# SMART MICROBOTS FOR CAPTURING AND DEGRADING CONTAMINANTS FROM WATER

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**Abstract**

Microrobots are miniature devices capable of performing complex tasks such as drug delivery, medical diagnostics, or environmental protection. They can have various mechanisms of motion induction based on the use of energy of external fields. The ability to control motion can be used in combination with another properties, ensuring specific functionalities. In this work, we developed a concept for microrobots designed to ensure environmental protection. The proposed robots are hybrid structures composed of functional shell and magneto-responsive core. The microrobots were characterized at each stage of their preparation using a number of analytical methods. The results showed that the environmental protection can be ensured by a specific shell design. In particular, the functionality of microrobots was determined by their ability to motion (externally triggered) and related enhanced interaction with surrounding medium.

**Keywords:** Microrobots, magnetics, MOF, detection, degradation, pollutant

## 1. INTRODUCTION

Pollution of water sources by organic contaminants, such as per- and polyfluorinated substances (PFAS such as GenX) and pharmaceutical compounds like diclofenac, represents an increasingly serious environmental and health issue. These substances are often present at very low concentrations, yet they have a significant impact on the environment and human health, mainly due to their chemical stability and bioaccumulation. Traditional water treatment methods are not always sufficiently effective in removing these compounds; therefore, there is a growing need for the development of new technologies for their detection and elimination.[1-3]

In recent years, considerable attention has been devoted to advanced materials such as metal–organic frameworks (MOFs), which, due to their high specific surface area, porosity, and tunable chemical structure, exhibit exceptional adsorption capabilities toward a wide range of contaminants. The specific internal surface area of MOFs can exceed 6000 $m^2/g$, depending on the structure. Therefore, their main uses include adsorption, separation, and gas storage. MOFs have also recently been studied in combination with various functional materials, such as polymers or nanoparticles.[4] The combination of MOF structures with externally responsive materials and nanomaterials, enables not only the efficient capture of undesired substances from external environment but can also increase the interaction with external environment.[5]

In this work, we propose the preparation and use of such hybrid nanomaterials for environmental monitoring and protection. These proposed materials consist of magneto-responsive core coated by highly porous MOF layer.[5, 7] Proposed combination ensures the selective entrapping and removal of undesired substances from environmental.[8]

## 2. EXPERIMENTAL

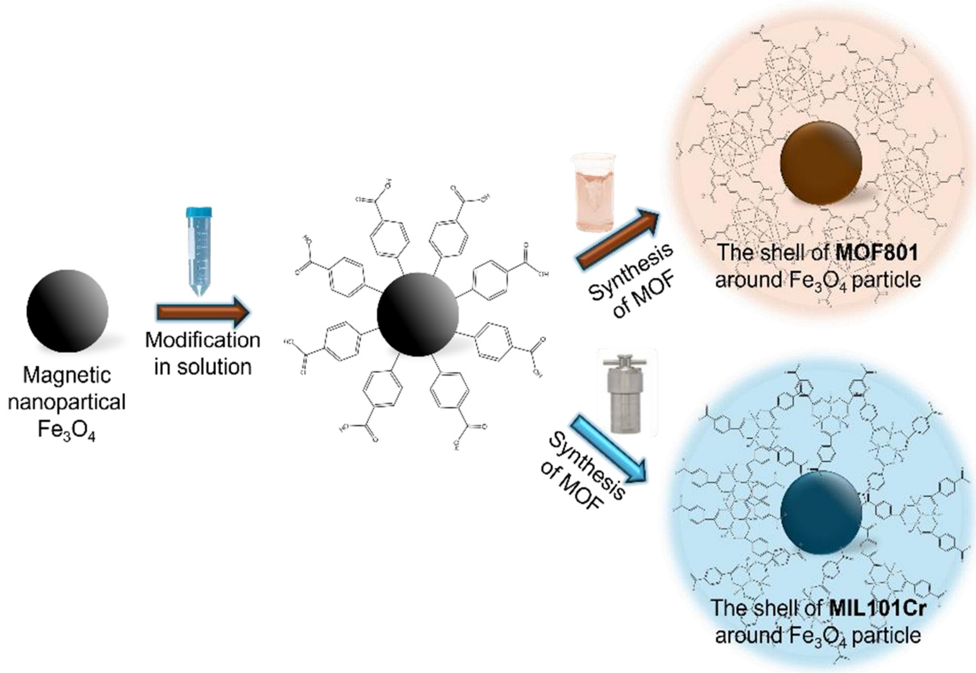


**Figure 1** Scheme of nanoparticle modification and subsequent synthesis of microrobots

The materials preparation is shown in **Figure 1**. The process begins with the creation of ferromagnetic core in a small centrifuge tube. The next step was to modify the magnetic core by coating it with porous shell layer. The magnetic core was coated with two different MOF structures depending on the functionality required. The coating is typically performed under mild solvothermal or hydrothermal conditions. As a result, we have developed a material that can be actuated by an external field and possesses a large surface area suitable for adsorbing undesired compounds from external environment.

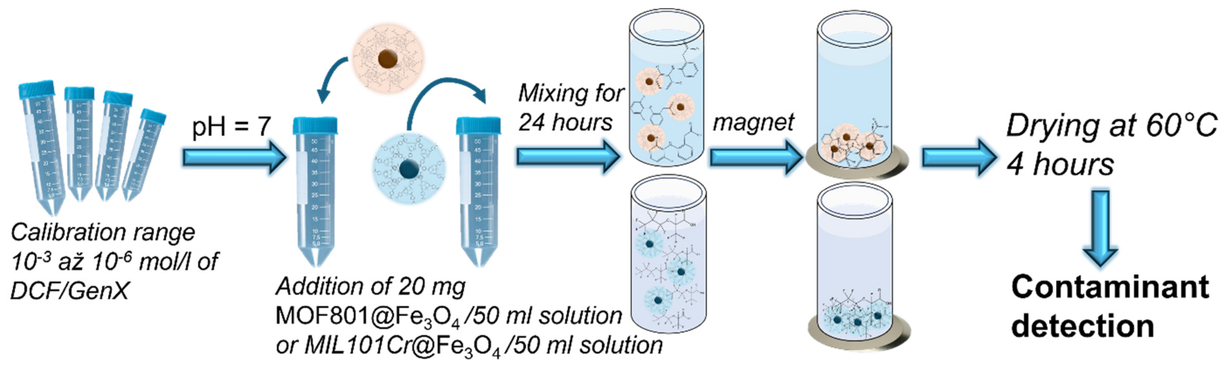


**Figure 2** Schematic Representation of incubation of organic pollutant to the structure Magnetic MOF-Based Microrobots

The schematic diagram in the **Figure 2** illustrates the experimental procedure for testing the adsorption performance of created materials. Initially, the synthesized particles were dispersed in aqueous solutions containing model contaminants. The microrobots were then introduced into the contaminated solutions, where they interacted with the pollutants under stirring to facilitate adsorption.

After a defined contact period, the nanoparticles were separated from the solution, dried, and characterized using a series of analytical methods. FTIR analysis could detect adsorbed contaminants in high concentrations, far above the allowed limits. Since the many toxic substances occur in low concentrations in the environment, we the detection was also performed using electrochemistry. The typical results of electrochemical measurement are presented in **Figure 3**.

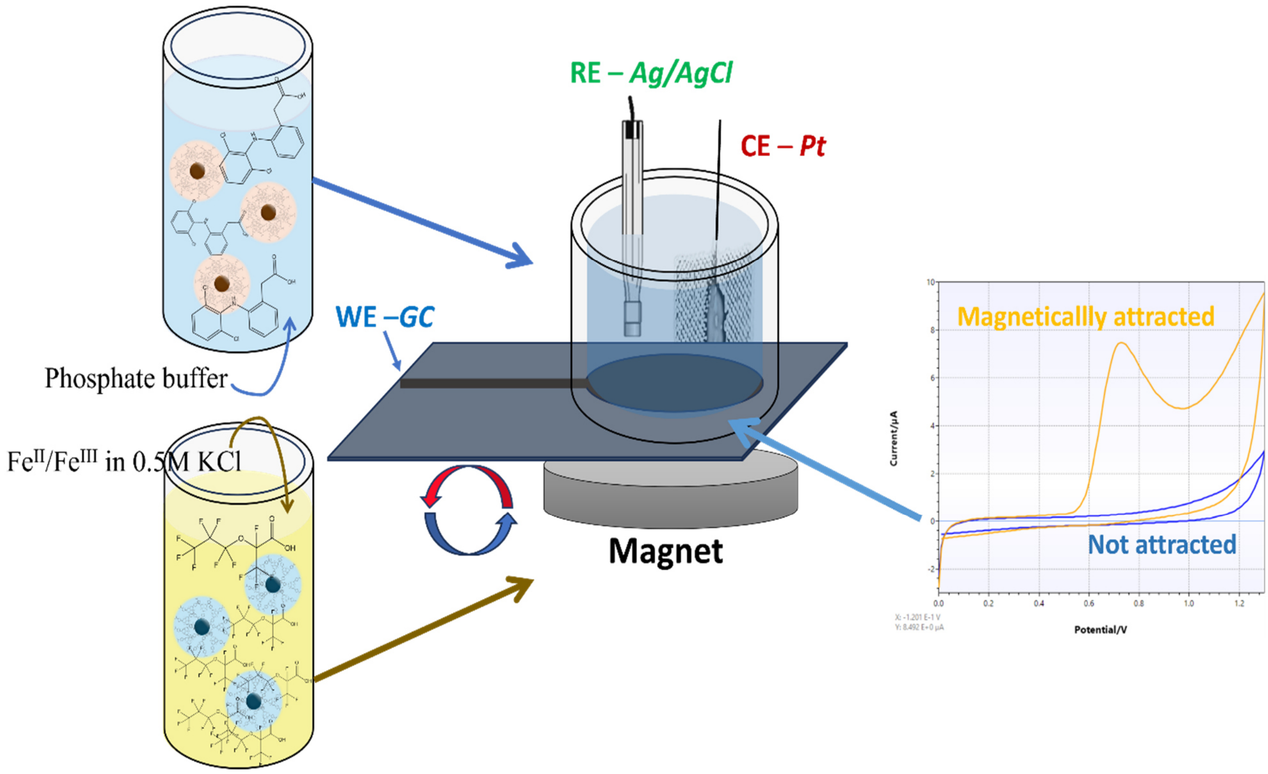


**Figure 3** Schematic diagram of electrochemical measurement

For the realization of experimental work, an specific experimental cell was developed (**Figure 3**). The design of the cell allows the position of created hybrid particles to be controlled by an external field. This makes it possible to control their interaction with the surface of the working electrode in a targeted manner and to capture the analyte after removing the magnetic field.

## 3. RESULTS AND DISCUSSION

### 3.1 Characterization of microrobots

The SEM image in **Figure 4a** shows the microstructure and shape of nanoparticles created before shell layer grafting. The particles are 200 to 400 nm in size and have an octahedral shape. On the right side of the SEM image, we can see $Fe_3O_4$@MOF. The particles are approximately the same size as initial crystals.

In **Figure 4b** shows the evaluation of the presence of organic contaminant from the FTIR spectrum of incubated. It was confirmed that the organic contaminant bound to functional shell layer. In the spectrum, we can observe characteristic pikes for contaminant itself. The pikes representing the vibrations of the -CF and C-O-C groups are located in the wavenumber range of 990, 1038, 1156, and 1219 $cm^{-1}$. In the wavenumber range of 1319 $cm^{-1}$, there is a characteristic band for the vibration of the $COO^-$ group. For clarity, **Figure 5c** shows the FTIR spectra of second MOF containing another organic contaminant. In the wavenumber range of 1450 $cm^{-1}$, a distinct characteristic peak of contaminant is evident and also appears in the FTIR spectrum after the interaction of functional microparticles with contaminated solution. Finally, **Figure 5d** shows Raman spectroscopy spectra, where several characteristic peaks for contaminant.

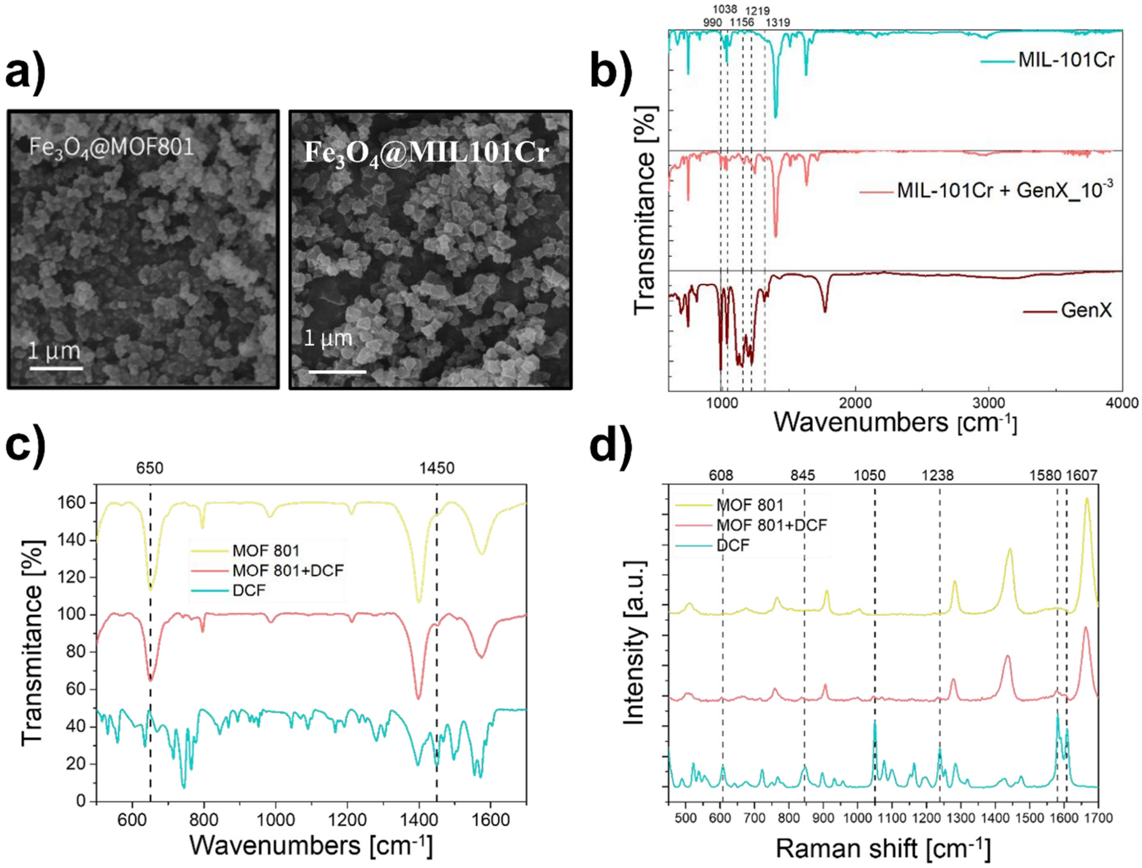


**Figure 4** Characterization of $Fe_3O_4$@MOF(a) and $Fe_3O_4$@MOF(b) a) SEM images, b) FTIR spectra of MOFs c) FTIR spectra of MOF with entrapped pollutant DCF, d) Raman specra

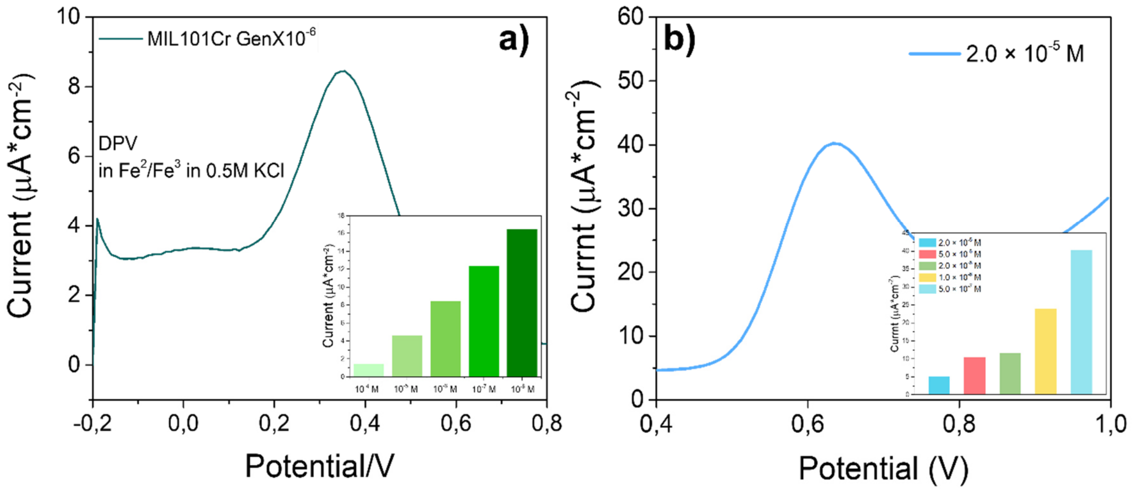


**Figure 5** DPV spectra: a) $Fe_3O_4$@MIL101Cr with adsorbed GenX, b) $Fe_3O_4$@MOF801 with adsorbed DCF

To determine the working sensitivity range of the magnetic microrobots, the electrochemistry was employed. The measurements were carried out in a descending order, starting from the highest concentration of organic contaminants. **Figure 5a** shows the typical measurement results. The apparent electrochemical peak reveals the presence of organic contaminants and its area was founded to be concentration-sensitive, allowing the potential detection of contaminants using the proposed approach.

## 4. CONCLUSION

In this work, hybrid micro-structures composed of microrobot core and functional shell were successfully synthesized and characterized. The resulting materials exhibit high structural stability, strong external responsiveness, and excellent adsorption capacity toward environmental contaminants. These properties enable both targeted manipulation and efficient removal of undesired substances from external environments. The findings demonstrate the potential of hybrid microparticles as intelligent, sustainable materials for purification and contribute to the advancement of next-generation environmental remediation technologies.

## ACKNOWLEDGEMENTS

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