CHAPTER 1 INTRODUCTION

1.1 Background

Magnetic-luminescent nanocomposites (MLNCs) are a new class of multifunctional nanomaterials that combine magnetic and luminescent properties in a single material. Their magnetic properties allow the nanocomposites to be controlled using an external magnetic field, while their luminescent properties enable them to emit light when excited. Currently, MLNCs are promising materials in the field of nanomedicine because they can be applied for various diagnostic purposes, such as bioimaging (Rajabzadeh et al., 2025), targeted drug delivery (Kuang et al., 2020), hyperthermia-based cancer therapy (Simeonidis et al., 2021), and various other biomedical applications.

Magnetite (Fe_3O_4) is a magnetic material widely used in MLNCs because it has good biocompatibility and relatively low toxicity compared to gadolinium-based MLNCs (Gd_2O_3), which are known to have higher toxicity levels (Blomqvist et al., 2022). Furthermore, magnetite is a ferromagnetic material that can become superparamagnetic when its particle size is reduced to below 20 nm (Koo et al., 2019). At this size range, its magnetic properties change from multidomain to single-domain. Reducing the particle size to the single-domain region causes the coercivity value to decrease to nearly zero, so that the nanoparticles exhibit superparamagnetic characteristics (Molaei and Salimi, 2022). One synthesis method that uses relatively safe and promising chemicals to produce superparamagnetic magnetite nanoparticles is the coprecipitation method.

Carbon Quantum Dots (CQDs) are a type of carbon-based fluorescent nanoparticle that shows great promise as a luminescent component in MLNCs. CQDs typically measure less than 10 nm and are capable of emitting fluorescence. In addition, CQDs offer various advantages, including low toxicity, ease of synthesis and modification, good chemical and photostability, and fluorescence emission that depends on the excitation wavelength. Therefore, the combination of Fe_3O_4 nanoparticles with CQDs results in MLNCs that combine magnetic, fluorescent, and biocompatible properties, making them a potential candidate for biomedical applications.

Various studies have reported the synthesis of Fe_3O_4/CQD nanocomposites using a variety of methods. One study successfully synthesized Fe_3O_4/CQD nanocomposites using a one-step synthesis method that simultaneously utilized CQD precursors and Fe_3O_4 nanoparticles, and demonstrated their potential for biomedical applications (Stepanova et al., 2022). Another study also successfully synthesized Fe_3O_4/CQD nanocomposites via a hydrothermal method and reported that the material has potential for development in bioimaging (Novita and Astuti, 2023). However, combining Fe_3O_4 with CQDs can lead to a decrease in CQD fluorescence intensity due to the quenching effect caused by Fe_3O_4. Additionally, CQD fluorescence intensity may also decrease as a result of direct interaction with the biological environment or bodily fluids during the application process. Therefore, Fe_3O_4/CQD nanocomposites need to be encapsulated with a biocompatible material to enhance their fluorescence intensity and protect the CQDs from the influence of the surrounding environment, while also maintaining the stability of the nanocomposite dispersion within the stbale range of a colloidal system, characterized by an absolute zeta potential value of ≥30 mV (Das et al., 2023).

An effort to encapsulate Fe_3O_4/CQD nanocomposites has been reported by Rahmadani (2025), specifically the encapsulation of Fe_3O_4/CQD nanocomposites with polylactic acid (PLA). The study reported an increase in fluorescence intensity and a zeta potential of approximately -32.2 mV, indicating good dispersion stability. However, PLA is a relatively non-porous polymer material, so further exploration of encapsulation materials with porous structures and high specific surface areas is still needed. These characteristics not only have the potential to protect Fe_3O_4/CQD nanocomposites from quenching effects and direct interaction with the biological environment during the application process, but can also provide additional functionality by utilizing their porous structure as a space for loading and delivering drug molecules. Thus, the use of porous materials as encapsulation agents has the potential to expand the function of Fe_3O_4/CQD from a magnetic-luminescent material to a multifunctional material that also holds potential for drug delivery applications. One material with these characteristics is Zeolitic Imidazolate Framework-8 (ZIF-8), which has a porous structure, high specific surface area, and pore characteristics suitable for the encapsulation and loading of molecules.

ZIF-8 is part of the ZIFs family, which belongs to the metal-organic frameworks (MOFs) subclass. ZIF-8 possesses various superior properties, such as biodegradability, biocompatibility, pH responsiveness, tunable pore size, high specific surface area, and ease of surface modification (Lin et al., 2019). ZIF-8 large specific surface area and porous structure enable the encapsulation of various molecules, such as fluorescent nanoparticles and drugs (Tran et al., 2025). Therefore, ZIF-8 has the potential to be used as a encapsulation material Fe_3O_4/CQD nanocomposites to support the development of multifunctional materials for various biomedical applications, including biological imaging, drug delivery, and theranostics.

In this study, Fe_3O_4/CQD@ZIF-8 nanocomposites were synthesized. The Fe_3O_4/CQD nanocomposite serves as the core, while ZIF-8 acts as the shell. The resulting Fe_3O_4/CQD@ZIF-8 nanocomposite is expected to enhance fluorescence intensity while maintaining dispersion stability within a stable colloidal range, namely ≥30 mV. Fe_3O_4 nanoparticles were synthesized using the coprecipitation method (Dizajyekan et al., 2024). CQD was synthesized using the solvothermal method (Gultom et al., 2024), while encapsulation with ZIF-8 was performed using the in-situ self-assembly method at room temperature (Li et al., 2022). The effect of the amount of ZIF-8 was investigated by varying the amount of Zn^{2+} and 2-Hmim precursors while maintaining a constant Zn^{2+}:2-Hmim ratio.

1.2 Purpose of the Research

This study aims to synthesize Fe_3O_4/CQD nanocomposites encapsulated using ZIF-8. In addition, this study also aims to examine the effect of varying the amounts of Zn^{2+} and 2-Hmim precursor, while maintaining a constant Zn^{2+} and 2-

Hmim ratio, on the fluorescence intensity and dispersion stability of the Fe_3O_4/CQD@ZIF-8 nanocomposites.

1.3 Benefits of the Research

1. Contributing to the development of magnetic-luminescent nanocomposite materials and enriching studies on the encapsulation of nanomaterials using ZIF-8.
2. Serving as a reference for further research on improving the stability and optical properties of Fe_3O_4/CQD nanocomposites.
3. Providing basic information for the development of multifunctional materials with potential for biomedical applications, particularly in bioimaging.

1.4 Scope of the Research

In order to avoid broadening the scope of the study, the scope of the problem is focused on the following:

1. The research focused on the synthesis of Fe_3O_4/CQD-based magnetic-luminescent nanocomposites encapsulated using ZIF-8.
2. The study examines the effect of varying the amounts Zn^{2+} and Hmim precursors, while maintaining a constant Zn^{2+} and Hmim ratio, on the dispersion stability and fluorescence intensity of the resulting Fe_3O_4/CQD@ZIF-8 nanocomposites.
3. The characterization of Fe_3O_4/CQD@ZIF-8 nanocomposites is limited to structural (XRD, FTIR, and AFM), dispersion stability (zeta potential), and fluorescence intensity (fluorescence spectroscopy).
4. The study does not include in vitro or in vivo biological testing, but only demonstrates the material's potential for biomedical applications.

1.5 Hypothesis

The hypothesis of this study is that the encapsulation of Fe_3O_4/CQD nanocomposites using ZIF-8, by varying the amounts of Zn^{2+} and 2-Hmim precursors, while maintaining a constant Zn^{2+} and 2-Hmim ratio affect the fluorescence intensity and dispersion stability of the resulting Fe_3O_4/CQD @ZIF-8 nanocomposites.