Synthesis and Characterization of Calcium- and Zinc-Based Metal-Organic Frameworks for Biomedical Applications

Milana Yessenguatova, Alibi Mugalim
Professor: Mannix Balanay
Mentors: R.A. Lagunay, A. Tleubekova

August, 2024

Abstract

Metal-Organic Frameworks (MOFs) have gained significant attention for their potential applications in drug delivery systems due to their high porosity, structural diversity, and biocompatibility. This study focuses on the synthesis and characterization of calcium- and zinc-based MOFs using trimesic acid as an organic linker, exploring both conventional room temperature and microwave-assisted methods. The primary objective was to compare the efficiency, yield, and structural characteristics of MOFs synthesized by these two methods and to evaluate their potential for topical drug delivery applications.

The results demonstrated that both synthesis methods produced MOFs with similar yields, though the microwave-assisted method offered advantages in terms of reduced reaction times and enhanced control over reaction conditions. Notably, zinc-based MOFs exhibited approximately 200% higher yields compared to calcium-based MOFs across all samples. Additionally, the presence of CTAB surfactant significantly increased the yield and influenced the particle size and morphology of the MOFs, suggesting its role in facilitating MOF formation.

Structural characterization through Fourier Transform Infrared Spectroscopy (FTIR) and Ultraviolet-Visible Spectroscopy (UV-Vis) confirmed the successful synthesis of MOFs, with differences observed

in particle size and crystallinity between the two methods. The zinc-based MOFs, particularly those synthesized with CTAB, showed promise for topical drug delivery due to their high yield, structural stability, and potential for controlled release of therapeutic agents.

This research highlights the advantages of microwave-assisted synthesis and the critical role of CTAB surfactant in optimizing MOF production. The findings suggest that zinc-based MOFs, with their enhanced yield and favorable properties, are particularly well-suited for topical drug delivery applications. These MOFs could serve as effective carriers for delivering a wide range of therapeutic agents, offering new opportunities for the development of advanced treatments for skin-related conditions.

Further research is needed to optimize the synthesis parameters and explore the full potential of these MOFs in biomedical applications, particularly in developing targeted and controlled drug delivery systems.

1 Introduction

Metal-organic frameworks (MOFs), also known as porous coordination polymers, have garnered significant attention since their discovery by Robson in 1989. These advanced materials, composed of metal oxide centers connected by organic linkers, exhibit unique physical properties such as tunable pore sizes, flexible networks, and easy functionalization. The reticular design of MOFs, introduced in 1999, has paved the way for their extensive study, leading to a remarkable increase in related publications over the past decades.

MOFs have attracted widespread interest from both academia and industry due to their unprecedented porosity, structural diversity, and the ability to tailor the pore environment to suit specific applications. Proposed uses of MOFs span a broad spectrum, including gas storage, separations, catalysis, sensing, and stimuli-responsive materials. Importantly, MOFs offer significant advantages over traditional porous materials like zeolites and activated carbons, particularly in terms of their ability to control structure and properties for targeted applications.

In recent years, MOFs have emerged as promising candidates for drug delivery systems due to their porous structures, high drug-loading capacities, and biocompatibility. MOFs can be designed to carry therapeutic agents such as drugs, nucleic acids, and proteins within their cavities, either by

non-covalent adsorption or through functionalized linkers. The use of MOFs in drug delivery leverages their ability to protect drugs from degradation, improve bioavailability, and ensure controlled release, making them particularly valuable for therapeutic applications. To be effective in these roles, MOFs must be biocompatible, non-toxic, and stable under physiological conditions, while also offering a degree of chemical instability to facilitate drug release.

However, the conventional solvothermal synthesis of MOFs poses several challenges, including long reaction times, low reproducibility, and high energy consumption, which limit their scalability and practical application. To overcome these challenges, alternative synthesis methods such as microwave-assisted synthesis have been developed. Microwave technology offers considerable benefits, including drastically reduced reaction times, lower energy consumption, and enhanced control over MOF properties such as particle size, morphology, and phase-selectivity.

In this study, we focus on the synthesis of MOFs using biocompatible metals—calcium and zinc—and trimesic acid as an organic linker. Calcium and zinc were selected due to their low toxicity and ability to form stable, porous frameworks suitable for drug delivery applications. The research explores two synthesis methods: a conventional room temperature method and a microwave-assisted method. The microwave-assisted approach is of particular interest due to its potential to improve reaction efficiency, yield, and control over the structural characteristics of the resulting MOFs. By comparing these two synthesis methods, we aim to provide insights into the advantages and limitations of each, contributing to the optimization of MOF synthesis for biomedical applications.

This paper also reviews the most recent developments in MOFs as potential nanocarriers for drug delivery, highlighting the synthesis, functionalization, and application of MOFs in transporting therapeutic agents within biological systems. We discuss the challenges and opportunities associated with using MOFs as drug delivery vehicles, aiming to advance their development as innovative platforms for therapeutic applications.

2 Materials and Methods

2.1 Trimesic Acid

Five grams of trimesic acid ($C_6H_3(CO_2H)_3$) were dissolved in 30 mL of water. Then, 6M HCl was added, followed by neutralization with 10M NaOH until the pH reached 6.5. The resulting solution was diluted to a concentration of 50 micrograms per mL.

2.2 Synthesis of MOFs

Eight different MOFs were synthesized, with four for each metal. Two were synthesized at room temperature, one with and one without CTAB surfactant. The other two were synthesized using a Discover SP microwave synthesizer (hereinafter referred to as CEM), also with and without CTAB.

112 micrograms of calcium nitrate tetrahydrate were dissolved in 4 mL of water. Four such solutions were prepared. 64.69 micrograms of zinc chloride were dissolved in 4 mL of water, and four such solutions were also prepared. To each solution, 2 mL of the previously prepared trimesic acid solution was added.

2.2.1 Room Temperature Synthesis

Two prepared solutions of each metal were taken. 19 micrograms of CTAB surfactant were added to one solution and not to the other. These four solutions were stirred for 10 minutes at 350 RPM.

2.2.2 CEM Synthesis

Similarly, two prepared solutions of each metal were taken. 19 micrograms of CTAB surfactant were added to one solution and not to the other. All four solutions were placed in the CEM for 10 minutes at 80°C, 300 psi pressure, 200W power, and medium stirring.

2.2.3 MOF Precipitation and Analysis

In all eight solutions, the resulting MOFs were precipitated by centrifugation, performed four times for 3 minutes each at 3000 RPM. The precipitates were separated and dried in a vacuum oven for 3 hours at 70°C.

The dried samples were then dissolved in water to a maximum concentration of 0.15 micrograms/mL. These solutions were analyzed using Ultraviolet-Visible Spectroscopy.

From these solutions, eight dilute solutions were prepared with a concentration of 0.003 micrograms/mL. These diluted solutions were used to calculate the refractive indexes of the solutions.

2.3 Characteristics

FTIR. We observe the expected peaks in the O-H region, but they are weakly and almost not pronounced in ZnMOF microwave and CaMOF microwave with CTAB. IR were taken using Jasco FTIR Spectrometer, Model 4600. Surfactants like CTAB could possibly change the hydrophilicity of the material, reducing the number of O-H bonds.

UV. All samples show absorption in 300nm region

Refractive index. Refractive indexes were calculated for every sample. These values can be used for further characterization, including DLS analysis that will tell us about size and charge of MOF

3 Results and Discussion

3.1 Comparative Analysis of Synthesis Methods

3.1.1 Room Temperature vs. Microwave-Assisted Synthesis

Efficiency and Yield: The comparison between room temperature and microwave-assisted synthesis methods reveals that both approaches produced MOFs with similar yields, indicating that the choice of synthesis method may not significantly affect the overall quantity of MOFs obtained. However, the microwave-assisted method, while yielding similar quantities, offers advantages in terms of reduced reaction times and potentially improved control over reaction conditions. This reduction in time and energy expenditure can be particularly beneficial for large-scale production and practical applications.

Yield Enhancement with Zinc and CTAB: Notably, zinc-based MOFs exhibited approximately 200% higher yields compared to calcium-

based MOFs across all samples. The presence of CTAB surfactant significantly increased the yield and influenced the particle size and morphology of the MOFs, suggesting its role in facilitating MOF formation.

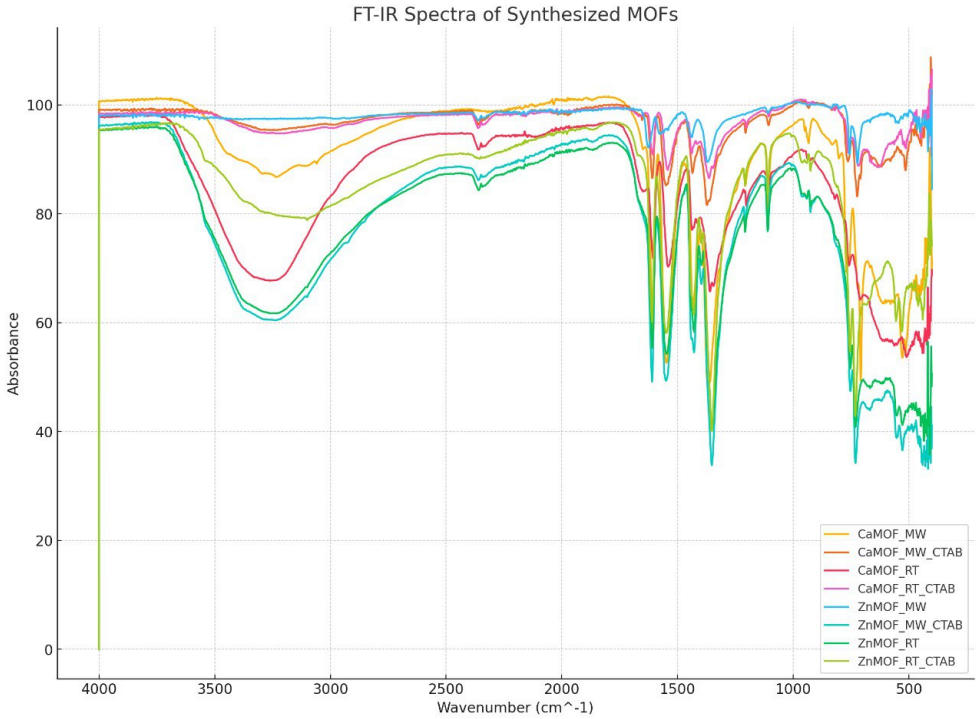
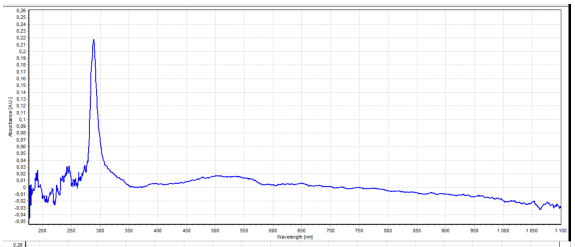
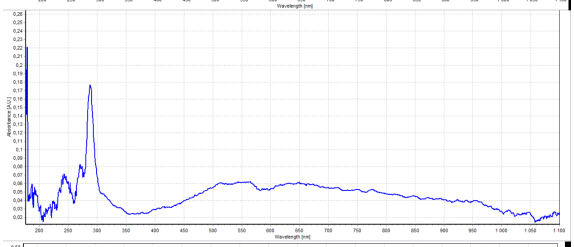
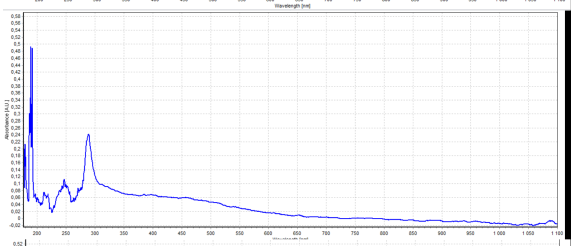
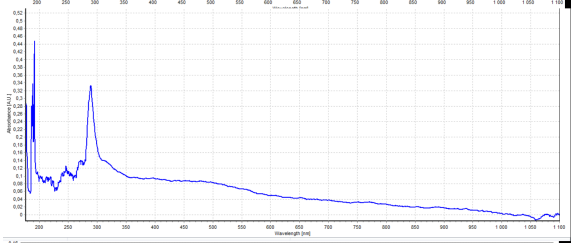


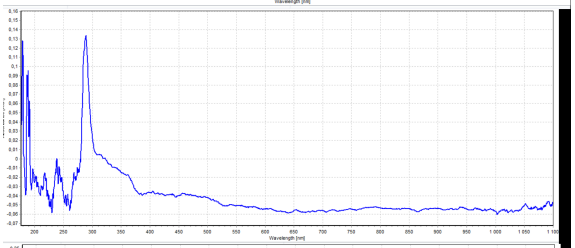
Figure 1. IR spectrums.

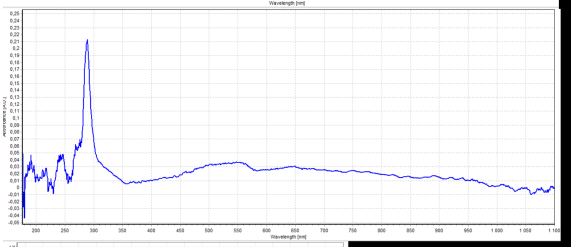

Absorbance (A.U.)
Wavelength [nm]

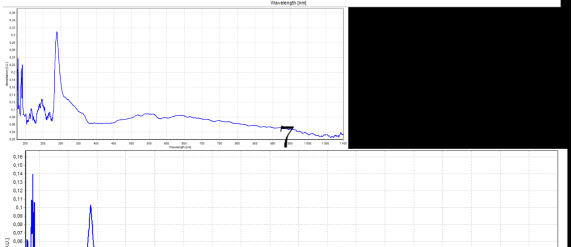

Absorbance (A.U.)
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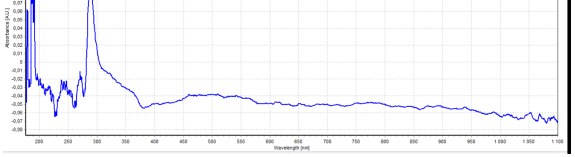
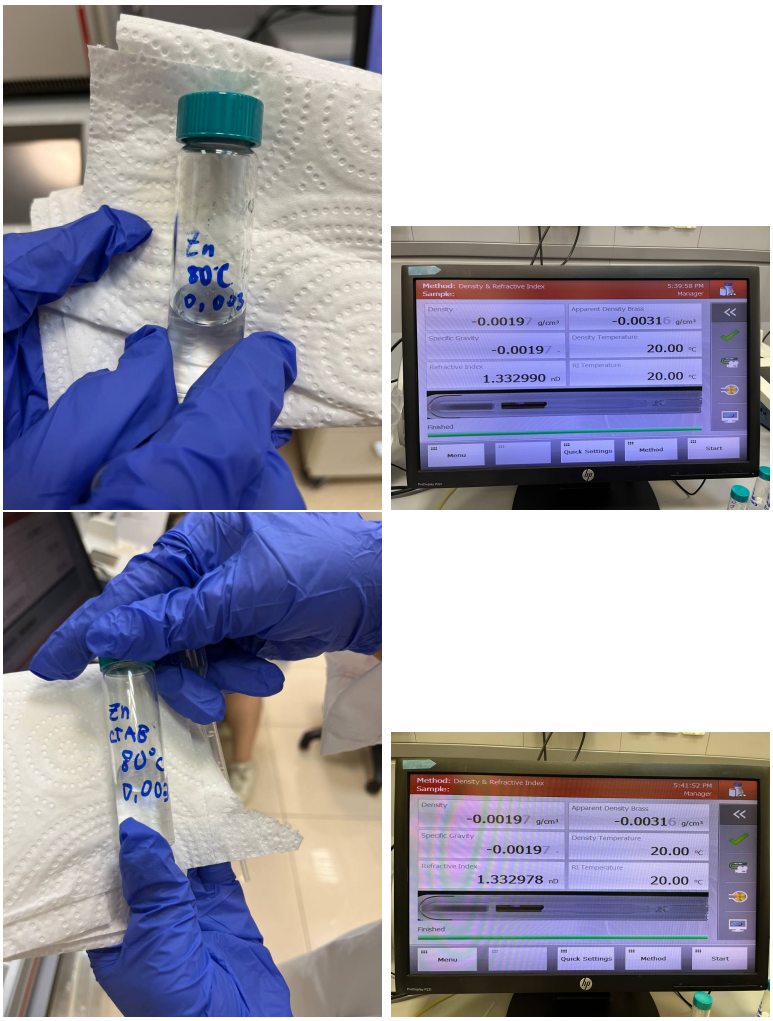
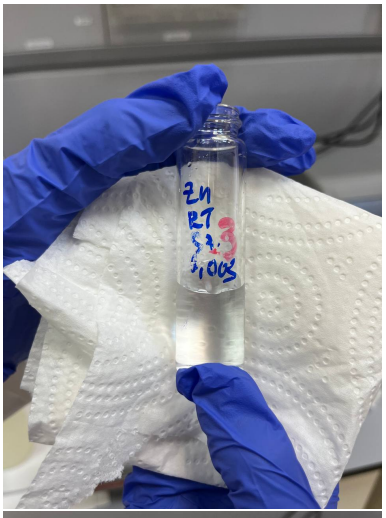
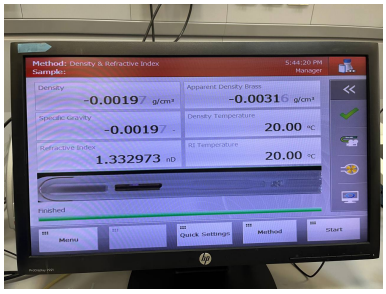

Wavelength [nm]

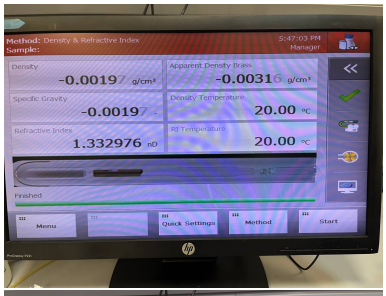
Figure 2. UV spectrums.



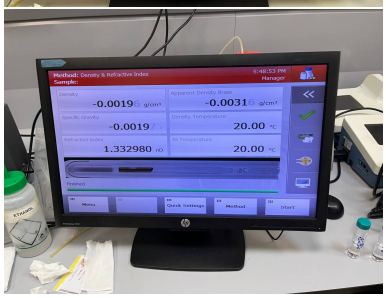



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Density Temperature
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RI Temperature
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Finished
Menu
Quick Settings
Method
Start




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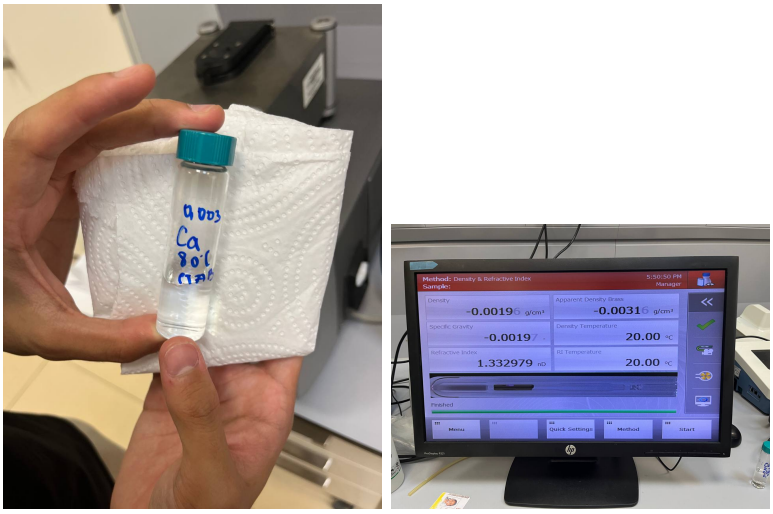


Figure 3. Refractive indexes.

4 Conclusion

The synthesis and characterization of calcium- and zinc-based MOFs using trimesic acid as an organic linker were successfully achieved through both conventional room temperature and microwave-assisted methods. The study highlights the advantages of the microwave-assisted synthesis, particularly in terms of reduced reaction times and improved control over MOF properties such as yield, particle size, and morphology.

Zinc-based MOFs, especially those synthesized with the addition of CTAB surfactant, demonstrated significantly higher yields and favorable structural characteristics, making them promising candidates for drug delivery applications. The use of microwave-assisted synthesis, in conjunction with surfactants like CTAB, may represent a valuable approach for optimizing the production of MOFs for biomedical purposes.

Future research should focus on further optimizing the synthesis parameters, exploring the full potential of these MOFs in drug delivery, and investigating the specific interactions between the MOF frameworks and various therapeutic agents. This will contribute to the development of advanced drug delivery systems that leverage the unique properties of MOFs to enhance therapeutic efficacy and patient outcomes.

5 References

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