

Review

Metal Organic Frameworks for Smart Storage and Delivery of Aromatic Volatiles and Essential Oils in Agrifood

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Abstract: Metal Organic Frameworks (MOFs) are a unique family of tailor-made porous materials that have gained significant attention for their properties and their applications in various fields, including agriculture and agrifood. The aim of this review is to explore the potential of MOFs as smart carriers and delivery mediums of essential oils (EOs) and/or aromatic volatiles. Emphasis is given to their potential to be applied in crop protection and fresh food preservation. MOFs indeed present highly promising physicochemical characteristics in order to be applied in such sectors. To name a few, their high surface area, tunable porosity, and customizable functionalities, make them ideal carriers for EOs, which are established for their antimicrobial properties but their wider practical applications are limited by their volatility and chemical sensitivity. The encapsulation of EOs in MOFs enhances their stability, controlled release, and bioavailability, providing effective solutions for sustainable agriculture and food safety. Furthermore, in this review we discuss various MOF types, emphasizing the most recent literature references, including cyclodextrin-based MOFs, Cu²⁺ based MOFs, Zn²⁺ based MOFs as well as Zr⁴⁺ MOFs. In this work, we attempt to highlight the interactions and physicochemical characteristics (e.g., pore size and pore functionality), that contribute to the encapsulation of different EOs within MOFs. We focus on a detailed discussion of the external stimuli that can trigger the targeted release of EOs, such as pH changes caused by pathogenic microbial activity. Additionally, we examine the potential benefits of the EOs encapsulation in MOFs, including the reduction of premature evaporation due to their volatile nature and their improved delivery to targeted sites. These aspects are explored within the frameworks' food safety enhancement, extended shelf life and the promotion of sustainable food preservation alternatives. Furthermore, we address MOFs' limitations such as biocompatibility, scalability and chemical stability under field conditions to further comprehend their potential as EO carriers in agrifood applications, emphasizing food preservation and protection. Finally, this work aims to contribute to global challenges in nutrition and sustainable agriculture.

Keywords: metal-organic frameworks; essential oils; agrifood; food packaging; smart delivery



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1. Introduction

Metal-organic frameworks (MOFs) are a class of tailor-made porous materials that have attracted attention across several scientific fields. Their unique physicochemical properties, resulting from the meticulous combination of inorganic and organic building blocks towards porous networks, have made them excellent candidates for a wide range

of applications [1,2]. This versatility has brought them to the forefront of chemical and materials science. More specifically, their high surface area, tunable porosity, and the ability to introduce specific functionalities make them ideal candidates for various fields, including the storage and separation of molecules ranging from gases to vapors, volatiles, and even larger pharmaceutical compounds [3–5]. MOFs can particularly serve as smart carriers of active compounds as they can adsorb and carry sensitive active compounds until they are released under specific external stimuli. More specifically, with the term “smart carriers”, we usually refer to nanostructured delivery systems, such as MOFs, that are engineered to enhance the stability of active ingredients and minimize their premature release. These systems enable controlled release, meaning the active compounds (e.g., pesticides, fertilizers, or drugs) are gradually and predictably released over time in response to environmental or biological stimuli. This not only improves delivery efficiency but also reduces the overall chemical input and the frequency of application. MOFs, in particular, offer tunable porosity and responsive degradation behavior, making them highly suitable as smart carriers for controlled release applications [6,7].

Over the past few decades, MOFs have played a leading role in environmental and energy-related applications, such as the storage of gases like H_2 and CO_2 , establishing their prominence in these fields [7–9]. However, their versatile nature and the freedom offered by their customizable building blocks have paved the way for their use in alternative sectors [8,10]. Leveraging their tunability, MOF networks can be synthesized with specific characteristics, such as pore shape and size, and can include functional groups at their backbone. These tailored features allow MOFs to serve as hosts for targeted molecules, either to protect and store them or to release them slowly into a specific environment under controlled conditions or specific triggers [10–12]. This unique behavior sets MOFs apart from other porous materials, making them promising candidates for innovative solutions to pressing global challenges. As such, their applications have expanded beyond energy and environmental fields into areas such as agriculture and agrifood science [13–15].

The constantly growing global population has increased the demand for crop production and has highlighted the need for novel and effective food storage approaches [6,7], particularly for post-harvest crops [16,17]. While synthetic chemicals have provided an effective solution for many years, their widespread use has led to a range of side effects, with bioaccumulation being the main concern [18,19]. To achieve more sustainable solutions, alternative approaches have been explored, with essential oils (EOs) and fragrances emerging as promising candidates [17,19,20]. EOs have been used for centuries and are well-known for their pharmaceutical properties, including strong antimicrobial activity, as they can inhibit the growth of pathogens such as fungi and bacteria [21,22]. Moreover, due to their chemical nature, EOs pose less risk of bioaccumulation and have less impact on non-pathogenic organisms, which can be beneficial to crop growth and soil health [20]. However, their highly volatile nature, combined with chemical sensitivity (e.g., degradation under specific conditions or photodegradation), limits their broader use and creates a need for smart carriers that can facilitate their application [22,23]. This is where MOFs, with their porous structure, offer a promising solution, as they can encapsulate diverse aromatic compounds, protecting them and enabling their controlled release under specific conditions.

In this review, we particularly emphasize the employment of MOFs for the encapsulation and targeted delivery of EOs and their active components (e.g., terpenes) in agrifood applications. Our objective is to provide a critical analysis of the physicochemical characteristics that make certain MOFs suitable for encapsulating volatile compounds as EOs, as well as the mechanisms that govern their controlled release under specific external stimuli. To this end, we review the types of MOFs that have been explored to date in this

context. To enhance clarity, we categorize the discussed materials into different families, highlighting the specific advantages of each family. This classification is based on the building blocks of each MOF, which directly influence their physicochemical behavior. We place particular emphasis on applications related to crop protection and food preservation. Additionally, we aim to identify key current limitations that these formulations face and propose future directions to address these challenges. Overall, through this work, we aim to support the development of more effective and sustainable strategies for food safety and agricultural productivity.

2. Metal-Organic Frameworks

MOFs are hybrid inorganic-organic open frameworks with potential high porosity. More specifically, they are built through the combination of organic linkers and inorganic building blocks, which can either be metal ions or polynuclear metal clusters, also described as secondary building units (SBUs) [24–26]. The combination of these building blocks towards the formation of a porous framework is governed by reticular chemistry principles [27,28], which have been proven to be a powerful tool for the design and synthesis of materials with specific structural characteristics and installed functionality to enhance their interactions with specific chemical moieties and improve their performance in targeted applications.

In detail, the organic building blocks of a MOF are usually organic carboxylate or azolate polytopic linkers of diverse geometry, which are pre-synthesized [26,29]. This makes them a robust building block that can dictate the structure of the final framework to a great extent, in contrast to the inorganic building block, which is rarely pre-synthesized [30,31], but usually forms *in situ* under specific reaction conditions. So, in this way the fact that the organic linker acts as an actual preformed building unit [26], not only allows us to a great extent to control and therefore target specific structural characteristics to the synthesized material but also to ensure that specific chemical groups are present to the backbone of the material [29,32]. This is very important because in this way we can synthesize porous materials that not only present specific pore shapes and sizes towards the storage of targeted molecules, but also through the presence of specific chemical groups. Thus, the affinity of the framework with the targeted molecules can be increased, achieving in this way high storage percentages.

Regarding the inorganic building blocks, also described as SBUs, they can be polynuclear oxo-metal clusters, one-dimensional metal-oxo chains, or single metal cations [28]. However, MOFs based on polynuclear metal oxo clusters have gained the attention of the scientific community in the last decade, and a plethora of groups have been dedicated to the exploratory synthesis of such novel frameworks. This is due to two main factors. Firstly, polynuclear metal clusters are known to adopt specific geometrical shapes, which is a crucial parameter as in this way the prediction of the final network can be more accurate by employing reticular chemistry principles [33–36]. Also, the increased connectivity that these kinds of inorganic moieties allow with the organic linkers enhances the stability of the final network, in a plethora of environments, including water, which is a crucial prerequisite for various applications concerning the environment, human health, and agriculture.

Recently, MOFs have been at the forefront of materials science due to a combination of key features, as their remarkable chemical stability, their unique tunability, their high surface area, and their modular synthesis [37,38]. These properties have established MOFs as a unique family of tailor-made highly porous materials that can be designed and synthesized for targeted applications across diverse fields. Also, their highly crystalline nature allows their detailed structural characterization and better understanding of their structure-property interactions, paving the way for future innovations [39]. Therefore,

MOFs have found widespread use in a broad range of applications as gas storage and separation [40], photoluminescence [41,42], sensing [41,43], magnetism [44] catalysis [45,46], optoelectronics [47] drug delivery [48–50], bioimaging [51,52], conductivity [53], energy storage [54–56], among others.

A full profile characterization of MOFs includes a combination of structural, morphological, and spectroscopic characterization methods employing state-of-the-art methodology. One of the most important characteristics of MOFs, which has brought them to the forefront of porous materials, is their crystallinity and the ability to be isolated in the form of single crystals. This allows their detailed structural characterization and the in depth understanding of their structure while enabling the strong correlation between structure and properties. This is enabled through Single Crystal X-ray Diffraction (XRD) [57], which is usually combined with Powder X-ray Diffraction (XRD), contributing to the verification of phase purity, especially in up-scaled reactions, as well as the estimation of the structure stability under different environments (e.g., solvents, temperature, air) [58]. Furthermore, the porosity of these materials, which usually present complex porous networks with smaller and larger interconnected cavities, is mapped through detailed Ar or N₂ sorption experiments at 87 K and 77 K, respectively. Through these measurements we can calculate the total pore volume of the materials, their specific surface area employing the Brunauer–Emmett–Teller (BET) method [59] and their pore size distribution. Additionally, the morphology of the materials can be studied using microscopy methods, such as Scanning Electron Microscopy (SEM). Also, their thermal stability in air or under an inert atmosphere is studied employing Thermogravimetric Analysis. Spectroscopic studies as Fourier transform infrared (FT-IR) and UV-Vis spectroscopy can also be employed to further comprehend the physicochemical characteristics of such materials. Furthermore, as far as their antimicrobial assay is concerned, microscopy as SEM or Transmission electron microscopy (TEM) can also be employed to study the damage on the pathogens' cells after their treatment with MOF formulations. Furthermore, protocols such as ASTM E2149-13a [60] and the microtiter broth dilution technique [61,62] can be utilized.

In this framework, MOFs' utilization in agriculture and pesticide technology represents a rapidly expanding area of application [63]. Specifically, their controlled pore size, high surface area, ease of chemical modification, and unique network structure render them promising candidates for the loading and controlled release of pesticides and other plant-protective compounds [64,65]. Also, their physicochemical profile allows the potential for “smart” combination with a multitude of functional ingredients [66], such as nanoparticles, active organic molecules (photosensitizers, catalysts), and polymers, allowing for the development of intelligent platforms with improved stability and enhanced responsiveness under specific conditions, related to the soil and plant growth environment (e.g., pH, salinity, temperature). These characteristics make them suitable for loading selected active substances and releasing them under controlled conditions to ensure maximum effectiveness [37,38].

Additionally, the freedom afforded by these materials regarding the selection of their building blocks enables not only the design of efficient active substance release systems but also the incorporation of molecules with desirable plant-protective action (e.g., aspartic acid, coumarin, fumaric acid, amino acids, zinc, copper) into their very framework, thereby enhancing the development of multifunctional systems with simultaneous action in different targeting areas [67]. To date, the international literature is continuously enriched with promising MOF-based materials aiming to crop protection through the control of phytopathogens, pest management, and weed management [68].

The first report on the use of MOFs as carriers for pesticide release dates back to 2015 (OPA-MOF, OPA: oxalate-phosphate-amine) for the gradual release of nutrient trace

elements such as nitrogen (N) and phosphorus (P) [69]. Another significant contribution to the field was the MOF-1201 ($[\text{Ca}_{14}(\text{L-lactate})_{20}(\text{acetate})_8\text{X}]$ (X: $\text{C}_2\text{H}_5\text{OH}$, H_2O)), based on the organic substituent L-Lactate and calcium metal ions. This material was used for the controlled release of the active substance cis-1,3-dichloropropene (1,3-DCPP) [70]. Beyond the gradual and slow-release rate of the active substance, the biodegradable nature of the material played a crucial role in its application, making it efficient and environmentally friendly, turning the research community's attention towards materials with these characteristics. Recent literature has a plethora of interesting MOF-agrochemicals hybrids for the prevention and treatment of different pathogens such as: (i) fungicides: diniconazole [71], prochloraz [72], tebuconazole, and zoxystrobin [73,74]; (ii) insecticides: chlorantraniliprole [75], λ -cyhalothrin [76], dinotefuran [77], imidacloprid [78], and thiamethoxam; (iii) fertilizers: urea; and (iv) plant growth regulators: gibberellin [67].

Apart from their direct applications in the field, MOFs are also starting to be employed in various areas related to food quality preservation (Figure 1), with examples regarding the extension of shelf life of fresh-cut fruits and vegetables, as it will also be presented in this work. Also, they are related to applications which are contributing to healthier soil and water conditions that indirectly enhance crop quality as it is presented in the following examples.

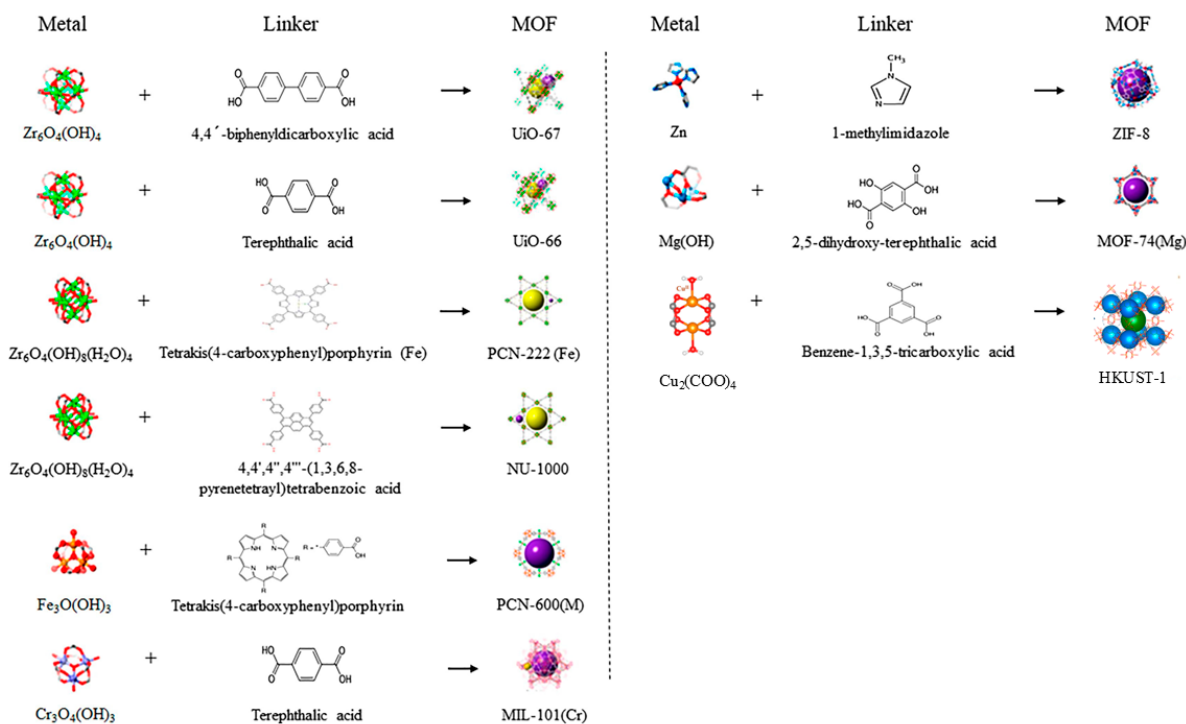


Figure 1. Examples of the most common MOFs used in agriculture and agrifood according to the literature [79]. Adapted with permission from Ref. [79] ©Elsevier 2021.

MOFs like HKUST-1 and ZIF-67 were found to be highly efficient for the removal of organic dyes through electrostatic and π - π interactions [43,80,81]. More specifically magnetic hybrids of HKUST-1, $\text{MnFe}_2\text{O}_4\text{-NH}_2\text{-HKUST-1}$ [81–83] were found remarkably productive for the removal of dyes found in industrial pollutants. In this work, it is presented that the hybrid magnetic HKUST-1 exhibits adsorption capacities of 108.69 mg/g for malachite green (MG), 70.42 mg/g for crystal violet (CV), and 156.25 mg/g for methylene blue (MB) [83,84]. Optimal dye removal—exceeding 75%—was achieved under specific conditions: pH levels of 5.5 for MG, 5 for CV, and 7 for MB; contact time of 5 min; and adsorbent dosages of 10 mg, 5.5 mg, and 1 mg, respectively. At the same time

due to its magnetic nature the adsorbent can be quickly and easily retrieved from the solution using an external magnet, thus eliminating the need for more labor-intensive separation methods like centrifugation [81]. Furthermore, ZIF-67 has been also found relatively effective for the removal of dyes, especially anionic ones along with pharmaceuticals and other organic molecules [43]. Actually ZIF-67 has been tested for the removal of a plethora of dyes, both anionic and cationic ones, such as Methyl Orange [80,85], Acid Orange-7 [86], Amaranth dye [87], Congo Red [88], Direct Blue-86 [89], Malachite Green [90], and Brilliant Green [91]. A magnetic ZIF-67 (Fe_3O_4 -PSS@ZIF-67) has been established for the removal of Methylene Orange [80] from MB. This specific hybrid presented a 92% removal rate and 96% separation efficiency [85]. Also, pristine ZIF-67 presents among the highest removal capacities for acid orange at 738 mg/g at pH = 8 compared to ZIF-8, UiO-66 and UiO-66- NH_2 [86]. The same MOF, presents also an excellent adsorption capacity for Congo Red at 714.3 mg/g at 301 K [92]. A similar behavior is recorded also for cationic dyes. For example ZIF-67 presents better performance than conventional adsorbents in the case of MG, with an adsorption capacity at 2430 mg/g [90]. Also, Zr-MOFs, as BUT-12 [93] and PCN-224 [94] and Cu-MOFs, like HKUST-1 [95], demonstrate high adsorption capacities for antibiotics, addressing the critical issue of antibiotic contamination in agricultural wastewater. BUT-12 exhibits a high adsorption capacity for the antibiotics nitrofurazone (NZF) and nitrofurantoin (NFT), whereas BUT-13 demonstrates rapid adsorption for NZF, NFT, oxazolidinone (ODZ), sulfonamide (SAM), and chloramphenicol (CAP). The variation in adsorption behavior between BUT-12 and BUT-13 is likely attributed to differences in their pore structures [93]. For PCN-224 particles with a diameter of 300 nm serve as an effective adsorbent for the removal of tetracycline (TC) and ciprofloxacin (CIP) from water. To better understand the adsorption process, kinetic, thermodynamic, and isotherm analyses were conducted for both antibiotics. The material demonstrated impressive adsorption capacities, reaching 354.81 mg/g for TC and 207.16 mg/g for CIP—values that are notably higher than those reported in previous studies [96]. Furthermore, MOFs like MIL-101- NH_2 and magnetic core-double-shell composites are effective in removing heavy metal ions, enhancing food safety by reducing environmental contamination [97]. Beyond remediation, luminescent MOFs, such as Eu(BTC)-MIP [98] and LMOF-241 [99], serve as sensitive sensors for detecting pollutants like antibiotics and aflatoxins, providing valuable tools for food quality monitoring [50,51].

In parallel with food preservation is concerned, MOFs offer innovative solutions for controlling ripening, preventing spoilage, and delivering antimicrobial agents. For example, they can regulate the production of ethylene which can directly affect the quality of packaged food. This can be achieved through storage and controlled release, as demonstrated by Cu-TPA MOF and Al-MOF encapsulated in alginate- Fe^{3+} composites [100]. MOFs like HKUST-1 and MIL-101@GO composites also function as effective moisture and oxygen scavengers, preventing pathogen contamination and lipid oxidation [101]. Moreover, MOFs can encapsulate and release antimicrobial essential oils, such as thymol, providing high-efficiency delivery and sustained antimicrobial activity. Also Ag-MOFs, for example, control the release of Ag^+ ions, exhibiting strong antimicrobial activity [102]. Au@ZIF-8 SERS paper [103] and Ce-PEDOT/GCE [104] serve as sensors for detecting biogenic amines and active substances, respectively, ensuring food quality monitoring. γ -CD-MOF-K and MgF embedded in films control ethylene levels, delaying fruit ripening [105]. While, Cat- β -CD-MOFs [106] and MOF-801 function as moisture and oxygen scavengers, maintaining food quality through smart packaging systems [107]. UiO-66- NH_2 and HKUST-1@CMCS control the release of antimicrobial agents [60,61,108], providing long-term antibacterial effects. Finally, Zr-MOF (BUT-17) detects toxic substances like polychlorinated dibenzop-dioxins (PCDDs), ensuring food safety [109]. These promising results have positioned

MOFs at the forefront of alternative agrochemical and agrifood solutions, broadening their applications beyond the environmental and energy sectors to the fascinating realm of storing and releasing chemical compounds, in response to specific triggers for plant, soil, or crop protection. The integration of these smart porous materials not only introduces a new area of interest but also presents a viable solution for employing natural, green substances in agrifood applications. Until now, the volatile nature and chemical sensitivity of these substances have limited their use despite their profound benefits in comparison to traditionally used chemical compounds

In general, MOFs are complicated tailor-made coordination polymers that can be synthesized from a plethora of metal ions and diverse organic linkers, which directly affects their toxicity regarding mammals and living organisms. Their biocompatibility is directly connected to that of their building blocks, but also to the physicochemical characteristics of the framework that they form [110]. Based on that, over the years, a plethora of attempts have been made towards the development of biocompatible MOFs, and indeed, an interesting category of bio-MOFs has emerged [111]. Recent advancements have focused on synthesizing MOFs using biocompatible metals such as Ca^{2+} , Mg^{2+} , Fe^{3+} , and Zn^{2+} , combined with endogenous organic linkers such as amino acids, peptides, and cyclodextrins (CDs). These building blocks are generally recognized for their low toxicity and compatibility with living organisms [110]. Importantly, CD-MOFs, synthesized from γ -CD and alkali metals (Na^+ and K^+), have demonstrated potential for food-related applications due to their biodegradability and edibility [112]. However, it is also important to note that even MOFs composed of the same metal ions can exhibit different toxicity profiles depending on the nature of their linker (Figure 2). For example, hydrophobic linkers such as nitro- or methyl-functionalized terephthalic acids are proven to increase toxicity in some cell lines, whereas hydrophilic linkers like 1,3,5-benzenetricarboxylic acid (BTC) show reduced cytotoxicity. Furthermore, toxicity does not always correlate directly with the individual toxicity of the organic linker, as the synthesized MOF and its physicochemical properties (e.g., surface charge, and hydrophilicity) can modify cellular interactions [113]. In vivo studies have further demonstrated that different linkers affect the biodistribution and clearance of MOFs in organs such as the liver and spleen, highlighting their potential influence on systemic toxicity. Although some linkers have been implicated in elevated toxicity (e.g., fumaric acid or BDC- NO_2), others like BTC or functionalized imidazoles have shown better biocompatibility depending on the context and host model [114,115]. Overall, while organic linkers do not unilaterally determine toxicity, their selection and combination with the appropriate metal ions is a critical design parameter for developing safe MOFs for agrifood applications.

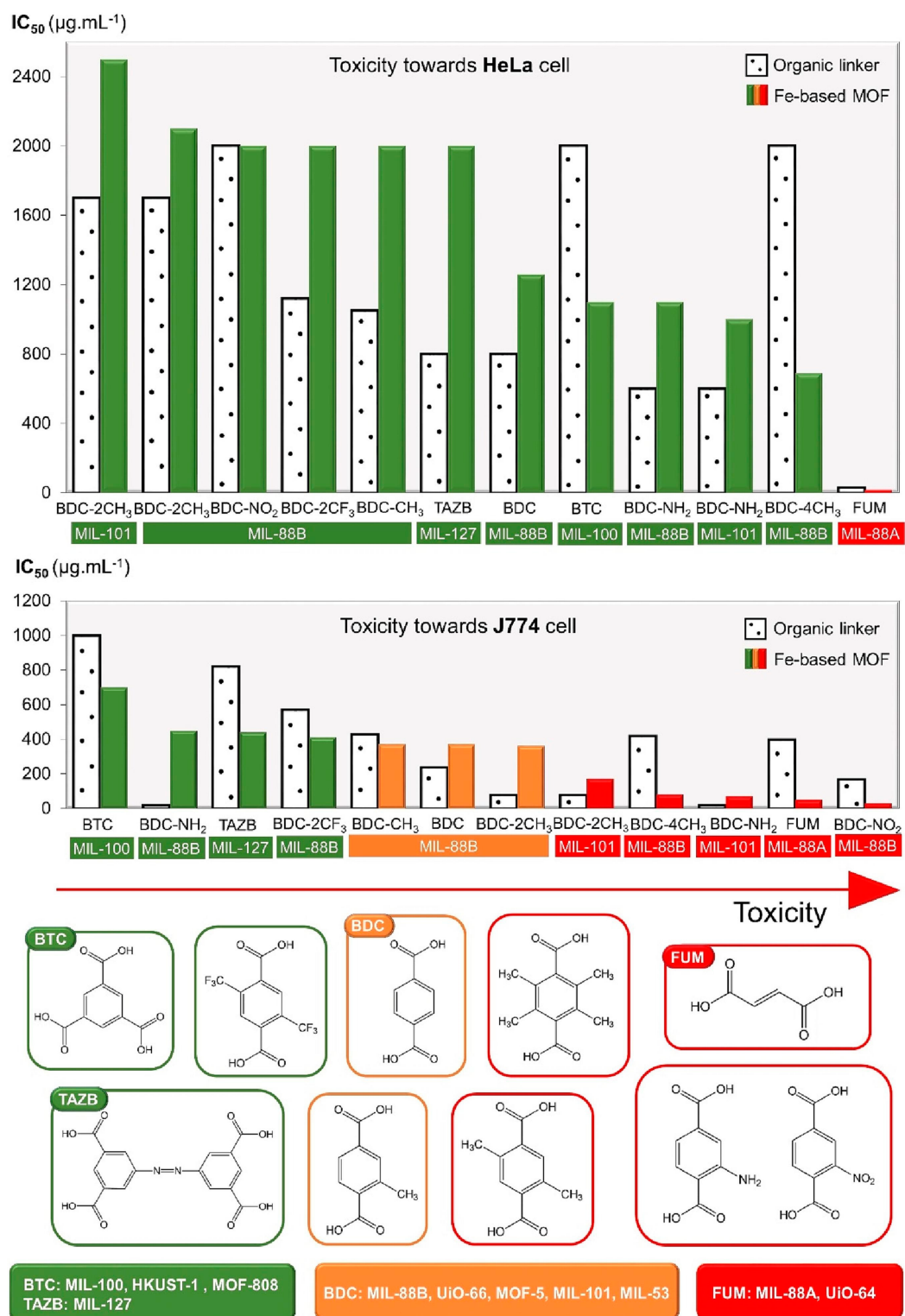


Figure 2. Toxicity of organic ligands and corresponding MOFs based on Fe, based on IC₅₀ data [110,114] Reprinted with permission from Ref. [110] ©Elsevier 2023.

3. Essential Oils, Terpenes and Terpenoids in Agrifood

The constantly increasing worldwide need for food and the consequent necessity for well-preserved crops and edibles have dictated the need to seek effective, sustainable, and biocompatible preservation methods. Currently, essential oils (EOs) have emerged as a highly promising alternative. Their antimicrobial properties enable them to effectively address issues caused by pests, weeds, fungi, and bacteria without harming

crops or causing bioaccumulation, a significant concern with commonly used chemical synthetic compounds.

More specifically, EOs are secondary metabolites produced by various plants in order to survive under extreme environmental conditions, such as high or low temperatures and non-optimal pH levels. These oils are rich in bioactive low molecular weight compounds, such as terpenes, aldehydes, ketones, esters, oxides, and alcohols (Figure 3) [113]. The chemical composition of EOs varies significantly across plant families and even within the same species, according to external environmental factors [116].

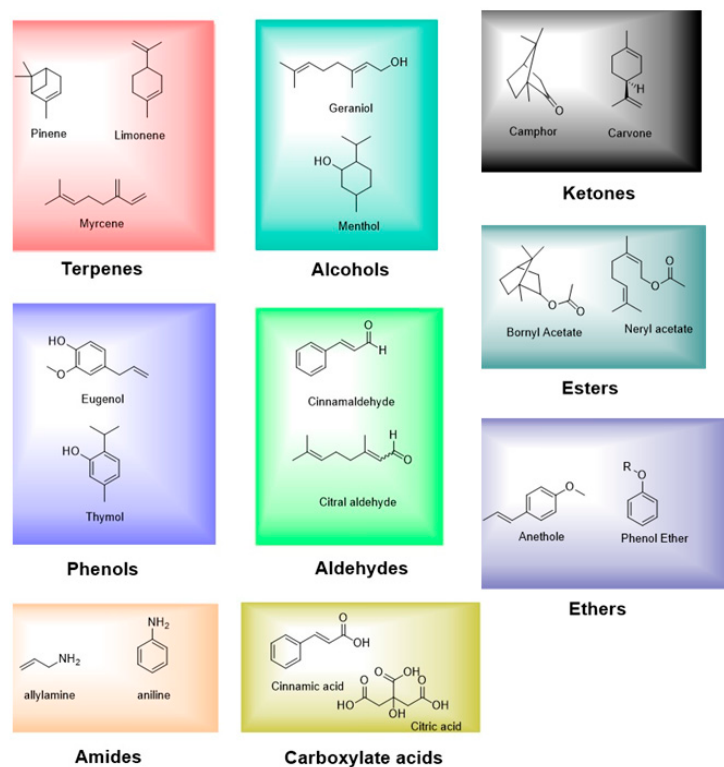


Figure 3. Bioactive low molecular weight components of Essential Oils.

For centuries, EOs are known for their antimicrobial properties and for this they have been studied in depth. Their diverse chemical nature enables them to be effective against various pathogens, such as bacteria, fungi, and viruses. For example, thyme (*Thymus vulgaris*) [117], oregano (*Origanum vulgare*) [118], and cinnamon (*Cinnamomum zeylanicum*) are known for their antibacterial [119] and antifungal activities [120]. This antimicrobial activity can be attributed to EOs' ability to disrupt cell membranes, interfere with ion transport within microorganisms, and induce leakage of cellular contents, that leads to cell death [68,69,121]. Furthermore, due to their natural origin, EOs do not present the risk of bioaccumulation, and for this reason the GRAS (Generally Recognized As Safe) status by the United States Food and Drug Administration has been attributed to them, making them a promising alternative in various agrifood sectors, including food preservation and sustainable biopesticides [122].

However, despite their potential, several challenges hinder their wider application as antipathogenic agents. To name a few, their intense aroma, high volatility, hydrophobicity, and potential interactions with food components can negatively impact organoleptic properties [123]. Additionally, their instability and limited solubility reduce their effectiveness as preservatives. It is important to note that in agricultural applications, biomass availability, chemical stability, formulation, and phytotoxicity present significant obstacles [124].

These promising characteristics necessitate scientific efforts to overcome these limitations, offering safe, economical, and environmentally friendly alternatives that address health hazards and contribute to food security in the face of a growing global population.

To mitigate these challenges, advanced delivery strategies such as nanoencapsulation, active packaging, and polymer-based coatings have been developed. Through these methods the EO stability is enhanced along with solubility, and controlled release, improving bio-efficacy and minimizing impacts on food sensory attributes [73,74]. In agriculture, novel application methods have been introduced. For example, seed coating with EOs, has demonstrated potential for inducing durable plant defenses with long-term effects using small amounts of EOs [124].

The aforementioned inherent challenges associated with the wider utilization of EOs, primarily their volatility and chemical instability, can be effectively addressed through encapsulation within porous materials. This route offers a multifaceted approach to enhancing the applicability of EOs across various sectors including that of agrifood. Through EOs' encapsulation in porous materials, these compounds can be protected against environmental stressors such as heat, light, oxygen, and moisture, significantly enhancing their stability and preventing the degradation of their active components. This protection is crucial for maintaining the efficacy of EOs over extended periods either in the field or on the shelf [24,125].

Furthermore, encapsulating aromatic volatiles, specifically EOs, in porous materials facilitates a controlled release, which provides a slow and continuous delivery of their active components [126]. This controlled release approach not only extends the effective duration of EOs but also minimizes the need for frequent reapplication. In this way a more efficient, practical and cost-effective solution is introduced. Encapsulation also effectively reduces the volatility of EOs, preventing rapid evaporation and ensuring that their valuable properties are retained for prolonged periods [127].

Beyond stability and controlled release, porous materials can improve the bioavailability of EOs, by enhancing their effectiveness in targeted applications such as in food preservation, or agriculture. Additionally, the encapsulation process can protect EOs from chemical degradation, including oxidation, isomerization, cyclization, and dehydrogenation, which can occur when they are exposed to harsh environments [128].

There are examples where encapsulated EOs demonstrate enhanced antimicrobial activity, inhibiting and eliminating more effectively pathogens. This enhanced activity, combined with their improved stability and controlled release is paving the way for versatile applications for EOs in various industries.

Thus, the use of porous materials for encapsulating EOs effectively mitigates the limitations posed by their volatility and instability, thereby significantly broadening their range of applications and enhancing their overall effectiveness. For example, several studies have demonstrated that encapsulation of EOs in mesoporous silica nanoparticles (MSNs) enhances their antimicrobial activity. For instance, peppermint EO encapsulated in SBA-15 silica exhibited improved efficacy against *Colletotrichum* species [129]. Similarly, cinnamon EO encapsulated in MSNs showed reduced volatility and prolonged antimicrobial effects [130]. Eugenol-loaded MSNs incorporated into PHBV films maintained sustained antimicrobial activity against foodborne bacteria over 15 days [131]. Additionally, cinnamaldehyde immobilized onto MSNs effectively eliminated over 99% of bacterial growth in various phytopathogens [132]. Such advancements pave the way for the more widespread and efficient utilization of EOs in diverse fields, leveraging their natural benefits for a variety of practical purposes.

MOFs can serve as effective porous matrices to protect and deliver these volatile and chemically sensitive compounds to their target. However, the physicochemical character-

istics of the MOFs used for this purpose must be carefully determined. Therefore, this review examines key MOF representatives that have been employed for EO encapsulation for them to be applied in the constantly expanding agrifood sector, aiming to elucidate the fundamental principles regarding the choice or even the design of a MOF for this purpose, along with their mechanisms of action and facilitate the development of improved systems.

4. MOFs as Smart Carriers and Delivery Systems of Sensitive Volatile Compounds

While MOFs exhibit unique physicochemical characteristics, several fundamental prerequisites must be considered before employing them for the encapsulation and controlled delivery of sensitive volatile chemical compounds. The vast diversity of organic ligands and inorganic building blocks available for MOF synthesis allows for tailored designs; however, the following key physicochemical characteristics are essential for successful application in this context.

Thus, in order to serve as effective encapsulation and delivery agents for volatile compounds in food and agrochemical-related applications MOF must fulfil the following prerequisites:

1. **Biocompatibility:** Ensuring safety in agrifood applications requires MOFs to be non-toxic and compatible with biological systems, to ensure the safety of consumers and avoid side effects caused by the ingredients of MOFs. This can be achieved through the utilization of biocompatible ligands such as cyclodextrins, amino acids, or nucleobases as well as the use of metals with low toxicity and a low hazard of bioaccumulation in the human body as K^+ or Na^+ [111].
2. **Stability under Physiological Conditions:** In the same framework, MOFs must maintain structural integrity and functionality across varying pH levels and temperatures encountered in the environments to that they will be exposed [133,134].
3. **High Porosity and Tunable Pore Size:** Efficient encapsulation and controlled release of the EO/volatile molecules necessitate high porosity and adjustable pore sizes to accommodate diverse molecular dimensions [135].
4. **High EO/volatile-Loading Capacity:** Maximizing antimicrobial efficacy demands a high capacity for loading and retaining substantial amounts of the EO/volatile compound. Also, high loading of MOFs ensures the employment of smaller mass of MOF, which is both cost effective as well as safer for humans and other nonpathogenic living organisms consuming the targeted product [135].
5. **Controlled Release Mechanisms:** Achieving sustained and targeted delivery requires mechanisms for controlled release, such as pH-sensitive or stimuli-responsive release. Many pathogens cause alterations in the physiological pH levels of the environment they parasitize. The immediate detection and action towards such a stimuli can be crucial [6].
6. **Functionalization Capabilities:** The ability to modify the surface or internal structure of MOFs enables improved targeting, solubility, and interaction with biological molecules [136].

Since these requirements are fulfilled, the advantages offered by MOFs as carriers for such compounds significantly underscore their potential. Encapsulation within MOFs can markedly enhance the solubility and stability of volatile bioactive compounds such as EOs, safeguarding them from degradation. Moreover, freedom in functionalization of their backbone, enables the design of MOFs that target the encapsulation or even the separation of EOs or their chemical components at a molecular level enabling the isolation of targeted active compounds e.g., terpenes and terpenoids [133,134,137]. Furthermore, the provision of controlled and sustained release of encapsulated compounds, maintaining

therapeutic levels over extended periods, is another key advantage. The versatility of MOFs, demonstrated by their capacity to encapsulate a broad spectrum of biological molecules, including drugs, enzymes, and nucleic acids, makes them suitable for diverse biomedical applications [138]. In the context of volatiles, these advantages translate to improved protection, controlled release, and enhanced stability, making MOFs promising platforms for their effective delivery and application.

In the last few years MOFs indeed have attracted the attention of scientists of the agrifood field. Various families of MOFs are currently explored regarding their capability to encapsulate a plethora of EOs targeting their delivery to specific environments under specific triggers which are in general related to the action of different pathogens (Table 1). Herein we attempt to review some of the key examples that have been reported up until today emphasizing on the issue of food pathogens.

Table 1. MOFs utilized for EOs controlled release, targeting food pathogens.

MOF	Essential Oil	Crop	Targeted Pathogens
γ -CD MOF [139]	Eugenol	Wheat	<i>F-graminearum</i>
γ -CD MOF [140]	Cinnamaldehyde	Cantaloupes	<i>E. coli</i>
IRMOF-3 [141]	Eugenol	Strawberries	<i>E. coli</i> and <i>S. aureus</i>
ZIF-8 [142]	Citral EO	Rice	<i>Magnaporthe oryzae</i> , <i>Botryosphaeria dothidea</i> , and <i>Fusarium oxysporum</i>
Zn-ascorbate MOF [135]	Marjoram EO	-	<i>E. coli</i> and <i>S. aureus</i>
γ -CD MOF [143]	Oregano EO	-	-
Cu-H ₃ BTC [144]	Cinnamon EO	Meat preservation	<i>S. aureus</i> , <i>S. enterica</i> , <i>E. coli</i> , and <i>L. monocytogenes</i>
CD MOFs (α , β , γ) [145]	Menthol	-	-
γ -CD-MOFs [146]	Thymol	Cherry Tomatoes	-
UiO-66,67,68 [147]	d-limonene (Lim), α -terpinene (Terp), myrcene (Myr), and α -pinene (Pine)	-	-
γ -CD MOF [148]	Carvacrol	Strawberries	<i>E. coli</i> , <i>S. aureus</i> and <i>B. cinerea</i>
Zn ₂ (BDC) ₂ (DABCO) [149]	Thymol	-	<i>E. coli</i> , <i>S. aureus</i>
IRMOF-3 [150]	Carvacrol	-	<i>E. coli</i> , <i>S. aureus</i>
IRMOF-3 [151]	Carvacrol	Pork preservation	<i>E. coli</i> , <i>S. aureus</i>
Ag-MOF [152]	Eugenol	Zucchini	<i>Staphylococcus aureus</i> , <i>E. coli</i>
IRMOF-3 [153]	Eugenol	Post harvest Strawberries	<i>Botrytis cinerea</i> , <i>Ralstonia</i> , <i>Sphingomonas</i> , <i>Erwinia</i> , <i>Rhodotorula</i>
γ -CD MOF@PCL [154]	Limonene	Preservation of fresh cut apples	<i>E. coli</i> and <i>S. aureus</i>
HKUST-1@ALG [155]	Tea Tree Oil	Fresh-cut pineapple preservation	<i>E. coli</i> and <i>S. aureus</i>
β -CD-MOF [156]	Clove EO	Chinese bacon	Inhibition of lipid oxidation
ZIF-67 [157]	Citral	Bamboo	<i>E. coli</i> and <i>S. aureus</i>
Zn-BDC-NH ₂ [158]	Thymol	-	<i>E. coli</i>
NH ₂ -UiO-66 [159]	Clove EO	Blueberries	<i>E. coli</i> and <i>S. aureus</i>
ZIF-8 [160]	Thymol	-	<i>Colletotrichum musae</i>
UiO-66-(COOH) ₂ [160]	Thymol	-	<i>Colletotrichum musae</i>

4.1. γ -CD-MOFs

Among the diverse families of MOFs those based on cyclodextrin (CD) are at the forefront of bio-related applications. That is due to their unique physicochemical and structural characteristics combined with their biocompatible nature. This unique family of materials combines the properties of MOFs and those of CDs (Figure 4) resulting to a smart versatile platform for bio-related applications including the smart release of molecules with biological interest, such as drugs, agrochemicals and active compounds with increased chemical sensitivity as scents and essential oils [161,162].

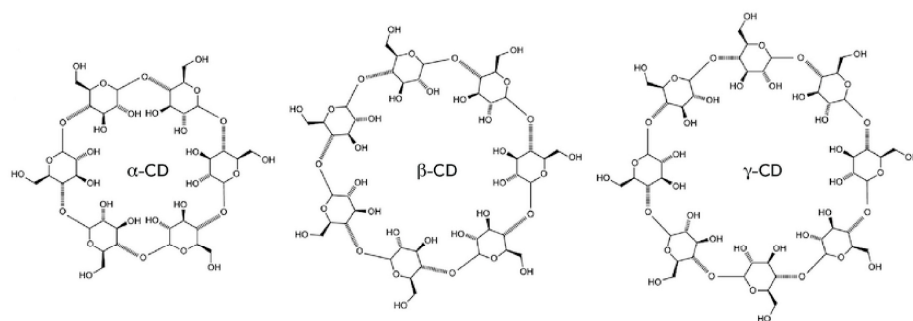


Figure 4. α -CD (6 glucose units and cavity size, 4.7–5.3 Å), β -CD (7 glucose units and cavity size, 6.0–6.5 Å), γ -CD (8 glucose units and cavity size, 7.5–8.3 Å) (CD refers to cyclodextrin) Reprinted with permission from Ref. [163]. © Elsevier 2022.

CD-MOFs are easily synthesized by combining CDs (Figure 4), serving as the organic ligand and potassium or sodium salts. CD-MOFs present high specific surface area values in combination with low density, due to the chemical nature of their building blocks, along with tunable pore size depending on the type of CD which is used. The increased available space that they provide in their framework allows the encapsulation of a high volume of active compounds, while the tunable pore sizes allow the encapsulation of diverse molecules of biological interest, ranging from small volatile molecules as terpenes and terpenoids to larger biomolecules.

In detail, CDs are cyclic saccharides with a conical hollow barrel structure, featuring a hydrophilic outer structure and a hydrophobic inner cavity. This leads to a unique framework architecture allowing the encapsulation of hydrophobic guest molecules e.g., EOs and their components (Figure 3), through van der Waals interactions or hydrogen bonding. At the same time, the hydrophilic outer space of these porous structures allows them to act as a vessel, transferring those hydrophobic molecules to hydrophilic environments which otherwise would not be approachable to them. Furthermore, the encapsulation of such active molecules, allows also their protection from degradation. Keeping in mind the chemical sensitivity of volatiles, their encapsulation in a porous framework helps them to be shielded against light, heat, or moisture improving their stability and therefore their mode of action. For example, CD-MOFs have been found effective towards the protection of curcumin, catechins and sucralose [161] but also, they have been employed for the safe and smart delivery for a plethora of volatiles as eugenol, cinnamaldehyde, oregano EO, thymol, carvacrol and clove EO just to name a few [139,140,148,162].

More specifically, recent studies highlight the versatility and effectiveness of CD-MOFs, particularly γ -CD and β -CD variants, in enhancing the preservation and functionality of various EOs. Below, we discuss important examples of CD-MOF-based carriers employed in agrifood sector, with a particular emphasis on food packaging examples.

A notable example that has been reported recently, is the in-situ growth of γ -CD-MOF on a chitosan-cellulose film aiming at the encapsulation of carvacrol EO. This hybrid material has been employed as an advanced packaging medium in order to extend the shelf-life

of sensitive fruits such as strawberries [148]. Through this approach, the physicochemical and structural characteristics of γ -CD-MOF are employed (namely, low toxicity, biocompatibility, and appropriate pore size) in order to prepare humidity-responsive active packaging. This work also highlights the challenges arising from employing non-toxic components for MOFs' synthesis while it also emphasizes on the benefits of employing in situ growth of MOFs on films in order to overcome the common issue of nanoparticle aggregation in such cases [148].

Beyond the utilization of γ -CD-MOFs for the encapsulation and smart delivery of carvacrol, this MOF has been found effective for the controlled release of various EOs, such as eugenol, cinnamaldehyde (CA), oregano essential oil (OEO), and thymol [139,140,143,146]. Encapsulating these EOs in the pores of γ -CD-MOFs was found to be an effective solution for their antibacterial and antifungal activity, strengthening the profile of EOs as green substitutes of chemical compounds. In detail, encapsulation of eugenol enhanced its antifungal activity against *F. graminearum* towards the protection of wheat [139] while the loading of CA in the pores of γ -CD-MOFs enabled its sustained release over 15 days, which resulted in the effective inhibition of bacterial growth in fresh-cut cantaloupes [140]. Also, the controlled release of OEO under the triggering presence of phosphate-buffered solution, presented a controlled release profile, bringing these systems to the forefront of various applications related to the agrifood industry, personal care and pharmaceuticals.

Recent advancements related to innovative synthesis and encapsulation methods, lead to improved γ -CD-MOF application in the field of alternative preservation methods of crops and fresh-cut fruit. An important example towards this direction is the synthesis of nanosized γ -CD MOFs' particles employing an ultrasound-based technique. Through this approach, the efficient encapsulation of limonene was achieved. A high loading reaching almost 170 mg g^{-1} was achieved combined with a content sustained release. This method combined with the deposition of γ -CD MOFs onto polycaprolactone (PCL) nanofibers, has resulted in a composite material with enhanced antibacterial activity against two of the most common pathogens, *E. coli* and *S. aureus*. The resulting formulation was successfully applied for the preservation of fresh-cut apples [154]. Another important parameter regarding the behavior of γ -CD-MOFs in terms of encapsulating EOs, is the molecular docking within the cavities of γ -CD monomers as well as in the internal cavities of the MOF. This behavior has been studied monitoring the controlled release of limonene in such platforms emphasizing on the effect of temperature and humidity in the process [154,160]. Accordingly, the micro-encapsulation of citral in these systems has demonstrated the potential for high encapsulation capacity and prolonged-release kinetics in comparison to plain cyclodextrin systems [164]. Furthermore, citral encapsulation in γ -CD-MOFs was further studied employing a vapor diffusion approach. This formulation has demonstrated enhanced thermal stability, and a control release mechanism mainly based on hydrogen bonding interactions. Spectroscopic and computational studies have provided valuable insights into the host-guest interactions, with molecular docking revealing the preferred binding sites and stabilization energies [164].

The meticulous study of cyclodextrin based MOFs for the encapsulation and controlled release of volatiles as EOs has been also enriched by the exploration of the influence of the potassium salts used for their synthesis, both on the structure and consequently on the encapsulation properties of γ -CD-MOFs. The latter were synthesized using different potassium salts as, exhibiting improved stability and enhanced thymol encapsulation. The KAc- γ -CD-MOF analogue was found to have the largest encapsulation content. Additionally, the high-temperature adsorption method described in these works proves to be an efficient technique to prepared thymol-loaded γ -CD-MOFs' formulation, offering higher encapsulation efficiency and capacity compared to co-crystallization [165].

On the same ground β -CD-MOFs have been successfully employed for the stabilization of clove EO (CEO). This has significantly contributed to the improvement of the EOs antioxidant activity and its contribution to the limitation of lipid oxidation in meat products. The porosity of β -CD-MOFs allows its sufficient loading with clove EO and its slow and controlled release. The encapsulation of clove EO in the pores of the MOF enhances its thermal and pH stability contributing to the strengthening of its activity. Furthermore, it has been demonstrated that encapsulation of the forementioned EO amplifies its reactive oxygen species scavenging action, making it a promising alternative to synthetic antioxidants [156].

4.2. Copper Based MOFs

Copper-based MOFs have also emerged as promising candidates for the encapsulation and controlled release of EOs in agrifood applications. Their unique structural characteristics combined with their potential high surface area, tunable pore size and functionality, can facilitate efficient EO loading and sustained release, thereby enhancing food preservation and extending shelf life. Additionally, the low cost of copper and its low toxicity compared to other heavy metals makes these materials promising candidates for such applications.

HKUST-1 is a well-established MOF, known for its large surface area and uncoordinated metal sites, which up until today has been tested for a plethora of applications [83,84]. In the framework of encapsulation and smart release of volatiles, it has been employed as a carrier for tea tree essential oil (TTO) formulated in moisture-responsive hydrogel beads. The synthesis of HKUST-1@ALG hydrogel beads has been achieved through alginate/copper ion cross-linking and in-situ growth, resulting in a hierarchical porous structure that presents high TTO loading capacity. The release of the active substance is based on moisture-triggered mechanism and has been found particularly effective for fresh-cut fruit preservation. In detail, increased moisture levels disarray the MOF's crystal framework, leading to a slow release of the encapsulated TTO. This formulation was successfully tested for the preservation of fresh-cut pineapple by maintaining cell membrane integrity, balancing reactive oxygen species (ROS) metabolism, and inhibiting cell wall-degrading enzymes. Furthermore, these MOF-EO hybrid beads offer excellent antimicrobial and antioxidant capacities, contributing to extended shelf life and reduced contamination risk. The bead form also provides better flowability and environmental sensitivity, making it a versatile delivery system [155].

Another recent study discusses the ability of Cu-BTC MOF to encapsulate the CEO, aiming to the preparation of active packaging films for the preservation of meat products. A Cu-BTC MOF was synthesized from copper ions and 1,3,5-benzenetricarboxylic acid (H3BTC). This Cu-MOF presented a high BET-specific surface area ($1476.70 \text{ m}^2/\text{g}$) and pore volume ($0.89 \text{ cm}^3/\text{g}$), providing the desired space for sufficient CEO encapsulation and controlled release. Trapping CEO in the porous structure of Cu-BTC ensures a gradual and sustained release of CEO, preventing premature evaporation and maximizing its antimicrobial and antioxidant efficacy. The verification of the successful encapsulation of CEO in the MOFs' pores was achieved through various spectroscopic methods such as UV-Vis and FT-IR spectroscopy. The presence of additional peaks in both spectra while comparing the plain MOF and the CEO@MOF was strong proof of the preparation of a loaded MOF-EO hybrid. At the same time, no remarkable change was detected at the PXRD diagrams of both materials indicating that the crystal structure of the MOF is not affected by the encapsulation of the EO. To form the final packaging medium, CEO@MOF was combined with a gelatin/pullulan mixture. The resulting gelatin/pullulan-based composite films, incorporating CEO@MOF, demonstrate significant antimicrobial activity against various foodborne pathogens, including *Staphylococcus aureus*, *Salmonella*

enterica, *Escherichia coli*, and *Listeria monocytogenes* [144]. These CEO@MOF films contribute to meat preservation through a complex mechanism. They exhibit high ABTS radical scavenging activity (98.16%). This protects meat from oxidation and provides excellent UV-blocking properties from 81.38% to 99.56% at 280 nm., preventing light-induced damage. Additionally, the films reduce moisture loss and maintain pH levels at 6.2, preserving meat texture and freshness by inhibiting bacterial growth by 99.9%. The release of CEO from the Cu-BTC MOF is influenced by the porous structure of the MOF and external environmental conditions, such as moisture and pH. The swelling of the gelatin/pullulan matrix in aqueous solutions facilitates the release of CEO, enhancing its radical scavenging effect. The release rate is also higher in water and acidic solutions compared to ethanol solutions, indicating that the surrounding medium significantly impacts the CEO release [144].

4.3. Zinc Based MOFs

Zn-MOFs are another highly promising family of MOFs for controlled release of volatile compounds with antimicrobial action, with a strong emphasis on agrochemical and agrifood applications. The appeal of this class of materials stems from several key advantages related to their ease of synthesis, low cost, low toxicity combined with their intrinsic antimicrobial properties originating from Zn itself. In general Zn-based MOFs can be characterized as cost-effective, tailorable frameworks which can be easily synthesized to be applied in diverse fields.

An important example towards this direction was the employment of a Zn, 2-amino terephthalic acid-based MOF, presenting a high surface area, as an ideal carrier for a temperature-sensitive volatile, as thymol. In this example, MOF loading with thymol is achieved through a simple soaking method, allowing the EO to be absorbed into the MOF's pores. The release mechanism of thymol is governed by non-covalent interactions, facilitating a sustained release that enhances antimicrobial efficacy. Thymol was loaded into the porous framework through soaking a dried amount of the MOF overnight into a thymol-CHCl₃ solution. This formulation was found to be efficient in the inhibition of bacteria growth. More specifically, it was found to have an activity against the growth of pathogenic strains like *E. coli* O157:H7. This MOF presented a strong antimicrobial activity, achieving a 4.4 log reduction of *E. coli* O157:H7 within 24 h. This approach offers prolonged antimicrobial activity, improved thymol dispersion in water, and the potential for indirect food applications, minimizing direct contamination risks [158].

Another important representative of the Zn-MOFs' family that has been utilized in such applications is IRMOF-3 and its functionalized analogues. The latter have been explored for carvacrol and eugenol encapsulation [141,151,153]. The encapsulation is prompted by π - π interactions between the aromatic rings of IRMOF-3 and the EO, enabling an effective loading and controlled release. Furthermore, post-synthetic modification of IRMOF-3, such as the installation of benzoic acid (BA-IRMOF-3), can enhance these interactions, through the addition of an aromatic ring to the system, resulting in stronger binding energies and slower release kinetics [151]. An active film, prepared by the hybridization of sodium alginate and BA-IRMOF-3 loaded with carvacrol, demonstrated improved mechanical and physical properties, sustained-release capabilities, and enhanced antibacterial and antioxidant activities. In detail, this film inhibits the growth of *E. coli* and *S. aureus*, extending in this way the shelf life of fresh pork by slowing down color, weight, and pH changes. Post-synthetic modification of IRMOF-3 through amide functionalization improved its binding affinity with CA (from -5.1 to -6.0 kcal/mol). The resulting BMC@SA active film exhibited notable sustained-release behavior and demonstrated antibacterial and antioxidant effects, reducing *E. coli* and *S. aureus* growth by 61.95% and 49.33%, respectively [151].

Similarly, chitosan/eugenol-loaded IRMOF-3 (CS/IRMOF-3-EU) based composite films present enhanced UV-blocking, improved mechanical properties, and sustained eugenol release. The release mechanism of eugenol has two steps. An initial fast-release step triggered by water absorption and polymer swelling. That step is followed by a gradual release of the EU, controlled by the diffusion of the release medium into the IRMOF-3-EU pores. These composite films effectively slow down the deterioration of strawberry quality, maintaining hardness, suppressing weight loss, and preserving enzyme activity [153]. Other examples are focusing on Zn-ascorbate MOFs, which utilize the non-toxic ascorbic acid linker, offering a biocompatible platform. This MOF has been used for the encapsulation of marjoram essential oil (MEO), presenting a loading percentage of ~4%. This attempt has led to the formation of an advanced composite material with antioxidant activity combined with an antipathogen activity against several *Gram*– and *Gram*+ pathogens, due to the synergistic action of Zn^{2+} and MEO. The antioxidant activity of MEO@ZnAsc was evaluated using a DPPH radical scavenging assay and demonstrated sustained-release behavior primarily attributed to l-ascorbic acid (l-Asc). While free l-Asc exhibited rapid and high scavenging (>95% at 0.5 mg/mL in 1 h), ZnAsc and MEO@ZnAsc showed delayed but increasing activity over 24 h, confirming the controlled release from the MOF matrix. Notably, MEO@ZnAsc achieved an average 83% increase in DPPH inhibition after 24 h, indicating the composite's ability to preserve antioxidant efficacy over time despite initial slower release due to interactions between MEO and the MOF structure [135]. $\text{Zn}_2(\text{BDC})_2(\text{DABCO})$ is another example of a MOF that was tested for its thymol encapsulation capability, due to its high surface area, appropriate pore size, and strong interactions with thymol, facilitated by π - π stacking and H-bonding. The combination of the thymol loaded $\text{Zn}_2(\text{BDC})_2(\text{DABCO})$ with chitosan resulted in the enhancement of thymol control release and the materials' overall antibacterial activity against *E. coli* and *S. aureus*, with high zones of inhibition and low minimum inhibitory concentrations. In detail, chitosan covers the MOF, controlling in this way thymol release [149].

4.4. ZIFs

ZIFs, particularly ZIF-8 and ZIF-67, have demonstrated significant potential as carriers for essential oils (EOs) in agrifood applications, offering controlled release and enhanced stability [82]. ZIF-8, presenting a high specific surface area, has been found to be an efficient nanocarrier for citral (CT). Encapsulating citral in ZIF-8s' framework can significantly delay its volatilization and enhance its stability. Furthermore, ZIF-8 provides a pH-responsive controlled release, releasing CT under specific pH conditions. This is particularly useful, considering the effect of pathogenic fungi at the pH levels of specific plants and crops. More specifically, CT@ZIF-8 exhibits strong antifungal activity against *Magnaporthe oryzae*, *Botryosphaeria dothidea*, and *Fusarium oxysporum*. It should be noted that the hybrid exhibits lower EC50 values compared to CT alone, indicating its enhanced antifungal action. The pH-responsive release is crucial. Acidic conditions were found to accelerate CT release, following non-Fickian diffusion involving both drug diffusion and ZIF-8 framework disruption. On the other hand, neutral and alkaline pH environments result in slower release via Fickian diffusion, while the structure of ZIF-8 remains intact. Additionally, encapsulation of citral in ZIF-8s' pore was found to be efficient towards photodegradation, ensuring prolonged effectiveness, while the high loading efficiency and controlled release contribute to sustained control efficacy against fungal infections. The bioactivity evaluation demonstrated that CT@ZIF-8 exhibited enhanced antifungal activity compared to free CT, as evidenced by lower EC50 values against *Magnaporthe oryzae*, *Botryosphaeria dothidea*, and *Fusarium oxysporum*. Notably, after 3 days of treatment, CT@ZIF-8 maintained effective control of rice blast and soft rot infections, achieving inhibition rates of 75.76% and 63.69%,

respectively [142]. Furthermore, ZIF-8 is also employed for the encapsulation of thymol and limonene, demonstrating its versatility as a porous medium for EO delivery. The sustained release of thymol from ZIF-8 inhibits the growth of *Colletotrichum musae* by continuously exposing fungal cells to the antifungal compound. Thymol's antifungal properties, combined with ZIF-8's-controlled release, maintain efficacy for extended periods, showcasing ZIF-8's potential in preserving agricultural products. These examples highlight the effectiveness of ZIFs in enhancing the stability and controlled release of EOs, offering promising solutions for antifungal and antimicrobial applications in agrifood sectors [160].

Similarly, ZIF-67 has been employed for the encapsulation and controlled release of citral [82]. Citral@ZIF-67 offers a green and sustainable alternative to traditional mildew preventives for bamboo. The encapsulation of the citral EO in ZIF-67, enables a slow-release mechanism, maintaining its antimildew properties over an extended period, even under high temperature and humidity. Encapsulation of citral in ZIF-67 enhances the EOs' stability while protecting it from oxidation and volatility. Thus, it contributes to intrinsic antibacterial properties against *E. coli* and *S. aureus*. The Citral@ZIF-67 hybrid is produced in a one-step reaction, which involves mixing 2-methylimidazole with cobalt nitrate, citral, and solvents, resulting in citral encapsulation within the ZIF-67 cage while the framework is formed. The release of citral follows a slow-release mechanism governed by Fickian diffusion as it was also reported for ZIF-8 above. This process ensures sustained antimicrobial activity without specific external stimuli. The uniform distribution of Citral@ZIF-67 within the bamboo structure provides consistent protection, strengthening the bamboo's durability and extending its useful life [157].

4.5. Zr-MOFs

Zirconium-based metal-organic frameworks (Zr-MOFs), particularly UiO analogues, have emerged as highly promising materials for the encapsulation and controlled release EOs, as well as smaller active compounds of EOs, such as monoterpenes, addressing the challenges of volatility, stability, and water solubility that limit their wider practical applications. These Zr-MOFs are characterized by their exceptional chemical and thermal stability, structural and functional tunability, and high loading efficiency, offering versatile platforms for enhancing the efficacy of bioactive compounds in agrifood applications.

For example, UiO-66-(COOH)₂, has been utilized for the encapsulation of thymol and limonene. This example demonstrated the ability of this MOF platform to accommodate both polar and non-polar molecules. More specifically, the presence of the free carboxyl functional groups in UiO-66-(COOH)₂ enhances its framework interaction with polar molecules like thymol, improving its encapsulation efficiency. The sustained release of thymol from UiO-66-(COOH)₂, was observed over 11 days at 25 °C. This formulation has been tested for its prolonged antifungal activity against *Colletotrichum musae*. This gradual diffusion of thymol from the pores of the MOF allows the continuous exposure of fungal cells to the antifungal compound, disrupting their cellular processes [160].

Regarding the exploration of the possibilities of the UiO family in the encapsulation of volatiles, their structural characteristics have been meticulously studied, emphasizing their cavities size and functionalization. In detail, the pore size effect of Zr-MOF is a critical factor in the encapsulation and release of volatiles as monoterpenes, which are actually the primary components of EOs. UiO-66, UiO-67, and UiO-68 are a family of isostructural MOFs, built from Zr₆-octahedra connected by dicarboxylate linkers of different length, forming three-dimensional structures with high stability that makes them ideal platforms for controlled release systems. Through the careful selection of the pore size of the MOFs, it is possible to achieve a high loading and at the next step a sustained release of encapsulated volatiles with antimicrobial and antioxidant activity. These MOFs have been studied

for their behavior regarding the smart release of monoterpenes providing us with key information in order to further expand and address key challenges as the relationship between pore size and guest molecule diffusion [147].

NH₂-UiO-66, with a pore size of 4.4 nm, has been successfully employed for the encapsulation of CEO, achieving a high loading capacity of 654.4 mg/g. The release kinetics of CEO from starch matrix packaging films incorporating NH₂-UiO-66 follow the Avrami model, indicating a slow and sustained release. This controlled release is attributed to the mesoporous structure and large specific surface area of NH₂-UiO-66, which effectively encapsulates CEO and limits its volatility and hydrophobicity. The resulting starch-based packaging films exhibit increased mechanical strength, enhanced oxidation resistance, and improved vapor and oxygen barrier properties [164]. The presence of eugenol, eugenyl acetate, and β -caryophyllene in CEO enhance its antimicrobial and antioxidant activity, as they can disrupt bacterial cell structures. The prepared films demonstrate excellent antibacterial activity against *E.coli* and *Staphylococcus aureus*. This highlights the potential of NH₂-UiO-66 as a carrier for antimicrobial EOs in food packaging applications [166]. The slow and sustained release of CEO from this MOF, as described by the Avrami model, ensures prolonged antibacterial effects, contributing to the extended shelf life of packaged products like blueberries [159].

In conclusion, Zr-MOFs, particularly UiO analogues, provide versatile platforms for the encapsulation and controlled release of EOs and monoterpenes. Their high stability, tunable pore sizes, and ability to enhance the efficacy of bioactive compounds make them valuable materials for developing advanced antimicrobial and antioxidant systems in agrifood applications. Addressing challenges related to pore size effects and structural integrity will further enhance their potential in various industries.

5. Conclusions

Through this work, the ability of MOFs to serve as carriers of volatile compounds, with an emphasis on EOs, has been reviewed, highlighting their potential to introduce novel and sustainable green solutions for improving the agri-food sector. Diverse examples of MOFs have been discussed regarding these applications, revealing the plethora of candidates that may arise from this large family of tailor-made materials. However, it is important to note that through this review a clear picture of the prerequisites that are dictated for a MOF to be a possible candidate is drawn. Thus, besides its overall chemical stability, and the appropriate pore size and functionality, biocompatibility arises as one of the most crucial parameters. This is further supported by the fact that the majority of the examples discussed herein focus on CD-based MOFs, which are well-known for their biocompatible character. These studies collectively highlight the versatility of γ -CD MOFs in encapsulating volatile compounds, offering significant potential for applications in food preservation and active packaging through tailored release mechanisms and enhanced bioactivity.

Across these studies, besides their biocompatible profile, CD-MOFs also demonstrate superior encapsulation efficiency and controlled release compared to CD alone, attributed to their porous structure and tunable properties. In this way, the formulation of these molecules into periodic structures strengthens the importance of further exploring the capabilities of MOFs in these applications, and the additional benefits that they can offer due to their physicochemical nature. The release mechanisms are often influenced by environmental conditions such as humidity, temperature, and pH, allowing for stimuli-responsive delivery. These findings underscore the potential of CD-MOFs as versatile and effective carriers for EOs in agrifood applications, offering enhanced stability, controlled release, and improved functionality for food preservation and other related fields.

However, despite the unique character of this category of MOFs, representatives of other MOF families were found to be effective. A few examples are reported regarding Cu^{2+} and Zn^{2+} MOFs, which come to the forefront of such applications regarding the additional value that their inorganic building blocks add to the antimicrobial activity of the final formulation as well as their cost-effective profile and their ease of synthesis. However, these materials are known for their weak stability in aqueous solutions, which might be a hindrance to their wider application, although, under careful design, they can be used as a trigger point for the release of the enclosed volatile under specific conditions. On this framework, more stable MOFs have also been tested as ZIFs, which are known for their chemical stability combined with their high porosity. Finally, the most recent reports also focus on the UiO family of Zr-MOFs, which are widely known for their intriguing porosity and their exceptional stability. These analogues provide versatile platforms for the encapsulation and controlled release of EOs and monoterpenes which usually are one of the main EOs' components. Their high stability, tunable pore sizes, and ability to enhance the efficacy of bioactive compounds make them valuable materials for developing advanced antimicrobial and antioxidant systems in agrifood applications. Addressing challenges related to pore size effects and structural integrity will further enhance their potential in various industries. Meticulous studies shedding light on the interactions between the backbone of the MOF and the targeted volatile will unlock new directions towards both the design and synthesis of novel materials, along with improving the properties of existing porous scaffolds through appropriate modifications.

However, despite the plethora of advantages that MOFs, as tailor-made materials, can offer in carrying and smart delivery of active compounds, several issues need to be addressed before their wider application, especially in agrifood. One of the most important issues is related to their large-scale synthesis and the related cost. More specifically, MOFs are synthesized from building blocks, especially their organic component, which presents a synthetic complexity that directly increases their cost and can also directly impact their biocompatibility, as larger aromatic building blocks can significantly contribute to the increase of their toxicity. Those are two important parameters that need to be further considered and explored for MOFs to be applied both in agriculture and agrifood. Therefore, the scientific community is focusing on the exploration of sustainable and renewable synthetic pathways to deal with issues. Also, the development of hybrid MOFs, combined with polymers, is meticulously explored as a medium to enhance both their scalability and contribute to the shaping of the final product. Furthermore, despite their promising results in adsorption and controlled release, their powder-like nature may be an obstacle. Further studies need to be conducted to develop stable formulations, such as tablets, films, or stable dispersions in the form of sprays, allowing for their practical application. Additionally, compliance with the existing regulations regarding the environmental impact, their efficacy, and the avoidance of toxic effects when used at a large scale need to be further explored, especially taking into consideration the limited existing regulations specified for MOFs. Finally, it is important to note that MOFs are a relatively new family of materials, which, although they are widely known among scientists, need to be further introduced to farmers and stakeholders, so that they are informed and educated regarding their advantages and safe use before their integration into existing technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

MOF	Metal Organic Framework
EO	Essential Oil
CEO	Clove Essential Oil
SBU	Secondary Building Unit
CD	Cyclodextrin
GRAS	Generally Recognized As Safe
TTO	Tea Tree Oil
CA	Cinnamaldehyde
OEO	Oregano Essential Oil
PCL	Polycaprolactone
REO	Reactive Oxygen Species
BA	Benzoic Acid
CA	Carvacrol
EU	Eugenol
CS	Chitosan
CT	Citral
MEO	Marjoram Essential Oil

References

1. Stock, N.; Biswas, S. Synthesis of Metal-Organic Frameworks (MOFs): Routes to Various MOF Topologies, Morphologies, and Composites. *Chem. Rev.* **2012**, *112*, 933–969. [\[CrossRef\]](#)
2. Yusuf, V.F.; Malek, N.I.; Kailasa, S.K. Review on Metal–Organic Framework Classification, Synthetic Approaches, and Influencing Factors: Applications in Energy, Drug Delivery, and Wastewater Treatment. *ACS Omega* **2022**, *7*, 44507–44531. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Li, D.; Yadav, A.; Zhou, H.; Roy, K.; Thanasekaran, P.; Lee, C. Advances and Applications of Metal-Organic Frameworks (MOFs) in Emerging Technologies: A Comprehensive Review. *Glob. Chall.* **2024**, *8*, 2300244. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Zheng, W.; Lee, L.Y.S. Metal–Organic Frameworks for Electrocatalysis: Catalyst or Precatalyst? *ACS Energy Lett.* **2021**, *6*, 2838–2843. [\[CrossRef\]](#)
5. Saboorizadeh, B.; Zare-Dorabei, R.; Safavi, M.; Safarifard, V. Applications of Metal–Organic Frameworks (MOFs) in Drug Delivery, Biosensing, and Therapy: A Comprehensive Review. *Langmuir* **2024**, *40*, 22477–22503. [\[CrossRef\]](#)
6. Guo, Z.; Xiao, Y.; Wu, W.; Zhe, M.; Yu, P.; Shakya, S.; Li, Z.; Xing, F. Metal–organic framework-based smart stimuli-responsive drug delivery systems for cancer therapy: Advances, challenges, and future perspectives. *J. Nanobiotechnology* **2025**, *23*, 157. [\[CrossRef\]](#)
7. Basak, S.; Bhattacharyya, P.; Lokhande, P.E.; Chakrabarti, S. MOF: A New Age Smart Material as Nano Carriers for Fertilizers and Pesticides. In *Biological Applications of Nanoparticles*; Sarkar, B., Sonawane, A., Eds.; Springer Nature: Singapore, 2023; pp. 135–148. [\[CrossRef\]](#)
8. Zhao, D.; Wang, X.; Yue, L.; He, Y.; Chen, B. Porous metal–organic frameworks for hydrogen storage. *Chem. Commun.* **2022**, *58*, 11059–11078. [\[CrossRef\]](#)
9. Sutton, A.L.; Mardel, J.I.; Hill, M.R. Metal-Organic Frameworks (MOFs) As Hydrogen Storage Materials At Near-Ambient Temperature. *Chem.-A Eur. J.* **2024**, *30*, e202400717. [\[CrossRef\]](#)
10. Wang, F.; Wang, C.-C.; Yi, S. Rational design and synthesis of metal–organic frameworks derivatives: A perspective on emerging techniques. *Chem. Eng. J.* **2024**, *495*, 153398. [\[CrossRef\]](#)
11. Trickett, C.A.; Helal, A.; Al-Maythaly, B.A.; Yamani, Z.H.; Cordova, K.E.; Yaghi, O.M. The chemistry of metal–organic frameworks for CO₂ capture, regeneration and conversion. *Nat. Rev. Mater.* **2017**, *2*, 17045. [\[CrossRef\]](#)

12. Vellingiri, K.; Szulejko, J.E.; Kumar, P.; Kwon, E.E.; Kim, K.-H.; Deep, A.; Boukhvalov, D.W.; Brown, R.J.C. Metal organic frameworks as sorption media for volatile and semi-volatile organic compounds at ambient conditions. *Sci. Rep.* **2016**, *6*, 27813. [[CrossRef](#)] [[PubMed](#)]
13. Huang, B.; Tan, Z. High Loading of Air-Sensitive Guest Molecules into Polycrystalline Metal–Organic Framework Hosts. *Inorg. Chem.* **2021**, *60*, 10830–10836. [[CrossRef](#)]
14. Wu, Q.; Liang, J.; Wang, D.; Wang, R.; Janiak, C. Host molecules inside metal–organic frameworks: Host@MOF and guest@host@MOF (Matrjoschka) materials. *Chem. Soc. Rev.* **2025**, *54*, 601–622. [[CrossRef](#)]
15. Yang, W.; Liu, S.; Ren, H.; Huang, Y.; Zheng, S.; Li, S.; Ling, Z.; Fan, W.; Tian, Y.; Pan, L.; et al. Metal–organic frameworks (MOFs)-based materials in food packaging: A review. *J. Mater. Sci.* **2024**, *59*, 20157–20175. [[CrossRef](#)]
16. Sani, M.A.; Jahed-Khaniki, G.; Shariatifar, N.; Khezerlou, A.; Abedini, A.; Rezvani-Ghalhari, M.; Hassani, S.; Tavassoli, M.; McClements, D.J. Metal Organic Frameworks (MOFs) as Advanced Functional Materials for Food Applications. *ACS Food Sci. Technol.* **2024**, *4*, 2272–2300. [[CrossRef](#)]
17. Muhie, S.H. Novel approaches and practices to sustainable agriculture. *J. Agric. Food Res.* **2022**, *10*, 100446. [[CrossRef](#)]
18. Mohan, B.; Sharma, H.K.; Ručman, S.; Singjai, P.; Pombeiro, A.J.L. Contaminants Removal and Monitoring: The Role of Hybrid MOFs in Agricultural Advancement and Soil Amendment. *Adv. Sustain. Syst.* **2025**, *9*, 2400637. [[CrossRef](#)]
19. Elumalai, P.; Gao, X.; Parthipan, P.; Luo, J.; Cui, J. Agrochemical pollution: A serious threat to environmental health. *Curr. Opin. Environ. Sci. Health* **2025**, *43*, 100597. [[CrossRef](#)]
20. Prakash, B.; Singh, P.P.; Gupta, V.; Raghuvanshi, T.S. Essential oils as green promising alternatives to chemical preservatives for agri-food products: New insight into molecular mechanism, toxicity assessment, and safety profile. *Food Chem. Toxicol.* **2024**, *183*, 114241. [[CrossRef](#)]
21. Jyotsna, B.; Patil, S.; Prakash, Y.S.; Rathnagiri, P.; Kishor, P.K.; Jalaja, N. Essential oils from plant resources as potent insecticides and repellents: Current status and future perspectives. *Biocatal. Agric. Biotechnol.* **2024**, *61*, 103395. [[CrossRef](#)]
22. Garrido-Miranda, K.A.; Giraldo, J.D.; Schoebitz, M. Essential Oils and Their Formulations for the Control of Curculionidae Pests. *Front. Agron.* **2022**, *4*, 876687. [[CrossRef](#)]
23. Puškárová, A.; Bučková, M.; Kraková, L.; Pangallo, D.; Kozics, K. The antibacterial and antifungal activity of six essential oils and their cyto/genotoxicity to human HEL 12469 cells. *Sci. Rep.* **2017**, *7*, 8211. [[CrossRef](#)]
24. Su, X.; Li, B.; Chen, S.; Wang, X.; Song, H.; Shen, B.; Zheng, Q.; Yang, M.; Yue, P. Pore engineering of micro/mesoporous nanomaterials for encapsulation, controlled release and variegated applications of essential oils. *J. Control. Release* **2024**, *367*, 107–134. [[CrossRef](#)]
25. Sundar, S.; Parikh, J.K. Advances and trends in encapsulation of essential oils. *Int. J. Pharm.* **2023**, *635*, 122668. [[CrossRef](#)]
26. Angeli, G.K.; Batzavali, D.; Mavronasou, K.; Tsangarakis, C.; Stuerzer, T.; Ott, H.; Trikalitis, P.N. Remarkable Structural Diversity between Zr/Hf and Rare-Earth MOFs via Ligand Functionalization and the Discovery of Unique (4, 8)-c and (4, 12)-connected Frameworks. *J. Am. Chem. Soc.* **2020**, *142*, 15986–15994. [[CrossRef](#)]
27. Zhang, Y.; Yang, X.; Zhou, H.-C. Synthesis of MOFs for heterogeneous catalysis via linker design. *Polyhedron* **2018**, *154*, 189–201. [[CrossRef](#)]
28. Ha, J.; Lee, J.H.; Moon, H.R. Alterations to secondary building units of metal–organic frameworks for the development of new functions. *Inorg. Chem. Front.* **2020**, *7*, 12–27. [[CrossRef](#)]
29. Razavi, S.A.A.; Morsali, A. Linker functionalized metal-organic frameworks. *Coord. Chem. Rev.* **2019**, *399*, 213023. [[CrossRef](#)]
30. Yaghi, O.M. Reticular Chemistry—Construction, Properties, and Precision Reactions of Frameworks. *J. Am. Chem. Soc.* **2016**, *138*, 15507–15509. [[CrossRef](#)]
31. Alezi, D.; Spanopoulos, I.; Tsangarakis, C.; Shkurenko, A.; Adil, K.; Belmabkhout, Y.; O’Keeffe, M.; Eddaoudi, M.; Trikalitis, P.N. Reticular Chemistry at Its Best: Directed Assembly of Hexagonal Building Units into the Awaited Metal–Organic Framework with the Intricate Polybenzene Topology, pbz-MOF. *J. Am. Chem. Soc.* **2016**, *138*, 12767–12770. [[CrossRef](#)]
32. Wang, K.; Feng, D.; Liu, T.-F.; Su, J.; Yuan, S.; Chen, Y.-P.; Bosch, M.; Zou, X.; Zhou, H.-C. A Series of Highly Stable Mesoporous Metalloporphyrin Fe-MOFs. *J. Am. Chem. Soc.* **2014**, *136*, 13983–13986. [[CrossRef](#)] [[PubMed](#)]
33. Nam, D.; Albalad, J.; Sánchez-Naya, R.; Ruiz-Relaño, S.; Cortés-Martínez, A.; Yang, Y.; Juanhuix, J.; Imaz, I.; MasPOCH, D. Isolation of the Secondary Building Unit of a 3D Metal–Organic Framework through Clip-Off Chemistry, and its Reuse to Synthesize New Frameworks by Dynamic Covalent Chemistry. *J. Am. Chem. Soc.* **2024**, *146*, 27255–27261. [[CrossRef](#)] [[PubMed](#)]
34. Yuan, N.; Church, T.L.; Brandt, E.G.; Hedin, N.; Zou, X.; Bernin, D. Insights into Functionalization of Metal–Organic Frameworks Using In Situ NMR Spectroscopy. *Sci. Rep.* **2018**, *8*, 17530. [[CrossRef](#)]
35. Vendrame, D.; Bragaggia, G.; Carraro, M.; Gross, S. Metal Oxocluster-Based Organic–Inorganic Hybrid Materials: From Design Principles to Applications. *Chem. Mater.* **2024**, *36*, 9259–9278. [[CrossRef](#)]
36. Wang, C.; Yan, J.; Chen, S.; Liu, Y. High-Valence Metal–Organic Framework Materials Constructed from Metal-Oxo Clusters: Opportunities and Challenges. *Chempluschem* **2023**, *88*, e202200462. [[CrossRef](#)] [[PubMed](#)]

37. Zeggai, F.Z.; Ait-Touchente, Z.; Bachari, K.; Elaissari, A. Investigation of Metal–Organic Frameworks (MOFs): Synthesis, Properties, and Applications—An In-Depth Review. *Chem. Phys. Impact* **2025**, *10*, 100864. [[CrossRef](#)]
38. Jimenez-Lopez, L.; Ospino, R.M.; de Araujo, L.G.; Celzard, A.; Fierro, V. Latest developments in the synthesis of metal–organic frameworks and their hybrids for hydrogen storage. *Nanoscale* **2025**, *17*, 6390–6413. [[CrossRef](#)] [[PubMed](#)]
39. Kirlikovali, K.O.; Hanna, S.L.; Son, F.A.; Farha, O.K. Back to the Basics: Developing Advanced Metal–Organic Frameworks Using Fundamental Chemistry Concepts. *ACS Nanosci. Au* **2023**, *3*, 37–45. [[CrossRef](#)]
40. Daglar, H.; Gulbalkan, H.C.; Avci, G.; Aksu, G.O.; Altundal, O.F.; Altintas, C.; Erucar, I.; Keskin, S. Effect of Metal–Organic Framework (MOF) Database Selection on the Assessment of Gas Storage and Separation Potentials of MOFs. *Angew. Chem. Int. Ed. Engl.* **2021**, *60*, 7828–7837. [[CrossRef](#)]
41. Cui, Y.; Yue, Y.; Qian, G.; Chen, B. Luminescent Functional Metal–Organic Frameworks. *Chem. Rev.* **2012**, *112*, 1126–1162. [[CrossRef](#)]
42. Dong, J.; Zhao, D.; Lu, Y.; Sun, W.-Y. Photoluminescent metal–organic frameworks and their application for sensing biomolecules. *J. Mater. Chem. A* **2019**, *7*, 22744–22767. [[CrossRef](#)]
43. Muthukumar, M.K.; Govindaraj, M.; Kogularasu, S.; Sriram, B.; Raja, B.K.; Wang, S.F.; Chang-Chien, G.P. Recent advances in metal–organic frameworks for electrochemical sensing applications. *Talanta Open* **2025**, *11*, 100396. [[CrossRef](#)]
44. Thorarinsdottir, A.E.; Harris, T.D. Metal–Organic Framework Magnets. *Chem. Rev.* **2020**, *120*, 8716–8789. [[CrossRef](#)] [[PubMed](#)]
45. Bavykina, A.; Kolobov, N.; Khan, I.S.; Bau, J.A.; Ramirez, A.; Gascon, J. Metal–Organic Frameworks in Heterogeneous Catalysis: Recent Progress, New Trends, and Future Perspectives. *Chem. Rev.* **2020**, *120*, 8468–8535. [[CrossRef](#)]
46. Malekshah, R.E.; Moharramnejad, M.; Gharanli, S.; Shahi, M.; Ehsani, A.; Haribabu, J.; Ouachtak, H.; Mirtamizdoust, B.; Kamwilaisak, K.; Sillanpää, M.; et al. MOFs as Versatile Catalysts: Synthesis Strategies and Applications in Value-Added Compound Production. *ACS Omega* **2023**, *8*, 31600–31619. [[CrossRef](#)] [[PubMed](#)]
47. Stavila, V.; Talin, A.A.; Allendorf, M.D. MOF-based electronic and opto-electronic devices. *Chem. Soc. Rev.* **2014**, *43*, 5994–6010. [[CrossRef](#)]
48. Kotzabasaki, M.; Froudakis, G.E. Review of computer simulations on anti-cancer drug delivery in MOFs. *Inorg. Chem. Front.* **2018**, *5*, 1255–1272. [[CrossRef](#)]
49. Lawson, H.D.; Walton, S.P.; Chan, C. Metal–Organic Frameworks for Drug Delivery: A Design Perspective. *ACS Appl. Mater. Interfaces* **2021**, *13*, 7004–7020. [[CrossRef](#)]
50. Khafaga, D.S.R.; El-Morsy, M.T.; Faried, H.; Diab, A.H.; Shehab, S.; Saleh, A.M.; Ali, G.A.M. Metal–organic frameworks in drug delivery: Engineering versatile platforms for therapeutic applications. *RSC Adv.* **2024**, *14*, 30201–30229. [[CrossRef](#)]
51. Liu, Y.; Jiang, T.; Liu, Z. Metal–Organic Frameworks for Bioimaging: Strategies and Challenges. *Nanotheranostics* **2022**, *6*, 143–160. [[CrossRef](#)]
52. Nguyen, N.T.T.; Nguyen, T.T.T.; Ge, S.; Liew, R.K.; Nguyen, D.T.C.; Van Tran, T. Recent progress and challenges of MOF-based nanocomposites in bioimaging, biosensing and biocarriers for drug delivery. *Nanoscale Adv.* **2024**, *6*, 1800–1821. [[CrossRef](#)] [[PubMed](#)]
53. Li, C.; Zhang, L.; Chen, J.; Li, X.; Sun, J.; Zhu, J.; Wang, X.; Fu, Y. Recent development and applications of electrical conductive MOFs. *Nanoscale* **2021**, *13*, 485–509. [[CrossRef](#)] [[PubMed](#)]
54. Chettiannan, B.; Dhandapani, E.; Arumugam, G.; Rajendran, R.; Selvaraj, M. Metal–organic frameworks: A comprehensive review on common approaches to enhance the energy storage capacity in supercapacitor. *Coord. Chem. Rev.* **2024**, *518*, 216048. [[CrossRef](#)]
55. Hazarika, U.N.; Borah, J.; Kakoti, A.; Brahma, R.; Sarmah, K.; Guha, A.K.; Khakhlary, P. Highly conductive three-dimensional metal organic frameworks from small in situ generated ligands. *Mater. Adv.* **2023**, *4*, 6304–6311. [[CrossRef](#)]
56. Sandhu, Z.A.; Raza, M.A.; Awwad, N.S.; Ibrahim, H.A.; Farwa, U.; Ashraf, S.; Dildar, A.; Fatima, E.; Ashraf, S.; Ali, F. Metal–organic frameworks for next-generation energy storage devices; a systematic review. *Mater. Adv.* **2024**, *5*, 30–50. [[CrossRef](#)]
57. Gándara, F.; Bennett, T.D. Crystallography of metal–organic frameworks. *IUCrJ* **2014**, *1*, 563–570. [[CrossRef](#)]
58. Angeli, G.K.; Loukopoulou, E.; Kouvidis, K.; Bosveli, A.; Tsangarakis, C.; Tylanakis, E.; Froudakis, G.; Trikalitis, P.N. Continuous Breathing Rare-Earth MOFs Based on Hexanuclear Clusters with Gas Trapping Properties. *J. Am. Chem. Soc.* **2021**, *143*, 10250–10260. [[CrossRef](#)]
59. Ambroz, F.; Macdonald, T.J.; Martis, V.; Parkin, I.P. Evaluation of the BET Theory for the Characterization of Meso and Microporous MOFs. *Small Methods* **2018**, *2*, 1800173. [[CrossRef](#)]
60. ASTM E2149-13a; Standard Test Method for Determining the Antimicrobial Activity of Antimicrobial Agents under Dynamic Contact Conditions. Annual Book of ASTM Standards. ASTM: West Conshohocken, PA, USA, 2013.
61. Xu, C.; Li, J.; Yang, L.; Shi, F.; Yang, L.; Ye, M. Antibacterial activity and a membrane damage mechanism of Lachnum YM30 melanin against *Vibrio parahaemolyticus* and *Staphylococcus aureus*. *Food Control* **2017**, *73*, 1445–1451. [[CrossRef](#)]
62. Moghimi, R.; Aliahmadi, A.; McClements, D.J.; Rafati, H. Investigations of the effectiveness of nanoemulsions from sage oil as antibacterial agents on some food borne pathogens. *LWT—Food Sci. Technol.* **2016**, *71*, 69–76. [[CrossRef](#)]

63. Negro, C.; Pérez-Cejuela, H.M.; Simó-Alfonso, E.F.; Herrero-Martínez, J.M.; Bruno, R.; Armentano, D.; Ferrando-Soria, J.; Pardo, E. Highly Efficient Removal of Neonicotinoid Insecticides by Thioether-Based (Multivariate) Metal–Organic Frameworks. *ACS Appl. Mater. Interfaces* **2021**, *13*, 28424–28432. [[CrossRef](#)] [[PubMed](#)]
64. Hu, S.; Yan, C.; Fei, Q.; Zhang, B.; Wu, W. MOF-based stimuli-responsive controlled release nanopesticide: Mini review. *Front. Chem.* **2023**, *11*, 1272725. [[CrossRef](#)]
65. Mahmoud, L.A.M.; dos Reis, R.A.; Chen, X.; Ting, V.P.; Nayak, S. Metal–Organic Frameworks as Potential Agents for Extraction and Delivery of Pesticides and Agrochemicals. *ACS Omega* **2022**, *7*, 45910–45934. [[CrossRef](#)]
66. dos Reis, R.A.; Mahmoud, L.A.M.; Ivanovska, E.H.; Telford, R.; Addicoat, M.A.; Terry, L.R.; Ting, V.P.; Nayak, S. Biodegradable Polymer-Metal–Organic Framework (MOF) Composites for Controlled and Sustainable Pesticide Delivery. *Adv. Sustain. Syst.* **2023**, *7*, 2300269. [[CrossRef](#)]
67. Rojas, S.; Rodríguez-Diéguez, A.; Horcajada, P. Metal–Organic Frameworks in Agriculture. *ACS Appl. Mater. Interfaces* **2022**, *14*, 16983–17007. [[CrossRef](#)]
68. Wang, C.-Y.; Qin, J.-C.; Yang, Y.-W. Multifunctional Metal–Organic Framework (MOF)-Based Nanoplatfroms for Crop Protection and Growth Promotion. *J. Agric. Food Chem.* **2023**, *71*, 5953–5972. [[CrossRef](#)]
69. Anstoetz, M.; Rose, T.J.; Clark, M.W.; Yee, L.H.; Raymond, C.A.; Vancov, T. Novel Applications for Oxalate-Phosphate-Amine Metal–Organic-Frameworks (OPA-MOFs): Can an Iron-Based OPA-MOF Be Used as Slow-Release Fertilizer? *PLoS ONE* **2015**, *10*, e0144169. [[CrossRef](#)] [[PubMed](#)]
70. Yang, J.; Trickett, C.A.; Alahmadi, S.B.; Alshammari, A.S.; Yaghi, O.M. Calcium L-Lactate Frameworks as Naturally Degradable Carriers for Pesticides. *J. Am. Chem. Soc.* **2017**, *139*, 8118–8121. [[CrossRef](#)] [[PubMed](#)]
71. Chen, H.; Shan, Y.; Cao, L.; Zhao, P.; Cao, C.; Li, F.; Huang, Q. Enhanced Fungicidal Efficacy by Co-Delivery of Azoxystrobin and Diniconazole with Cauliflower-Like Metal–Organic Frameworks NH₂-Al-MIL-101. *Int. J. Mol. Sci.* **2021**, *22*, 10412. [[CrossRef](#)]
72. Huang, W.; Wang, M.; Hu, Z.; Yang, T.; Pei, H.; Zhang, F. Multifunctional metal-organic framework with pH-response for co-delivery of prochloraz and siRNA to synergistic control pathogenic fungi. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *670*, 131563. [[CrossRef](#)]
73. Shan, Y.; Cao, L.; Muhammad, B.; Xu, B.; Zhao, P.; Cao, C.; Huang, Q. Iron-based porous metal–organic frameworks with crop nutritional function as carriers for controlled fungicide release. *J. Colloid Interface Sci.* **2020**, *566*, 383–393. [[CrossRef](#)]
74. Hou, Y.; Zhang, Y.; Huang, Y.; Zhou, A.; Han, J.; Yang, K.; Zhao, Y.; Zhou, J.; Wang, J.; Chen, G.; et al. A pH-responsive MOFs@MPN nanocarrier with enhancing antifungal activity for sustainable controlling myclobutanil release. *Chem. Eng. J.* **2024**, *497*, 155713. [[CrossRef](#)]
75. Hou, C.; Wei, N.; Liang, Q.; Tan, Y.; Li, X.; Feng, J. Nano-pesticide delivery system based on UiO-66 with pH sensitivity for precise control of *Spodoptera frugiperda*. *Pest Manag. Sci.* **2025**, *81*, 798–808. [[CrossRef](#)] [[PubMed](#)]
76. Meng, W.; Tian, Z.; Yao, P.; Fang, X.; Wu, T.; Cheng, J.; Zou, A. Preparation of a novel sustained-release system for pyrethroids by using metal-organic frameworks (MOFs) nanoparticle. *Colloids Surfaces A Physicochem. Eng. Asp.* **2020**, *604*, 125266. [[CrossRef](#)]
77. He, Y.; Min, Q.; Chen, L.; Lai, J.; Pang, B.; Qian, K. Preparation of DNF@UiO-67 and the insecticidal activity study and safety evaluation. *Pest Manag. Sci.* **2025**. [[CrossRef](#)] [[PubMed](#)]
78. Shu, H.; Lai, T.; Ren, J.; Cui, X.; Tian, X.; Yang, Z.; Xiao, X.; Wang, Y. Trimetallic metal-organic frameworks (Fe, Co, Ni-MOF) derived as efficient electrochemical determination for ultra-micro imidacloprid in vegetables. *Nanotechnology* **2022**, *33*, 135502. [[CrossRef](#)]
79. Magri, A.; Petriccione, M.; Gutiérrez, T.J. Metal-organic frameworks for food applications: A review. *Food Chem.* **2021**, *354*, 129533. [[CrossRef](#)]
80. Zhang, Z.-H.; Zhang, J.-L.; Liu, J.-M.; Xiong, Z.-H.; Chen, X. Selective and Competitive Adsorption of Azo Dyes on the Metal–Organic Framework ZIF-67. *Water Air Soil Pollut.* **2016**, *227*, 1–12. [[CrossRef](#)]
81. Mohammadnejad, M.; Alizadeh, S. MnFe₂O₄-NH₂-HKUST-1, MOF magnetic composite, as a novel sorbent for efficient dye removal: Fabrication, characterization and isotherm studies. *Sci. Rep.* **2024**, *14*, 9048. [[CrossRef](#)]
82. Sarker, T.; Tahmid, I.; Sarker, R.K.; Dey, S.C.; Islam, M.T.; Sarker, M. ZIF-67-based materials as adsorbent for liquid phase adsorption-a review. *Polyhedron* **2024**, *260*, 117069. [[CrossRef](#)]
83. Sellaoui, L.; Edi-Soetaredjo, F.; Mohamed, M.; Ismadi, S.; Ernst, B.; Bonilla-Petriciolet, A.; Ben Lamine, A.; Dell'Angelo, D.; Badawi, M. A novel application of HKUST-1 for textile dyes removal in single and binary solutions: Experimental investigation combined with physical modelling. *Chem. Eng. J.* **2024**, *480*, 147958. [[CrossRef](#)]
84. Mohammadnejad, M.; Nekoo, N.M.; Alizadeh, S.; Sadeghi, S.; Geranmayeh, S. Enhanced removal of organic dyes from aqueous solutions by new magnetic HKUST-1: Facile strategy for synthesis. *Sci. Rep.* **2023**, *13*, 17981. [[CrossRef](#)]
85. Yang, Q.; Ren, S.; Zhao, Q.; Lu, R.; Hang, C.; Chen, Z.; Zheng, H. Selective separation of methyl orange from water using magnetic ZIF-67 composites. *Chem. Eng. J.* **2018**, *333*, 49–57. [[CrossRef](#)]
86. Yoon, S.; Calvo, J.J.; So, M.C. Removal of Acid Orange 7 from Aqueous Solution by Metal–Organic Frameworks. *Crystals* **2019**, *9*, 17. [[CrossRef](#)]

87. Lin, K.A.; Wu, C. Efficient Adsorptive Removal of Toxic Amaranth Dye from Water using a Zeolitic Imidazolate Framework. *Water Environ. Res.* **2018**, *90*, 1947–1955. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Sharma, U.; Pandey, R.; Basu, S.; Saravanan, P. ZIF-67 blended PVDF membrane for improved Congo red removal and antifouling properties: A correlation establishment between morphological features and ultra-filtration parameters. *Chemosphere* **2023**, *320*, 138075. [\[CrossRef\]](#)
89. Li, M.; Gao, D.; Cui, S.; Shi, Y.; Liu, N. Fabrication of Fe₃O₄/ZIF-67 composite for removal of direct blue 80 from water. *Water Environ. Res.* **2020**, *92*, 740–748. [\[CrossRef\]](#)
90. Lin, K.-Y.A.; Chang, H.-A. Ultra-high adsorption capacity of zeolitic imidazole framework-67 (ZIF-67) for removal of malachite green from water. *Chemosphere* **2015**, *139*, 624–631. [\[CrossRef\]](#)
91. Wang, H.; Cheng, Z.; Zhang, P.; Ye, J.; Ding, L.; Jia, W. Ultra-high adsorption behavior of zeolitic imidazole framework-67 nanoparticles for removing brilliant green dye. *AIP Adv.* **2021**, *11*, 095304. [\[CrossRef\]](#)
92. Tu, N.T.T.; Thien, T.V.; Du, P.D.; Chau, V.T.T.; Mau, T.X.; Khieu, D.Q. Adsorptive removal of Congo red from aqueous solution using zeolitic imidazolate framework-67. *J. Environ. Chem. Eng.* **2018**, *6*, 2269–2280. [\[CrossRef\]](#)
93. Wang, B.; Lv, X.-L.; Feng, D.; Xie, L.-H.; Zhang, J.; Li, M.; Xie, Y.; Li, J.-R.; Zhou, H.-C. Highly Stable Zr(IV)-Based Metal–Organic Frameworks for the Detection and Removal of Antibiotics and Organic Explosives in Water. *J. Am. Chem. Soc.* **2016**, *138*, 6204–6216. [\[CrossRef\]](#)
94. Zong, Y.; Ma, S.; Gao, J.; Xu, M.; Xue, J.; Wang, M. Synthesis of Porphyrin Zr-MOFs for the Adsorption and Photodegradation of Antibiotics under Visible Light. *ACS Omega* **2021**, *6*, 17228–17238. [\[CrossRef\]](#) [\[PubMed\]](#)
95. Azhar, M.R.; Abid, H.R.; Sun, H.; Periasamy, V.; Tadé, M.O.; Wang, S. Excellent performance of copper based metal organic framework in adsorptive removal of toxic sulfonamide antibiotics from wastewater. *J. Colloid Interface Sci.* **2016**, *478*, 344–352. [\[CrossRef\]](#) [\[PubMed\]](#)
96. Khezerlou, A.; Tavassoli, M.; Abedi-Firoozjah, R.; Sani, M.A.; Ehsani, A.; Varma, R.S. MOFs-based adsorbents for the removal of tetracycline from water and food samples. *Sci. Rep.* **2025**, *15*, 502. [\[CrossRef\]](#)
97. Guo, Z.; Wu, X.; Meng, J.; Li, X.; Li, Y.; Hu, L. Preparation of Mg@MIL-101(Fe)/NH₂-MIL-125(Ti) bis-MIL composites and their sorption performance towards Pb(II) from aqueous solution. *Sep. Purif. Technol.* **2024**, *339*, 126692. [\[CrossRef\]](#)
98. Wu, P.; Du, Q.; Sun, Y.; Li, Z.; He, H. MIP-coated Eu(BTC) for the fluorometric determination of lincomycin in eggs. *Anal. Methods* **2019**, *11*, 4501–4510. [\[CrossRef\]](#)
99. Hu, Z.; Lustig, W.P.; Zhang, J.; Zheng, C.; Wang, H.; Teat, S.J.; Gong, Q.; Rudd, N.D.; Li, J. Effective Detection of Mycotoxins by a Highly Luminescent Metal–Organic Framework. *J. Am. Chem. Soc.* **2015**, *137*, 16209–16215. [\[CrossRef\]](#)
100. Fu, Y.; Yang, D.; Chen, Y.; Shi, J.; Zhang, X.; Hao, Y.; Zhang, Z.; Sun, Y.; Zhang, J. MOF-Based Active Packaging Materials for Extending Post-Harvest Shelf-Life of Fruits and Vegetables. *Materials* **2023**, *16*, 3406. [\[CrossRef\]](#)
101. Zhang, Q.; Yang, H.; Zhou, T.; Chen, X.; Li, W.; Pang, H. Metal–Organic Frameworks and Their Composites for Environmental Applications. *Adv. Sci.* **2022**, *9*, e2204141. [\[CrossRef\]](#)
102. Chen, N.; Wang, C.; Kong, F.; Wang, S. In situ facile synthesis and antibacterial activity of Ag-MOFs/cellulose filter paper composites for fruit fresh-keeping. *Int. J. Biol. Macromol.* **2024**, *256*, 128424. [\[CrossRef\]](#)
103. Kim, H.; Trinh, B.T.; Kim, K.H.; Moon, J.; Kang, H.; Jo, K.; Akter, R.; Jeong, J.; Lim, E.-K.; Jung, J.; et al. Au@ZIF-8 SERS paper for food spoilage detection. *Biosens. Bioelectron.* **2021**, *179*, 113063. [\[CrossRef\]](#) [\[PubMed\]](#)
104. Wang, Y.; Chen, J.; Wang, C.; Zhang, L.; Yang, Y.; Chen, C.; Xie, Y.; Zhao, P.; Fei, J. An electrochemical sensor based on Ce-MOF-derived Ce-doped poly(3,4-ethylenedioxythiophene) composite for efficient determination of rutin in food. *Talanta* **2023**, *263*, 124678. [\[CrossRef\]](#) [\[PubMed\]](#)
105. Li, S.; Hu, X.; Chen, S.; Wang, X.; Shang, H.; Zhou, Y.; Dai, J.; Xiao, L.; Qin, W.; Liu, Y. Synthesis of γ -cyclodextrin metal-organic framework as ethylene absorber for improving postharvest quality of kiwi fruit. *Food Hydrocoll.* **2023**, *136*, 108294. [\[CrossRef\]](#)
106. Saxena, S.; Lis, M.J. Native Cyclodextrin-Based Metal–Organic Frameworks (MOFs): Synthesis, Characterization, and Potential Applications in Food Industry. *Molecules* **2025**, *30*, 293. [\[CrossRef\]](#)
107. Bae, Y.J.; Cho, E.S.; Qiu, F.; Sun, D.T.; Williams, T.E.; Urban, J.J.; Queen, W.L. Transparent Metal–Organic Framework/Polymer Mixed Matrix Membranes as Water Vapor Barriers. *ACS Appl. Mater. Interfaces* **2016**, *8*, 10098–10103. [\[CrossRef\]](#)
108. Huang, G.; Li, Y.; Qin, Z.; Liang, Q.; Xu, C.; Lin, B. Hybridization of carboxymethyl chitosan with MOFs to construct recyclable, long-acting and intelligent antibacterial agent carrier. *Carbohydr. Polym.* **2020**, *233*, 115848. [\[CrossRef\]](#)
109. Wang, B.; Wang, P.; Xie, L.-H.; Lin, R.-B.; Lv, J.; Li, J.-R.; Chen, B. A stable zirconium based metal-organic framework for specific recognition of representative polychlorinated dibenzo-p-dioxin molecules. *Nat. Commun.* **2019**, *10*, 3861. [\[CrossRef\]](#)
110. Wiśniewska, P.; Haponiuk, J.; Saeb, M.R.; Rabiee, N.; Bencherif, S.A. Mitigating metal-organic framework (MOF) toxicity for biomedical applications. *Chem. Eng. J.* **2023**, *471*, 144400. [\[CrossRef\]](#)
111. Singh, N.; Qutub, S.; Khashab, N.M. Biocompatibility and biodegradability of metal organic frameworks for biomedical applications. *J. Mater. Chem. B* **2021**, *9*, 5925–5934. [\[CrossRef\]](#)

112. Zhao, R.-N.; Zhu, B.-W.; Xu, Y.; Yu, S.-F.; Wang, W.-J.; Liu, D.-H.; Hu, J.-N. Cyclodextrin-based metal-organic framework materials: Classifications, synthesis strategies and applications in variegated delivery systems. *Carbohydr. Polym.* **2023**, *319*, 121198. [\[CrossRef\]](#)
113. Baldim, I.; Tonani, L.; Kress, M.R.v.Z.; Oliveira, W.P. Lippia sidoides essential oil encapsulated in lipid nanosystem as an anti-*Candida* agent. *Ind. Crops Prod.* **2019**, *127*, 73–81. [\[CrossRef\]](#)
114. Tamames-Tabar, C.; Cunha, D.; Imbuluzqueta, E.; Ragon, F.; Serre, C.; Blanco-Prieto, M.J.; Horcajada, P. Cytotoxicity of nanoscaled metal-organic frameworks. *J. Mater. Chem. B* **2014**, *2*, 262–271. [\[CrossRef\]](#) [\[PubMed\]](#)
115. Baati, T.; Njim, L.; Neffati, F.; Kerkeni, A.; Bouttemi, M.; Gref, R.; Najjar, M.F.; Zakhama, A.; Couvreur, P.; Serre, C.; et al. In depth analysis of the in vivo toxicity of nanoparticles of porous iron(iii) metal-organic frameworks. *Chem. Sci.* **2013**, *4*, 1597–1607. [\[CrossRef\]](#)
116. Sampaio, B.L.; Edrada-Ebel, R.; Da Costa, F.B. Effect of the environment on the secondary metabolic profile of *Tithonia diversifolia*: A model for environmental metabolomics of plants. *Sci. Rep.* **2016**, *6*, 29265. [\[CrossRef\]](#) [\[PubMed\]](#)
117. Cai, C.C.; Ma, R.J.; Duan, M.W.; Lu, D.J. Preparation and antimicrobial activity of thyme essential oil microcapsules prepared with gum arabic. *RSC Adv.* **2019**, *9*, 19740–19747. [\[CrossRef\]](#)
118. Leyva-López, N.; Gutiérrez-Grijalva, E.P.; Vazquez-Olivo, G.; Heredia, J.B. Essential Oils of Oregano: Biological Activity beyond Their Antimicrobial Properties. *Molecules* **2017**, *22*, 989. [\[CrossRef\]](#)
119. Lopez-Romero, J.C.; González-Ríos, H.; Borges, A.; Simões, M. Antibacterial Effects and Mode of Action of Selected Essential Oils Components against *Escherichia coli* and *Staphylococcus aureus*. *Evid.-Based Complement. Altern. Med.* **2015**, *2015*, 795435. [\[CrossRef\]](#)
120. Wang, M.; Liu, H.; Dang, Y.; Li, D.; Qiao, Z.; Wang, G.; Liu, G.; Xu, J.; Li, E. Antifungal Mechanism of Cinnamon Essential Oil against Chinese Yam-Derived *Aspergillus niger*. *J. Food Process. Preserv.* **2023**, *2023*, 1–9. [\[CrossRef\]](#)
121. Chouhan, S.; Sharma, K.; Guleria, S. Antimicrobial Activity of Some Essential Oils—Present Status and Future Perspectives. *Medicines* **2017**, *4*, 58. [\[CrossRef\]](#)
122. Jackson-Davis, A.; White, S.; Kassama, L.S.; Coleman, S.; Shaw, A.; Mendonca, A.; Cooper, B.; Thomas-Popo, E.; Gordon, K.; London, L. A Review of Regulatory Standards and Advances in Essential Oils as Antimicrobials in Foods. *J. Food Prot.* **2023**, *86*, 100025. [\[CrossRef\]](#)
123. Raveau, R.; Fontaine, J.; Sahraoui, A.L.-H. Essential Oils as Potential Alternative Biocontrol Products against Plant Pathogens and Weeds: A Review. *Foods* **2020**, *9*, 365. [\[CrossRef\]](#)
124. Kesraoui, S.; Andrés, M.F.; Berrocal-Lobo, M.; Soudani, S.; Gonzalez-Coloma, A. Direct and Indirect Effects of Essential Oils for Sustainable Crop Protection. *Plants* **2022**, *11*, 2144. [\[CrossRef\]](#) [\[PubMed\]](#)
125. Andarzabakhsh, K.; Sharafi-Badr, P.; Ehsandoost, E.; Morad, H.; Rezazadeh, A.; Kazemian, H. Encapsulation of biological molecules in metal-organic frameworks for biomedical applications: Recent developments and future perspectives. *Inorg. Chem. Commun.* **2024**, *169*, 113029. [\[CrossRef\]](#)
126. Pugazhendhi, A.; Alshehri, M.A.; Kandasamy, S.; Sarangi, P.K.; Sharma, A. Deciphering the importance of nanoencapsulation to improve the availability of bioactive molecules in food sources to the human body. *Food Chem.* **2025**, *464*, 141762. [\[CrossRef\]](#) [\[PubMed\]](#)
127. Reis, D.R.; Ambrosi, A.; Di Luccio, M. Encapsulated essential oils: A perspective in food preservation. *Futur. Foods* **2022**, *5*, 100126. [\[CrossRef\]](#)
128. Dupuis, V.; Cerbu, C.; Witkowski, L.; Potarniche, A.V.; Timar, M.C.; Żychska, M.; Sabliov, C.M. Nanodelivery of essential oils as efficient tools against antimicrobial resistance: A review of the type and physical-chemical properties of the delivery systems and applications. *Drug Deliv.* **2022**, *29*, 1007–1024. [\[CrossRef\]](#)
129. Weisany, W.; Samadi, S.; Tahir, N.A.-R.; Amini, J.; Hossaini, S. Nano-encapsulated with mesoporous silica enhanced the antifungal activity of essential oil against *Botrytis cinerea* (Helotiales; Sclerotiniaceae) and *Colletotrichum nymphaeae* (Glomerellales; Glomerellaceae). *Physiol. Mol. Plant Pathol.* **2022**, *122*, 101902. [\[CrossRef\]](#)
130. Attia, R.G.; Khalil, M.M.H.; Hussein, M.A.; Fattah, H.M.A.; Rizk, S.A.; Ma'moun, S.A.M. Cinnamon Oil Encapsulated with Silica Nanoparticles: Chemical Characterization and Evaluation of Insecticidal Activity Against the Rice Moth, *Corcyra cephalonica*. *Neotropical Entomol.* **2023**, *52*, 500–511. [\[CrossRef\]](#)
131. Melendez-Rodriguez, B.; Figueroa-Lopez, K.J.; Bernardos, A.; Martínez-Máñez, R.; Cabedo, L.; Torres-Giner, S.; Lagaron, J.M. Electrospun Antimicrobial Films of Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) Containing Eugenol Essential Oil Encapsulated in Mesoporous Silica Nanoparticles. *Nanomaterials* **2019**, *9*, 227. [\[CrossRef\]](#)
132. Cadena, M.B.; Preston, G.M.; Van der Hoorn, R.A.; Townley, H.E.; Thompson, I.P. Species-specific antimicrobial activity of essential oils and enhancement by encapsulation in mesoporous silica nanoparticles. *Ind. Crops Prod.* **2018**, *122*, 582–590. [\[CrossRef\]](#)
133. Overmans, S.; Alflayyeh, Y.; Gutiérrez, S.; Aldlaigan, Y.; Lauersen, K.J. Treatment with metal-organic frameworks (MOFs) elicits secondary metabolite accumulation in *Aquilaria crassna* (agarwood) callus culture. *Discov. Plants* **2025**, *2*, 104. [\[CrossRef\]](#)

134. Liu, Y.; Liu, L.; Chen, X.; Liu, Y.; Han, Y.; Cui, Y. Single-Crystalline Ultrathin 2D Porous Nanosheets of Chiral Metal–Organic Frameworks. *J. Am. Chem. Soc.* **2021**, *143*, 3509–3518. [\[CrossRef\]](#) [\[PubMed\]](#)
135. Haikal, R.R.; El Salakawy, N.; Ibrahim, A.; Ali, S.L.; Mamdouh, W. Synergistic antioxidant and antibacterial effects of a Zn–ascorbate metal–organic framework loaded with marjoram essential oil. *Nanoscale Adv.* **2024**, *6*, 4664–4671. [\[CrossRef\]](#)
136. Liu, B.; Jiang, M.; Zhu, D.; Zhang, J.; Wei, G. Metal-organic frameworks functionalized with nucleic acids and amino acids for structure- and function-specific applications: A tutorial review. *Chem. Eng. J.* **2022**, *428*, 131118. [\[CrossRef\]](#)
137. Núñez-Rico, J.L.; Cabezas-Giménez, J.; Lillo, V.; Balestra, S.R.G.; Galán-Mascarós, J.R.; Calero, S.; Vidal-Ferran, A. TAMOF-1 as a Versatile and Predictable Chiral Stationary Phase for the Resolution of Racemic Mixtures. *ACS Appl. Mater. Interfaces* **2023**, *15*, 39594–39605. [\[CrossRef\]](#)
138. Nagarajan, V.; Kizhaeral, S.S.; Subramanian, M.; Rajendran, S.; Ranjan, J. Encapsulation of a Volatile Biomolecule (Hexanal) in Cyclodextrin Metal–Organic Frameworks for Slow Release and Its Effect on Preservation of Mangoes. *ACS Food Sci. Technol.* **2021**, *1*, 1936–1944. [\[CrossRef\]](#)
139. Cai, L.; Li, L.; Li, D.; Wu, Y.; Bai, J.; Zhong, K.; Gao, H. A nanoscale γ -cyclodextrin metal-organic framework loaded with eugenol (CMFE) for controlling *F. graminearum* on the wheat during harvest time. *Ind. Crops Prod.* **2024**, *221*, 119314. [\[CrossRef\]](#)
140. Che, J.; Chen, K.; Song, J.; Tu, Y.; Reymick, O.O.; Chen, X.; Tao, N. Fabrication of γ -cyclodextrin-Based metal-organic frameworks as a carrier of cinnamaldehyde and its application in fresh-cut cantaloupes. *Curr. Res. Food Sci.* **2022**, *5*, 2114–2124. [\[CrossRef\]](#)
141. Chen, K.; Brennan, C.; Cao, J.; Cheng, G.; Li, L.; Qin, Y.; Chen, H. Characterization of chitosan/eugenol-loaded IRMOF-3 nanoparticles composite films with sustained antibacterial activity and their application in postharvest preservation of strawberries. *LWT* **2023**, *186*, 115270. [\[CrossRef\]](#)
142. Ding, Y.; Yuan, J.; Mo, F.; Wu, S.; Ma, Y.; Li, R.; Li, M. A pH-Responsive Essential Oil Delivery System Based on Metal–organic Framework (ZIF-8) for Preventing Fungal Disease. *J. Agric. Food Chem.* **2023**, *71*, 18312–18322. [\[CrossRef\]](#)
143. He, W.; Ye, K.; Li, H.; Wang, C.; Wei, H.; Dang, L. Novel γ -cyclodextrin-based metal–organic frameworks for the effective encapsulation of oregano essential oil and controlled release. *New J. Chem.* **2023**, *47*, 10322–10332. [\[CrossRef\]](#)
144. Hong, S.J.; Riahi, Z.; Shin, G.H.; Kim, J.T. Development of innovative active packaging films using gelatin/pullulan-based composites incorporated with cinnamon essential oil-loaded metal-organic frameworks for meat preservation. *Int. J. Biol. Macromol.* **2024**, *267*, 131606. [\[CrossRef\]](#)
145. Hu, Z.; Li, S.; Wang, S.; Zhang, B.; Huang, Q. Encapsulation of menthol into cyclodextrin metal-organic frameworks: Preparation, structure characterization and evaluation of complexing capacity. *Food Chem.* **2021**, *338*, 127839. [\[CrossRef\]](#)
146. Li, Z.; Sun, Y.; Pan, X.; Gao, T.; He, T.; Chen, C.; Zhang, B.; Fu, X.; Huang, Q. Controlled Release of Thymol by Cyclodextrin Metal–Organic Frameworks for Preservation of Cherry Tomatoes. *Foods* **2022**, *11*, 3818. [\[CrossRef\]](#)
147. Liu, Y.; Zhao, Y.; Zhou, Z.; Shen, Y.; Jiang, L. Pore size effect of zirconium-based metal-organic frameworks for encapsulation and release of volatile monoterpenes. *Colloids Surfaces A Physicochem. Eng. Asp.* **2023**, *674*, 131907. [\[CrossRef\]](#)
148. Min, T.; Lei, Y.; Cheng, C.; Luo, Y.; Zhang, Y.; Yue, J. Highly efficient anchoring of γ -cyclodextrin-MOFs on chitosan/cellulose film by in situ growth to enhance encapsulation and controlled release of carvacrol. *Food Hydrocoll.* **2024**, *150*, 109633. [\[CrossRef\]](#)
149. Motakef-Kazemi, N.; Ghorbani, M. Adsorption and release of thymol using metal organic framework $\text{Zn}_2(\text{BDC})_2(\text{DABCO})$ and its chitosan nanocomposite. *J. Theor. Appl. Phys.* **2024**, *30*, 18. [\[CrossRef\]](#)
150. Ning, H.; Lu, L.; Xu, J.; Lu, L.; Pan, L.; Lin, Z. Development of sodium alginate-based antioxidant and antibacterial bioactive films added with IRMOF-3/Carvacrol. *Carbohydr. Polym.* **2022**, *292*, 119682. [\[CrossRef\]](#)
151. Ning, H.; Lu, L.; Zhang, Y. Isoreticular metal-organic framework-3 post-synthetic modification: Application in a new active film based on sodium alginate and carvacrol for pork preservation. *Food Biosci.* **2024**, *59*, 103926. [\[CrossRef\]](#)
152. Qin, Y.; Wang, Y.; Huang, Y.; Xiao, S.; Cui, R.; Yuan, M.; Brennan, M.; Brennan, C. Preparation and characterization of Ag@MOF-eugenol/poly (lactic acid) composite films for zucchini preservation. *Int. J. Biol. Macromol.* **2024**, *282*, 136809. [\[CrossRef\]](#)
153. Qin, Y.; Yu, H.; Chen, K.; Cui, R.; Cao, J.; Wang, Z.; Zhang, Z.-H.; Soteyome, T. Effects of chitosan/eugenol-loaded IRMOF-3 nanoparticles composite films on reactive oxygen species metabolism and microbial community dynamics in postharvest strawberries. *Food Biosci.* **2025**, *63*, 105652. [\[CrossRef\]](#)
154. Qin, Z.; Jiang, Q.; Zou, Y.; Chen, M.; Li, J.; Li, Y.; Zhang, H. Synthesis of Nanosized γ -Cyclodextrin Metal–Organic Frameworks as Carriers of Limonene for Fresh-Cut Fruit Preservation Based on Polycaprolactone Nanofibers. *Small* **2024**, *20*, 2400399. [\[CrossRef\]](#)
155. Tian, Y.; Zhou, L.; Liu, J.; Yu, K.; Yu, W.; Jiang, H.; Chen, X.; Peng, S.; Zhong, J.; Liu, W. Metal-organic frameworks-based moisture responsive essential oil hydrogel beads for fresh-cut pineapple preservation. *Food Chem.* **2024**, *451*, 139440. [\[CrossRef\]](#) [\[PubMed\]](#)
156. Wang, Y.; Du, Y.-T.; Xue, W.-Y.; Wang, L.; Li, R.; Jiang, Z.-T.; Tang, S.-H.; Tan, J. Enhanced preservation effects of clove (*Syzygium aromaticum*) essential oil on the processing of Chinese bacon (preserved meat products) by beta cyclodextrin metal organic frameworks (β -CD-MOFs). *Meat Sci.* **2023**, *195*, 108998. [\[CrossRef\]](#) [\[PubMed\]](#)
157. Wang, N.; Zhou, X.; Dong, Y.; Zhang, Y.; Liu, R.; Kang, H.; Wang, K.; Li, J. Citral Encapsulated into a Zeolite Imidazolate Framework-67 (ZIF-67) Cage via Biomimetic Mineralization as an Efficient Preservative for Long-Term Antimildew Efficacy of Bamboo. *ACS Sustain. Chem. Eng.* **2024**, *12*, 15991–16000. [\[CrossRef\]](#)

158. Wu, Y.; Luo, Y.; Zhou, B.; Mei, L.; Wang, Q.; Zhang, B. Porous metal-organic framework (MOF) Carrier for incorporation of volatile antimicrobial essential oil. *Food Control*. **2019**, *98*, 174–178. [[CrossRef](#)]
159. Zhang, K.; Jin, D.; Guo, X.; Shu, C.; Ouyang, H.; He, Y.; Tang, K.; Zhu, P.; Wang, Y.; Li, H. Preparation, characterization, and application on storage blueberries of starch matrix packaging film with slow-release activity by clove essential oil loaded in a zirconium-based metal-organic framework. *Ind. Crops Prod.* **2024**, *220*, 119205. [[CrossRef](#)]
160. Zuniega, J.; Grabulos, J.; Lebrun, M.; Aumond, T.; Daniel, C.; Brat, P.; Farrusseng, D. Encapsulation of thymol and limonene in metal-organic frameworks for inhibition of *Colletotrichum musae* growth. *Int. J. Food Sci. Technol.* **2024**, *59*, 730–742. [[CrossRef](#)]
161. Liang, M.; Xing, S.; Bai, F.; Tan, M.; Su, W. Cyclodextrin-based metal-organic frameworks as microreactors: Purification and stabilization of food bioactive compounds in Confined Spaces. *Trends Food Sci. Technol.* **2024**, *150*, 104588. [[CrossRef](#)]
162. Zhang, B.; Huang, J.; Liu, K.; Zhou, Z.; Jiang, L.; Shen, Y.; Zhao, D. Biocompatible Cyclodextrin-Based Metal–Organic Frameworks for Long-Term Sustained Release of Fragrances. *Ind. Eng. Chem. Res.* **2019**, *58*, 19767–19777. [[CrossRef](#)]
163. Gayen, P.; Karmakar, A.; Sepay, N.; Sinha, C. Influence of the cavity size of cyclodextrins on the photochromism of azoimidazoles. *J. Indian Chem. Soc.* **2022**, *99*, 100295. [[CrossRef](#)]
164. Kathuria, A.; Kumar, L.; Gaikwad, K.K.; El Badawy, A.; Kivy, M.B. Micro-encapsulation of citral using edible γ -cyclodextrin metal organic framework. *J. Incl. Phenom. Macrocycl. Chem.* **2024**, *104*, 99–108. [[CrossRef](#)]
165. Pan, X.; Junejo, S.A.; Tan, C.P.; Zhang, B.; Fu, X.; Huang, Q. Effect of potassium salts on the structure of γ -cyclodextrin MOF and the encapsulation properties with thymol. *J. Sci. Food Agric.* **2022**, *102*, 6387–6396. [[CrossRef](#)]
166. Xu, Y.; Chen, L.; Zhang, Y.; Huang, Y.; Cao, J.; Jiang, W. Antimicrobial and controlled release properties of nanocomposite film containing thymol and carvacrol loaded UiO-66-NH₂ for active food packaging. *Food Chem.* **2023**, *404*, 134427. [[CrossRef](#)]

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