [7]

Impact on crystal growth dynamics: Waters in $Cu(NO_3)_2{\cdot}3H_2O$ compound play an important role in regulating the growth rate of crystals. By virtue of these waters, the rheological conditions of the solution are regulated and it is possible to form porous structures with controllable pore sizes. This is particularly important in MOFs such as HKUST-1, which use copper as the central element [8]

Ease of availability and affordability: From an economic point of view, $Cu(NO_3)_2{\cdot}3H_2O$ as an inexpensive and readily available chemical, is a suitable option for research and industrial applications; Therefore, its use in the synthesis of MOFs helps to reduce production costs and scalability of industrial processes [13]

In the following, the methods of synthesis of copper metal-based MOFs, especially using $Cu(NO_3)_2 \cdot 3H_2O$ are discussed in detail. In this review, a review of conventional synthetic methods, optimal use of metal precursor $Cu(NO_3)_2 \cdot 3H_2O$, the effect of synthesis parameters and innovations in this field are mentioned.

An overview of conventional synthetic methods

(a) Hydrothermal/salothermal synthesis:

Hydrothermal synthesis is one of the common methods for preparing MOFs, where the reaction takes place in an aqueous or combined medium (usually including water along with organic solvents such as DMF or DEF) at high temperature and at closed pressure (in an autoclave or self-baking reactor). This method is widely used due to its high control over crystal growth and the possibility of achieving regular and quality structures [8]

Also, the salothermal method, which is very similar to hydrothermal, is used in organic solvents without the presence of water. In both methods, parameters such as temperature, reaction time and type of solvent play a decisive role in the formation of the final structure.

(b) Electrochemical synthesis electrolysis:

The electrolysis method has been proposed as a new approach for the synthesis of MOFs. In this method, by applying an electric current to a solution comprising metal precursors and ligands, it is possible to provide the necessary conditions for the formation of chorodination bonds. This method is used in cases where rapid synthesis with less energy is required; Although it has not yet been widely used in the field of copper-based MOFs [1]

c) Mechanical synthesis (micromechanical:

In mechanical or micromechanical synthesis, ball mills or compression methods are used without the use of solvents to disturb and combine materials. This method has been noticed in recent years due to its advantages such as reducing solvent consumption and saving time; But careful control over the growth of crystals and achieving homogeneous structures is still a challenge[6]

d) Synthesis using new technologies such as microwave and radiation:

Microwave technology is used as an advanced method to accelerate synthetic reactions. In this method, microwave energy causes rapid heating of the reaction solution and reduces synthesis time. Also, the use of ultraviolet waves or laser rays has been applied in some studies in order to stimulate synthetic reactions and improve the quality of crystals derived from MOFs [6]

4.3 . Use of $Cu(NO_3)_2{\cdot}3H_2O$: optimal methods and conditions

a) Importance of $Cu(NO_3)_2{\cdot}3H_2O$ as a precursor to copper metal:

This compound, $Cu(NO_3)_2{\cdot}3H_2O$, is easily soluble in polar solvents such as water and DMF due to its three water molecules and acts as a reliable source of Cu(II). The hydration conditions present in this compound play an important role in the rapid and effective disruption of copper ions with ligands. For this reason, this precursor is widely applied in the synthesis of copper-based MOFs [7]

b) Synthesis methods using $Cu(NO_3)_2{\cdot}3H_2O$:

Hydrothermal synthesis: In this method, $Cu(NO_3)_2{\cdot}3H_2O$ along with the desired ligands (for example, 1,4-benzene dicarboxylic acid or other multimodal ligands) are dissolved in an aqueous or combined solvent and the reaction is carried out at a temperature between 100 and 200 degrees Celsius and in a period of 12 to 72 hours. Optimization of conditions includes selecting the appropriate metal-to-ligand ratio, controlling the temperature and reaction time, and using compound solvents that can influence the size and quality of the resulting crystals [13]

Microwave synthesis: The use of microwave technology in the synthesis of Cu-MOFs allows reducing the reaction time to a few minutes. In this method, $Cu(NO_3)_2{\cdot}3H_2O$ and ligand are placed in suitable solvents (such as DMF) and the reaction takes place faster by applying microwave. In addition to saving time, this method improves uniformity and more precise control over the structure of crystals [22]

Electrochemical methods: In some new studies, electrolysis methods have been used to synthesize Cu MOFs; In this method, by applying electric current to solutions containing $Cu(NO_3)_2{\cdot}3H_2O$ and ligands, the synthesis reaction takes place in a controlled manner. Although this method has not yet been widely used compared to hydrothermal synthesis, it has potential advantages in terms of reducing reaction time and energy consumption [28]

4.4 . Impact of synthesis parameters (temperature, time, solvents, pH and...

A) Temperature:

Temperature is one of the most important parameters of synthesis. In hydrothermal methods, higher temperatures (usually between 100 and 200 degrees Celsius) can increase the speed of crystal growth, but must be adjusted to prevent structure degradation. Temperature affects the size and quality of the resulting crystals as well as the final porosity [19]

b) Time:

The duration of the reaction plays a decisive role in the completion of the reaction and the proper growth of the crystals. Longer times may lead to larger growth of crystals and increased uniformity of structure, but on the other hand, it may cause defects such as overlapping of ligands or destruction of structure under high temperature conditions [4]

c) Solvents:

Solvent selection has a direct effect on the solubility of metal precursors and ligands, as well as on the reaction rate. Solvents such as DMF, DEF and water are widely used in the synthesis of copper-based MOFs. The combination of polar and organic solvents can create suitable conditions for the formation of porous crystalline networks and prevent the formation of by-products [5]

d) PH:

The pH content of the synthesis solution can affect the cheordination state of the metal and ligands. Acidic or alkaline conditions are carefully adjusted to inhibit overlapping reactions and the formation of irregular structures. Usually, the pH of the solution is adjusted so that the metallic state is optimally maintained and the formation of high quality chorodination bonds takes place [1]

5. Innovations and advanced approaches in synthesis

In recent years, researchers have been looking for approaches to improve efficiency and reduce the cost of synthesizing copper metal-based MOFs. Some of the prominent innovations are:

Synthesis using continuous flow reactors: The use of continuous flow reactors as a modern approach has allowed for more precise control of synthesis conditions and high scalability. This method is particularly applicable in the industrial production of MOFs, reducing reaction times and increasing uniformity of products.

Synthesis using microwave technology: As mentioned in the previous sections, microwave technology allows to achieve rapid and controlled reactions. In addition to reducing the synthesis time, this approach brings an improvement in the crystal structure and a reduction in energy consumption.

Electrochemical methods: Some new studies have used electrochemical approaches to synthesize MOFs, in which by applying electric current, improved reaction conditions and a final structure with desirable characteristics are obtained.

Mechanical (micromechanical) synthesis: The use of ball mills and solvent-free compression methods has been proposed as a green and economical approach in the synthesis of MOFs. Although there are challenges in controlling crystal growth and structure uniformity, this method has the potential to reduce solvent and energy consumption.

In the following, the structural analysis and physical characteristics of copper metal-based MOFs are examined in detail.

5.1. Crystal structure and molecular order determination

MOFs are formed as porous crystalline materials, from the regular combination of metal ions (or metal clusters) and organic ligands. These structures have regular three-dimensional networks whose molecular order is established by chorodination bonds between metals and functional groups of ligands. Determining the crystal structure and molecular order in MOFs is usually done through X-ray diffraction (XRD); This technique provides the possibility of determining lattice parameters, angles between structural units and coordination between them. For example, the characteristic diffraction pattern of a MOF indicates its regular and reproducible structure, which order directly affects performance in applications such as gas absorption and drug release [2]

5.2. Characterization techniques: XRD, SEM, TEM, FTIR, NMR

A set of advanced techniques are used to accurately evaluate the structure and physical properties of MOFs:

• X-ray diffraction (XRD):

This method is the main tool for determining the crystal structure. By analyzing the diffraction pattern, it is possible to determine the molecular order, unit cell size, and angles between structural units. Information from XRD shows how well the structure is a regular and uniform MOF, which is central to the control of molecular adsorption and transport properties [2]

• Scanning electron microscopy (SEM) and transmission electron microscopy (TEM):

SEM provides the possibility of examining surface morphology and measuring particle dimensions at the nanoscale; While TEM provides high-resolution images of internal structure and molecular order. These techniques allow researchers to analyze the shape, size and presence of structural defects in MOF crystals [21]

• Infrared spectroscopy (FTIR):

FTIR is employed to identify functional groups present in ligands and to verify the presence of chorodination bonds between the metal and the ligand. This method can also characterize chemical changes due to synthesis or postsynthetic modification[28]

• Magnetic nuclear spectroscopy (NMR):

NMR provides detailed information about the molecular structure, chemical composition of ligands and how they bind to metal ions. The use of NMR is particularly useful in identifying minor changes in structure and investigating dynamic molecular reactions [11]

5.3. Analysis of morphology, surface area and pore distribution

Detailed analysis of morphology and measurement of surface area and pore distribution is an important step in evaluating the efficiency of MOFs in adsorption and separation applications:

• Morphology analysis:

The use of SEM and TEM allows a detailed examination of the shape, size, uniformity and presence of surface defects in MOF crystals. Images obtained from these techniques can show whether the crystal structure of MOF is fully formed or defects such as surface instability or small patches have occurred.

• Surface area measurements:

The surface area of MOFs is typically measured through a nitrogen capture (BET) method. Increased surface area due to high porosity is a key feature of MOFs, directly related to the adsorption capacity of materials (such as gases or drugs). These measurements help optimize the synthesis process and related applications [2]

• Pore distribution:

The pore size distribution in MOFs helps to check the uniformity and exact pore size present in the structure. Techniques such as pore volume distribution (BJH) as well as BET data analysis provide the necessary information to determine pore size and number. Pore distribution determines the speed and efficiency of molecular absorption and affects separation and storage applications[8]

5.4 CONCLUSIONS Structural analysis and physical characteristics

The combination of XRD, SEM, TEM, FTIR and NMR techniques along with surface area measurement and pore distribution methods provides the possibility of comprehensive and accurate analysis of crystal structure and physical characteristics of copper metal-based MOFs. Strict control of structural parameters, molecular order and morphology analysis are among the most important steps in improving the performance of these materials in absorption, separation and drug delivery applications. The use of these approaches enables researchers to benefit from the unique features of MOFs and achieve the optimization of synthesis processes and future applications in various fields.

6. Applications of copper metal-based MOFs are examined in detail.

6.1 Catalytic applications

Copper metal MOFs are known as effective catalysts in chemical reactions due to their metal active centers and structure fine tunability. The presence of Cu(II) ions in crystal structures allows the creation of high-availability catalytic sites; Hence, these MOFs are used in reactions such as hydrogenation, oxidation and molecular rearrangement. For example, in oxidation reactions that require electron transfer, the presence of copper ions increases the reaction speed and improves efficiency. Furthermore, the adjustability of the chemical environment surrounding the metal through the alteration of ligands allows the optimization of reaction conditions and the reduction of activation energy [2]

6.2 Absorption and separation of gases (CO_2, H_2 and...)

One of the most important applications of copper metal MOFs is the adsorption and separation of gases. The porous structures and the high specific surface of these materials provide a suitable basis for the absorption of gas molecules. For example, copper-based MOFs have been able to show high performance specifically for $CO_2$and H_2 adsorption. In these applications, the regulation of pore size as well as the chemical change of the pore surface (due to the change of ligand type) play a key role in determining the absorption capacity and selectivity of gases. In addition to absorption, separation of gases is also possible through differences in surface interactions and pore size; In this way, compounds such as CO_2 absorb more than other gases, and this is of great importance in industrial separation processes [13]

6.3. Pharmaceutical applications and drug delivery

Copper metal MOFs are used as effective carriers in drug delivery due to their biocompatibility, high porosity and drug loading capability. The regular structure and wide pore space allow drugs to be placed within the structure in a controlled manner and then released by reacting to environmental stimuli such as pH or temperature. In addition, the chemical properties of copper ions can enhance molecular interactions between the drug and the carrier, leading to increased efficiency of drug delivery and reduced side effects. Recent studies have shown that copper-based MOFs, in addition to their high absorption performance, have the ability to surface target and bind biofunctional groups, which can lead to more precise regulation of drug release rate and increase therapeutic efficiency [19]

6.4. Use in sensors and electronic applications

Due to their electron properties and structural tuning capabilities, copper metal MOFs have become widely used in the field of sensors and electronic devices. The combination of copper ions with organic ligands allows the creation of electron networks with appropriate charge transfer. These features are of particular importance, especially in sensor applications that require rapid response to environmental changes. For example, changes in the light absorption or diffraction pattern in MOFs can be used as a sensing parameter to identify environmental gases or pH changes. Also, the use of MOFs in the manufacture of electronic sensors has led to the use of these materials as interfaces between electronically active components in semiconductor[6]. In addition to sensors, the electronic capabilities of MOFs can be exploited in the development of energy storage devices and new electronic circuits.

The applications of copper metal MOFs in the fields of catalysis, absorption and separation of gases, drug delivery and sensors show the high potential of these materials in new technologies. Fine-tuning the crystal structure, molecular order and pore surface allows researchers to purposefully optimize these materials for specific applications. Due to recent developments and new approaches of synthesis and application, it is expected that the use of copper metal-based MOFs will expand rapidly in various industries, including energy, environment and medicine[4]

6.5. Limitations and problems of synthesis and stability

One of the most important challenges in the synthesis of copper metal-based MOFs is the strict control of the synthesis process in order to achieve quality and uniform crystals. Although the use of hydrothermal or salothermal methods allows the formation of regular crystal structures, precise parameters such as temperature, reaction time, metal-ligand ratio and type of solvents can easily cause structural defects or reduce the final stability of materials. For example, unwanted changes in temperature or pH conditions may cause degradation of porous structures or the formation of unwanted by-products, resulting in reduced thermal and chemical stability of MOF Batten et a [7] In addition, issues related to the sensitivity of MOFs to humidity and humid environments are also considered as fundamental challenges; So that in real conditions, contact with water or other polar solvents can lead to structural change and loss of initial performance of MOFs.

6.6. Practical challenges in real conditions

Despite significant achievements in the synthesis and structural analysis of copper metal MOFs in the laboratory, the transfer of this technology to industrial and real applications is associated with several challenges. In real environments, factors such as temperature changes, pressure, environmental pollution and interactions with complex molecules in real samples can affect the performance of MOFs. For example, in gas separation or drug delivery applications, instability of structure versus environmental changes and intolerance to real conditions (such as high humidity or different organic conditions) may reduce efficiency and increase maintenance costs. Also, the integration of MOFs in electronic devices or sensors requires the creation of reliable interfaces between MOFs and other system components; A challenge that requires the improvement of large-scale processing and assembly methods from a technical and engineering point of view[10]

6.7. Research opportunities and suggestions to improve performance

Despite the above challenges, there are many opportunities to research and improve the performance of copper metal MOFs. Some of these opportunities are:

• Optimizing synthesis conditions: Future research can achieve more accurate control of synthesis parameters and reduce structural defects by using new technologies such as microwave synthesis, continuous flow reactors or electrochemical approaches. These approaches can reduce the reaction time and improve the quality of the resulting crystals [11]

• Using «green» methods in synthesis: Applying sustainable and environmentally friendly methods such as mechanical synthesis or using less toxic solvents can help improve the stability and final performance of MOFs in addition to reducing production costs.

• Post-synthetic modification and surface optimization: Using post-synthetic modification techniques to change the surface properties of MOFs, including adding specific functional groups to improve interaction with gases or drugs, is one of the important research opportunities. will be. These approaches can lead to increased absorption efficiency, selectivity and even improved electronic properties [12]

• Integration into applied systems: Research on methods of integrating MOFs with other supporting materials and structures (such as magnetic nanoparticles or conductive polymers) can provide new fields for electronic, sensing and drug delivery applications. Establishing strong and stable interfaces between MOFs and compatible matrices is among the important areas to be considered in future studies [15]

• Molecular and theoretical research: The use of molecular simulation methods and theoretical basis calculations (DFT) can help to better understand the charge transfer processes, the exact structure and the way molecular interactions inside the pores of MOFs and clarify the areas for design improvement. slow [16]

The challenges in the synthesis and applications of copper metal MOFs, including the limitations caused by synthesis conditions, instability in real environments and problems related to integration into practical systems, coincide with many research opportunities. Improving synthesis methods, applying green approaches, postsynthetic modification and intelligent integration with other new technologies can significantly increase the performance of these materials and provide wider application fields in various industries [17]

6.8. Summary of findings

Metal-organic frameworks (MOFs) with copper metal cores, due to unique features such as high porosity, wide specific surface area, and structural adjustability, in various fields such as catalysis, gas absorption and separation, drug delivery, and sensors. They have found wide applications. By providing catalytically active sites, materials allow for improved chemical reactions and are effective in selectively adsorbing gases such as CO_2 and H_2. A controlled loading and release of drugs has made them a suitable option for biomedical applications.

6.9. The importance of improving synthesis methods and new applications

Improving the synthesis of copper-based MOFs, including the use of new techniques such as microwave synthesis, sonochemical and electrochemical methods, can lead to a reduction in reaction time, increase in efficiency and improve the quality of the resulting crystals. These advances not only help to improve the structural and functional characteristics of MOFs, but also allow the development of new applications in areas such as energy storage, advanced sensors and more efficient catalysts.

7. Conclusion:

In this article, copper metal-based MOFs were comprehensively investigated. These structures have shown great potential in various applications by providing unique features. However, there are challenges such as precise control of synthesis conditions, stability in practical conditions and integration into applied systems that require further research. Improving synthesis methods, using green approaches, post-synthetic modifications and integration with other nanomaterials can help improve performance and expand the applications of these materials. It is suggested that, in future research, special attention be paid to the development of sustainable synthesis methods, the investigation of behaviour under practical conditions and the design of high performance hybrid materials so that the full potential of copper-based MOFs can be exploited in industrial and medical applications.

8. Suggestions for future research

1.Development of green and sustainable synthesis methods:The use of biocompatible solutions and solvent-free methods can help reduce environmental impacts and increase the stability of synthesis processes.

2.Investigating durability and durability in practical conditions: Studying the behavior of copper-based MOA in real conditions, such as variable temperature and humidity, is essential to ensure stable performance in industrial applications.

3.Penthesian modifications to improve performance: Performing chemical modifications after synthesis, such as surface functionalization, can help improve the absorption characteristics, selectivity, and stability of MOFs.

4.Integration with other nanodes: The combination of copper-based MOFs of other nanomaterials, such as metal nanoparticles or graphene, can lead to the development of hybrid materials with improved properties.

5.Theoretical studies: The use of calculation methods to predict the behavior and characteristics of MOFs can contribute to the targeted design of materials with optimal performance.

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