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ABSTRACT

The presence of iron in industrial effluents and water resources has become an important environmental concern, and the development of efficient, cost-effective and reliable sensing platforms for its detection. In this work, a carboxymethyl tamarind kernel gum (CMTKG) modified by phenanthroline was used to prepare a hydrogel based on acrylamide for the selective detection of iron ions. The hydrogel matrix was optimized for a good swelling property and biocompatibility of CMTKG and a strong metal-chelating ability of phenanthroline, so as to improve the sensing property of the hydrogel toward iron.

The synthesized hydrogel was analyzed for its chemical structure, surface morphology and crystalline behavior by Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). The successful modification and formation of the hydrogel network were confirmed by characterization results, which gave suitable active sites for interaction with iron ions. The sensing material developed showed a clear response when exposed to iron ions which could be utilized for the fast and effective monitoring.

The proposed hydrogel-based sensing platform has potential applications in iron detection in industrial wastewater and environmental samples due to its simplicity of fabrication, low cost, and environmentally friendly nature. The study suggests that modified biopolymer hydrogels can be a better tool for sustainable monitoring and management of water quality in industrial effluents.

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LIST OF ABBREVIATIONS AND SYMBOLS

AM- Acrylamide

Phen – Phenanthroline

CMTKG- Carboxymethyl Tamarind Kernel Gum

TG- Tragacanth Gum

PAM- Polyacrylamide

KPS- Potassium persulfate

MBA- N, N'-methylene-bis-acrylamide

g- Grams

mg- Milligrams

rpm- Rounds per minute

ml- Milliliter

FTIR- Fourier Transform Infrared Spectroscopy

XRD- X-ray Diffraction

SEM- Scanning Electron Microscope

Ppm- parts per million

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 INDUSTRIAL WASTE WATER AND HEAVY METAL POLLUTION

The Kashmiri proverb “it is easy to throw anything in the river once it is in, it is hard to take it out again” underlines the importance of water resources and need for prevention of pollution. Civilization, industrialization, and urbanization have all surged in recent years, and there is growing demand for sustainable solutions that can help to improve the health and wellbeing of people and communities. But many activities emit pollutants that can be harmful to the environment and human health. In order for environmental sustainability to be achieved, effective pollution control systems and advanced pollution treatment technologies are needed. Water is considered one of the universal solvents, and it is widely used in different applications. the generation of industrial wastewater with hazardous substances, mainly heavy metal, is produced in large volumes from industrial activities [1]. The most common sources of heavy metal pollution in aquatic systems include industries, batteries textile processing and tanning etc. major sources of heavy metal to water are direct industrial discharge, accidental spills and leakages, corrosion of pipelines and deterioration of metal equipment. these are polluting materials that do not break down easily and dissolves in water and build up for the nature over time. this inorganic makeup and tendency to form stable compounds makes them readily transported through aquatic systems. The metal generally considered to be heavy metal have densities of more than 4.5g/cm3. The most frequent heavy metals are lead, mercury, cadmium and iron, which are known to be highly harmful to nature and human health [2]. Heavy metals

are present everywhere in the nature and occur in the air, soil and aquatic nature mainly due to industrial emissions, mining and waste disposal. Because they enter into the food chain via inhalation, ingestion, or direct physical contact, there are significant health concerns. Exposure to high levels of heavy metals can cause harmful effects such as growth and development retardation, organ damage and even death [1,3]. With increasing awareness of the harmful effects of heavy metals, there has been a lot of research on how best to treat wastewater. Heavy metal removal using treatment process such as adsorption, flotation and electrochemical process. But they have major drawbacks such as less efficient in highly acidic wastewater, lower performance of removal efficiency and too much sludge formation [3]. In order to reduce these shortcomings, new treatment technologies have become more popular. these new technologies can often provide more efficient, sustainable and cost-effective solutions compared to conventional technologies [3].

1.2 IRON CONTAMINATION AND ITS ENVIRONMENTAL IMPACT

Iron is a naturally occurring metallic element and is one of the most abundant elements presents on earth. It plays an essential role in biological systems and industrial applications due to strength, conductivity and chemical properties [5]. Iron often grouped under heavy metals because it possesses relatively high atomic weight and density compared to lighter elements. Its excessive concentration becomes harmful as it accumulates in water and soil [3,5].

1.2.1 SOURCES OF IRON CONTAMINATION

Iron is the most plentiful elements in the earth's is seldom found in its metallic state and is usually associated with another metallic compound. Of this iron oxides are of special significance for the nature. The chemical form of iron in water largely depends on oxygen

availability in the absence of oxygen iron is mainly in the ferrous form (fe+2), which is highly soluble in water[4]. Oxygen rich nature, on the other hand would oxidize ferrous ion to ferric ion, a less soluble state that is very easily converted to ferric hydroxide. This precipitation is often manifested as the typical reddish brown, orange. yellow staining found on water with an iron component. Ground water that has limited oxygen and great sources of iron often have high levels of dissolved ferrous ion that will quickly [5].

Results of iron contamination are rusting of sinks (kitchen, wash basin), metallic taste of water, clothes damaged during washing. Though iron is important for biological functioning, excess may cause more harm to body and home [6].

Source of iron pollution:

Iron enters your water supply in several ways

1)Pyrite in coal reacts with air and water during mining, producing sulfuric acid and releasing iron into the water. In flooded, low-oxygen mines, the iron stays dissolved, so the water looks clear. When the water reaches the surface and mixes with oxygen, the iron forms solid particles that turn the water yellow, orange, or red and leave deposits. The same thing can happen with iron-rich well water when it is exposed to air [3].

2)Corroded Pipes: Older plumbing systems often contain iron pipes. Over time, these corrode and release iron particles into your water [4]

3)Industrial Pollution: In some regions, industrial discharge contributes to higher levels of iron in surface or groundwater sources.

1.2.2 OCCURRENCE AND ENVIRONMENTAL IMPACT OF IRON IN INDUSTRIAL WASTEWATER

The iron and steel industry is a major contributor to industrial waste generation worldwide. Significant amounts of by product including sludge, dust and mill scale are generated at every stage of the raw material processing[6]. Apart of these wastes can be recycled and reused in various process like sintering and production converter, however a major part is deposited in disposal sites, sedimentation ponds and landfills. These wastes may contain hazardous materials such as lead, zinc and oils which can have potential environmental impacts. Iron is crucial for a variety of processes in human body such as oxygen transport, cellular metabolism and enzymatic activity. but over exposure to iron, especially from drinking water sources, had adverse health impacts[7]. several chronic metabolic diseases such as type 2 diabetes mellitus, obesity, on alcoholic fatty liver have been linked to high iron levels. Impaired glucose and lipid, metabolism including the pancreases, liver, muscles and adipose tissue may be adversely affected by iron overload and could be factors in the developmental of complications from chronic diseases. because of its prooxidant activity iron is tightly regulated in humans with lots of proteins and hormones that control it such transferrin, ferritin etc[6,7]. These regulate the absorption, storage and excretion of iron. So, it is recommended that iron levels must be monitored regularly, especially in people with chronic metabolic disorders. Iron contamination can have profound impact on aquatic eco system in addition to their impacts on human health. The precipitation and settling of ferric hydroxide and iron organic matter on the biological surface and stream beds can interfere with normal physiological processes of aquatic organisms[8]. It disrupts osmoregulation, and impact benthic habitat structure and quality. Iron cycling is well influenced by the variation of physical chemical and biological processes throughout the seasons; therefore,

details study from both spatial and temporal perspective is necessary to properly determine its effect on aquatic ecosystem and environmental health[9].

1.2.3 NEED FOR MONITORING AND DETECTING IRON IONS

Iron is an important element for living organisms and industrial processes, however, high concentrations of iron ions in water and environment could cause serious ecological, industrial and health-related problems. Thus, it is important to monitor and detect iron ions accurately and continuously [10]. Elevated concentrations of iron in drinking water may cause an unpleasant taste and staining of household fixtures, and, in extreme cases, health problems such as iron overload disorders. The water has to be tested on a regular basis to ensure that it is safe and healthy. Therefore, the development of sensitive, rapid, inexpensive and selective methods for the detection of iron ions has become more and more important for environmental monitoring, water quality assessment and public health protection[11].

1.3 HYDROGEL BASED SENSORS

In order to detect heavy metals, several advanced methods were available which includes atomic absorption spectroscopy, EDX, and ICP-MS, they all require costly equipment. These are intricate, time-consuming procedures that require strong operational skills[12]. As a result, there is a strong need for an easy-to-use, affordable solution based on simplicity, affordability, sensitivity, and selectivity for many analytes. Therefore, colorimetric sensing stands out a widely used facile technology, it is a technique that respond to environmental stimuli by changing color visible to the naked eye. Several fluorescence probes were employed to detect heavy metal ions in the literature accessible at the time like calcein, fluorescein-based probes, phenanthroline based probes etc[13]. These show good design for sensing and thermal stability.

However, these methods have drawbacks such as high cost, poor stability, low cost, high efficiency, and broad applicability. Therefore, there is need for materials which overcomes these challenges. Some of them are piezoelectric materials, electroactive polymers, shape memory alloys, hydrogels, etc. Among all, hydrogel emerged as a groundbreaking material with unique properties such as biocompatible, facile synthesis method, and cost effective[14].

1.3.1 INTRODUCTION TO HYDROGELS

Hydrogels are three-dimensional (3D) networks, often of polymers, able may ingest huge amounts of water. The hydrogel network is produced by covalent bonds or noncovalent interactions[14]. Various synthetic and natural polymers like polyacrylamide, poly (vinyl alcohol), polypeptides, polysaccharides and DNA have been widely investigated to generate hydrogels with desirable features[15].it has many physiochemical qualities linked with strength ,conductivity ,toughness, elasticity ,self-healing ability and as a sensing material .Therefore ,they have the capability for biosensing the substance ,they employed as self-healer as they have the potential to self-heal the wounds. Hydrogels are increasingly being used in different applications[16]. Biomedical applications of hydrogels include cartilage tissue regeneration, boronic ester cross linking hydrogels, interpenetrating polymer network hydrogels, peptide hydrogels, the use of sticky hydrogels in accelerated wound healing and corneal stromal defect healing[17].

1.3.2 HYDROGEL BASED BIOSENSOR FOR ENVIRONMENTAL MONITORING

The proposed bio sensor is the hydrogel-based sensor which detects environmental contaminants by measuring the change in its optical property. Hier has been a great interest in sensor capital of

detecting biological responses and converted them into detectable signal in recent year. Sensor derives a measurable signal based on chemical reaction by combining biologically active components with appropriate transducers[18]. Hydrogels are physically non covalent contacts and \or chemically covalent compounds ,crosslinked three dimensional water soluble structure .these smart materials are biocompatible but are expected to progressively undergo integration biosystem with harmful consequences[19] .their ability to interact with biological components at the molecular level, regulates viscoelastic properties react to method for incorporating bioreceptors into their highly wet structure are just a few of the features that have made them popular for biosensing applications[20].

The biological events that can be detected by hydrogel-based sensors and can be done by two approaches. Hydrogel without bioreceptors whose swelling properties change with some specific biological interactions.in this group a large portion of the research. With appropriate change in the ionic change strength of the outside aqueous biosystem ,ph. sensitive gel are able to take up or release protons[21].in the both cases ionized ionic hydrogels enhance electrostatic repulsions between polymeric chains will lead to a negative or positive swelling ratio. The same condition has been found with polyelectronic gels in reaction to an electric field. the swelling and deswelling process are caused by the electric fields in density[22].

CHAPTER 2

MATERIALS AND METHODS

2.1 MATERIALS AND INSTRUMENTS

To achieve this objective biopolymer CMTKG as a biopolymer was utilized which is obtained from indigenous plant named *Tamarindus Indica* commonly named as Imli Tree. Polyacrylamide is used to enhance strength of the synthesized matrix. As a result, we created a "phenanthroline modified Carboxymethyl tamarind gum/Polyacrylamide" (Phen/CMTKG/PAM) biopolymeric hydrogel composite and used it as a colorimetric biosensor. Furthermore, it was employed in industrial waste to test its effectiveness in real-time applications. CDH (India) supplied potassium persulfate. Phenanthroline was acquired from Thermo-Fischer in India. Hindustan Gum and Chemicals Ltd., Haryana (India) provided a carboxymethyl formulation of tamarind gum (CMTKG) with Feso4 salt. Merck, Germany supplied N, N'-methylenebisacrylamide (MBA) and acrylamide (Aam). All of the solutions used were produced using distilled water. To ensure the synthesized sensor's repeatability, the trials were repeated three times. A Shimadzu UV 1900i Spectrophotometer was used to get the UV-visible spectra. An FTIR spectrophotometer (Model: Nicolet iS50 FTIR) was used to gather the FTIR spectra, which were recorded between 4000 and 400 cm-1. Cu Kα radiation with k = 1.54 Å was used in a high-resolution XRD D8 Bruker model to analyze PXRD patterns of the generated material. PXRD patterns were recorded at a scan rate of 1.0 s per step and a step size of 0.02º. The investigation was conducted between 2θ = 5-70º at 298 K. A JEOL SEM was used to examine the SEM morphology.

CHAPTER 3

EXPERIMENTAL SECTION

3.1 SYNTHESIS

3.1.1 SYNTHESIS OF CMTKG/PAM HYDROGEL AND PHENANTHROLINE INCORPORATED CMTKG/PAM HYDROGEL COMPOSITE

A homogenous solution was created by dissolving 0.3 g of CMTKG in 15 mL of distilled water and stirring the mixture. After agitating 1.0 g of acrylamide (AM) for 25 minutes, 0.05 g of KPS, an initiator, was added. The crosslinker, 0.050 g MBA, was then added, and the mixture was rapidly agitated for 30 minutes to create a homogeneous solution. To the aforesaid solution, 10 mg of phenanthroline was also added. water. The reaction mixture was put into the test tube and kept in the water bath at 55 °C for 40 minutes after being agitated until a homogenous solution was obtained. Test tubes were then broken and sliced into bits in order to extract the acquired product. The product was dried at 40 °C in the oven to get the dried hydrogel pieces. The obtained product was pale yellow in color as represented in Scheme 1. Similarly, control hydrogel (CMTKG/PAM) was also made without addition of phenanthroline.

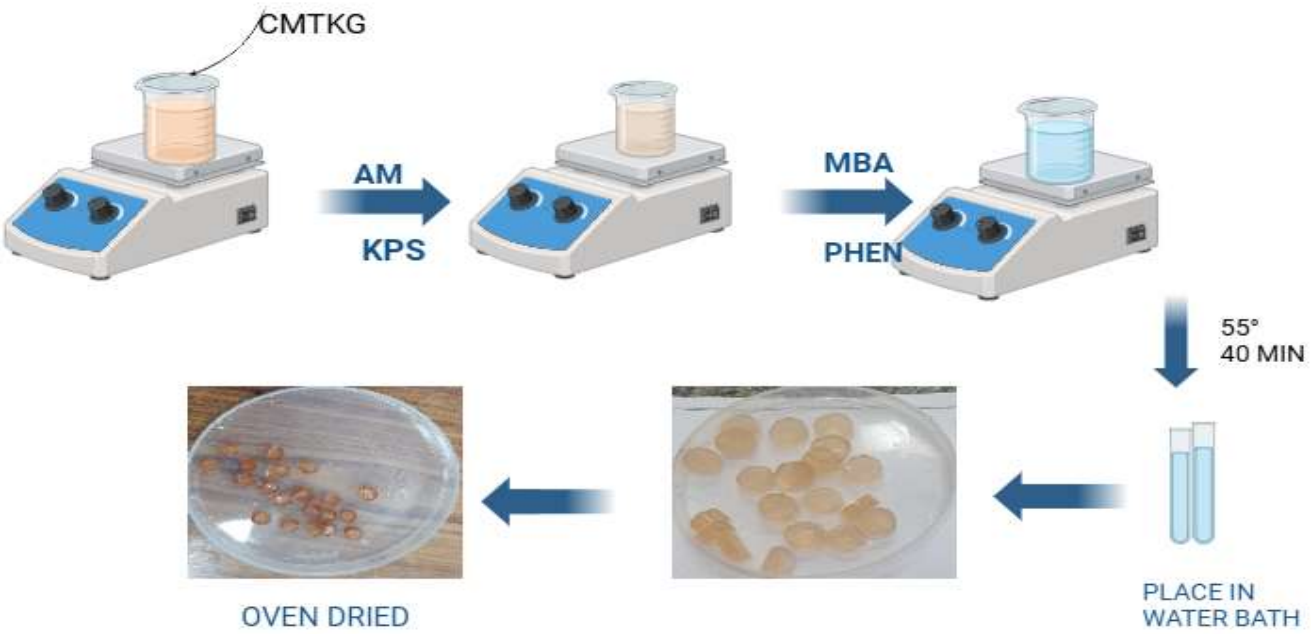


Figure 1. Synthesis of CMTG/PAM/Phen hydrogel composite

3.1.2 SYNTHESIS OF PHENANTHROLINE

Phenanthroline is an organic ligand with restricted water solubility because of its somewhat hydrophobic aromatic structure[23]. Consequently, it was discovered that the best solvent solution for dissolving phenanthroline and promoting its integration into the hydrogel matrix was a constant ratio of 1:1 of water[24]. Phenanthroline was then effectively incorporated into the hydrogel matrix based on biopolymers. The effective inclusion of phenanthroline was confirmed by the pale orange hue of the produced hydrogel. Thus, the synthesis of the phenanthroline-loaded CMTKG/PAM biopolymeric hydrogel was accomplished.

3.1.3 Sensing studies

A synthetic hydrogel containing phenanthroline was used in the sensing investigation to determine if iron was present in aqueous environments. Alkali metal salt and alkaline earth metal salt solutions may be detected and scanned by the phenanthroline-incorporated hydrogel. Time, temperature, and the synthesized hydrogel's concentration-dependent sensitivity are only a few of the variables in this investigation. A study was carried out to determine how the synthesized sensors were affected by pH and the concentration of employed metal ions. Additionally, the sensor was used to detect metal ions in effluent from industries. Every experiment used in this investigation was carried out three times.

CHAPTER 4

RESULT AND DISCUSSION

4.1 CHARACTERISATION

4.1.1 FTIR

FTIR spectroscopy then used to investigate the interaction between hydrogel matrix and its composition. The OH and NH overlapping stretching vibration bands at 3332 cm^{-1} and 3184 cm^{-1} observed in Phen/CMTKG/PAM hydrogel composite ,and bands observed at 3339 cm^{-1} and 3191 cm^{-1} in CMTKG/PAM hydrogel indicated that CMTKG/PAM hydrogel shows strong hydrophilicity of cross linked polymer structure ,which is due to the vast network of hydroxyl group[] .The carbonyl group are confirmed by the strong and sharp peak at 1651 cm^{-1} in

PHEN/CMTKG/PAM hydrogel composite at 1600 cm^{-1} in CMTKG/PAM hydrogel. FTIR absorption spectrum of the hydrogel composite with added phenanthroline showed that the main structure of the hydrogel backbone was not affected by the addition of phenanthroline, since the spectrum absorption bands that were originally present in the control hydrogel (CMTKG/PAM) remained the same. There were, however, some changes in the band position for each of the bands, indicating a possible interaction between phenanthroline and the hydrogel matrix. In particular, the bands which appear in the fingerprint region at about 1091 $cm^{-1}$and 1099 cm^{-1} are generally assigned to C-O-C or C-O bending vibrations [27]. No significant changes or new peaks are observed in the typical peaks of hydrogels, suggesting that phenanthroline is physically contained in the polymer matrix. This implies that the loading mechanism probably depends on weak non-covalent interactions, like hydrogen bonding or electrostatic interactions, instead of on covalent bond formation.

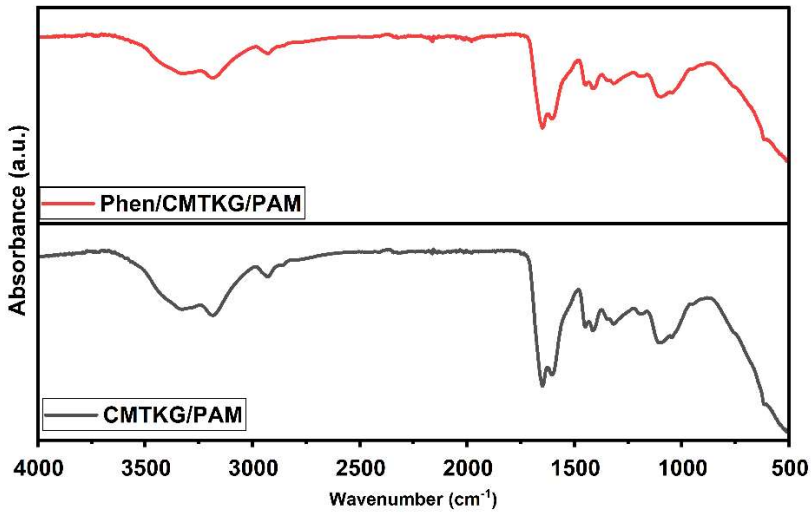


Figure 2. Plot for FTIR of control (CMTKG/PAM) hydrogel and Phen/CMTKG/PAM hydrogel composite

4.1.2. SEM

SEM micrographs of the CMTKG/PAM hydrogel and Phen/CMTKG/PAM hydrogel composite are displayed in Figure 3. The surface of the CMTKG/PAM hydrogel was found to be somewhat uneven, rough, and porous [13]. While roughness and visibility were found to be decreased in Phen/CMTKG/PAM hydrogel due to the insertion of phenanthroline into the polymer matrix.

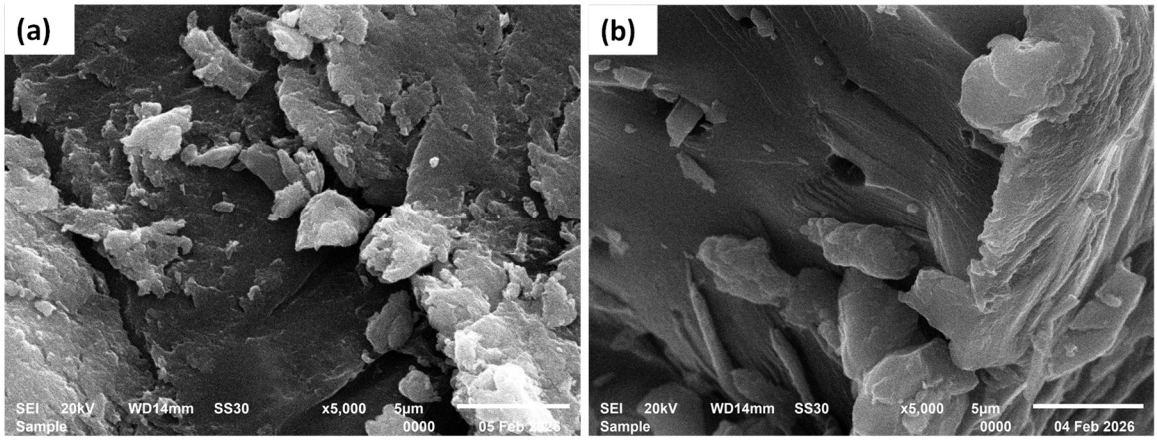


Figure 3. Plot for Surface morphology of control (CMTKG/PAM) hydrogel and Phen/CMTKG/PAM hydrogel composite

4.1.3 XRD

To check the crystallinity of the fabricated hydrogel network, XRD was performed. The XRD pattern was examined for Fe-Phen/CMTKG/PAM hydrogel composite and Phen/CMTKG/PAM hydrogel, as depicted in Figure 4. The Fe-Phen/CMTKG/PAM hydrogel composite and Phen/CMTKG/PAM hydrogel exhibit a broad peak range from 20° to 22°, suggesting their amorphous nature. While the diffraction patterns observed from 29° to 32° have slightly less intensity in Fe-Phen/CMTKG/PAM hydrogel composite, suggesting that incorporation of iron reduces its crystallinity. No other peaks were observed after the insertion of iron during sensing, suggesting that it is uniformly bound to the matrix. Additionally, CMTKG/PAM hydrogel shows an amorphous nature of the hydrogel matrix, as studied by our group [12].

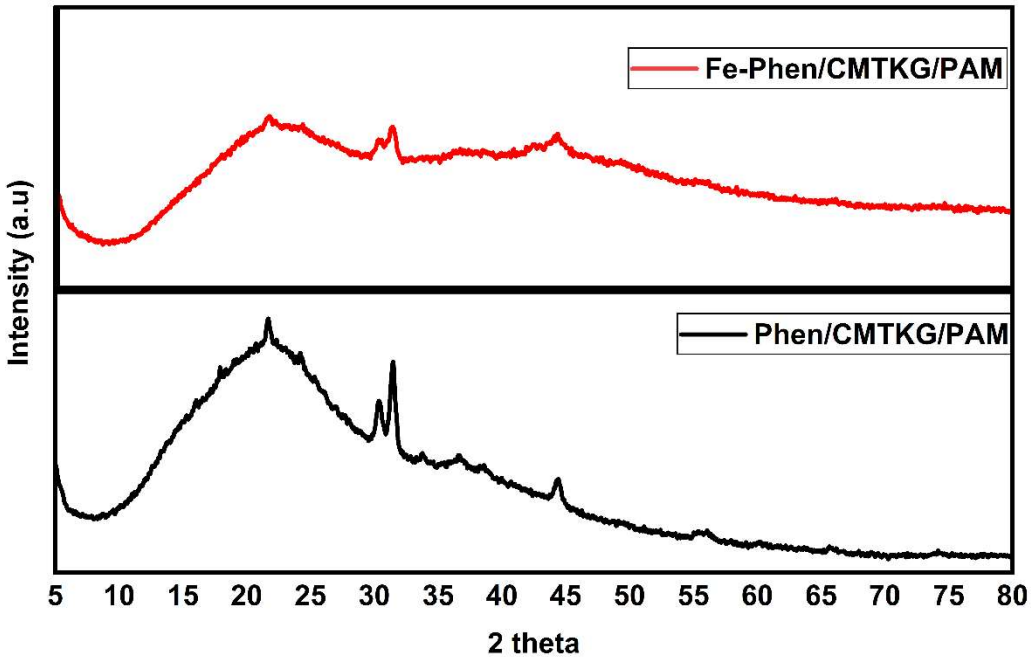


Figure 4. Plot for XRD of Phen/CMTKG/PAM hydrogel and Fe-Phen/CMTKG/PAM hydrogel

4.2 SENSING STUDIES

Our primary objective is to create a biosensor capable of detecting Fe metal ions in aqueous solutions. This metal ion is largely spectroscopically quiet, making detection difficult [24]. To get around this hydrophobicity, we have created a simple route between the hydrogel matrix and the organic moiety phenanthroline. The hydrogel that was created had a light orange hue. The sensing capacity in aqueous medium was then assessed using the synthesized phenanthroline-modified CMTKG/PAM hydrogel. This was accomplished by incubating the synthesized probe at 100 rpm in a preset concentration of metal salt. Following metalation, the modified hydrogel's color altered, as seen in figure 5a.However, heavy metals frequently coexist with other alkali, alkaline metal salts, and metal ions in water systems. As a result, it is now essential and difficult to identify

dangerous heavy metals that are spectroscopically quiet [26]. When the influence of coexisting ions was investigated, it was found that the produced hydrogel probe did not exhibit any discernible color change as a result of interfering ions. The produced hydrogel may be in charge of trapping metal ions in the hydrogel matrix even if the polymer-based hydrogel matrix contains a polar group. However, on-site detection cannot be examined with the unaided eye. According to this study, the synthesized probe's color changed after interacting with ferric ions, making it possible to employ the sensor for on-site inspections .When phenanthroline is encircled by other metal ions, it is specifically bonded to them, which may result in a color shift [26]. Therefore, even when other metal ions are present, the produced hydrogel may be utilized as a "sensor" to determine the ferric ions.

Sensing tests for CMTKG/PAM hydrogel (control) were also conducted. The experiment was carried out under identical conditions to verify the sensing of ferric ions in aqueous media via CMTKG/PAM hydrogel, and it was found that no color change was visible to the unaided eye, as shown in Figure 5b.

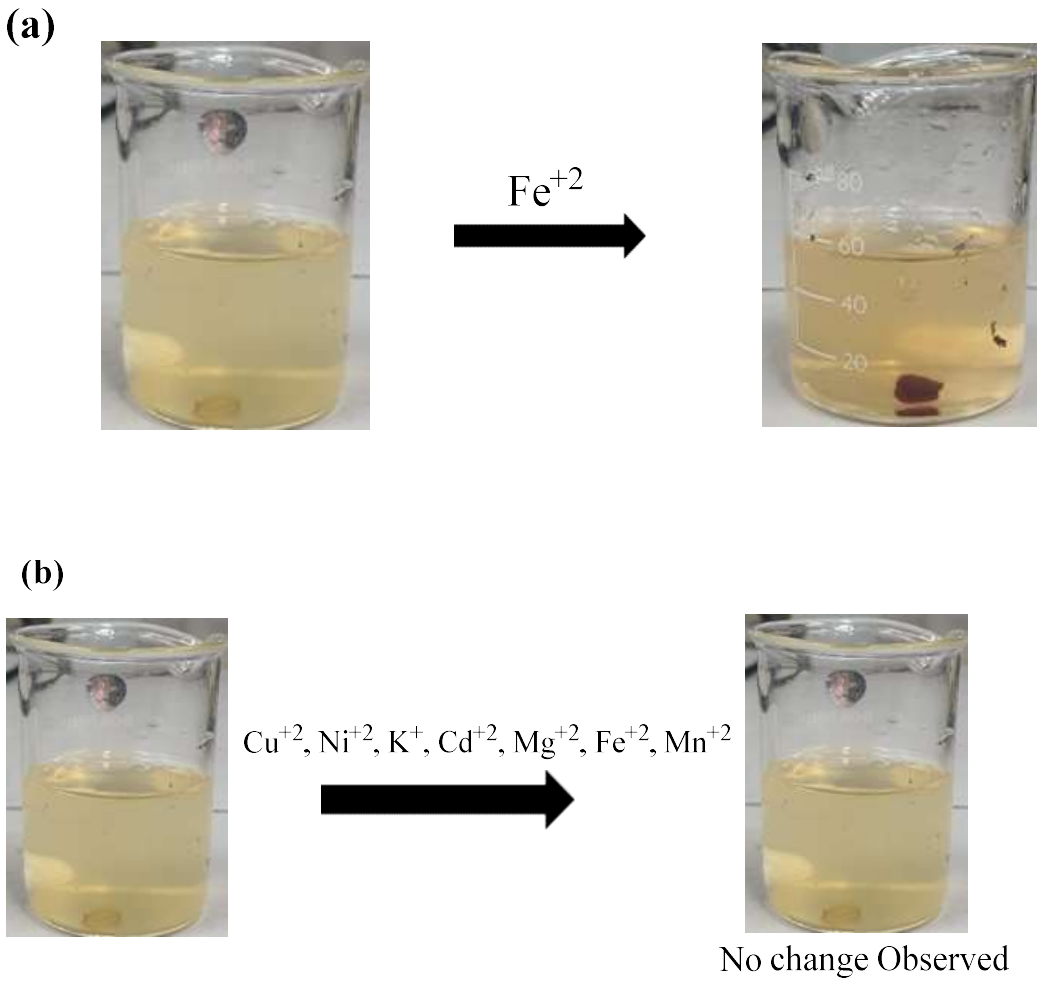


Figure 5. Plot for **(a)** sensing of iron from aqueous media using Phen/CMTKG/PAM hydrogel composite and **(b)** impact of sensing on other ions using control (CMTKG/PAM) hydrogel

4.2.1 IMPACT OF SENSING TIME

The color shift over time has been used to assess the sensor's selectivity. The sensor has no discernible impact in basic or acidic environments and, once metalated, cannot be undone. A piece of hydrogel was immersed in a test tube containing a solution containing different amounts of metal ions. Modified hydrogel immersed in 50 mg L-1 of Fe+2 ions was found to exhibit

alterations in 600 seconds at 33°Cand in 52 sec at 60 °C the time for sensing in Fe^{+2} ion (50 mg L^{-1}), showed changes in 20 sec at 33°Cand 5 sec at 60 °C as shown in table 1, respectively.

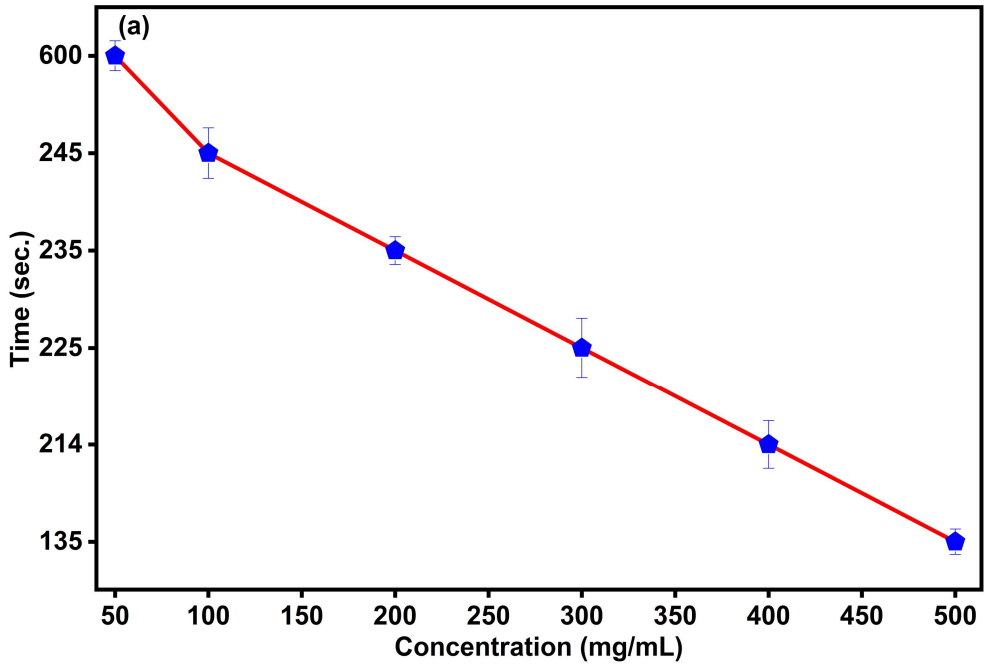
Table 1. Impact of sensing time at different temperatures

Test Performed	**Solvent (mL)**	**Amount of synthesized Probe (mg)**	**Speed (RPM)**	**Time(h) of the color change of hydrogel at 33℃**	**Time(h/min) of the color change of hydrogel at 60 ℃**
H_2O	50	30	200	No change	No change
$FeSO_4$(50 ppm)	50	30	200	600 s	52 s
$FeSO_4$(0.05M)	50	30	200	20 s	5 s

4.2.2 TEMPERATURE AND CONCENTRATION DEPENDENT STUDY

We conducted a study to investigate the color change of the synthesized sensor in order to clarify the impact of temperature on a fixed concentration of metal ions. At

a constant temperature of 30°C and a fixed concentration of 50 ppm, color changes were observed in 10 minutes for 100 ppm, 4 minutes for 200 ppm, 3 minutes and 55 seconds for 300 ppm, 3 minutes and 40 seconds for 300 ppm, and approximately 3 minutes for 400 ppm and 500 ppm. Additional research was done to see how the temperature affected the sensing time at different Fe concentrations. t was shown that the hydrogel needs more time to detect metal ions in low concentrations but less time for high concentrations, and that the sensing time reduces as the solution's temperature rises. As a result, in aqueous solutions, the detection time lowers as temperature and metal ion concentration rise



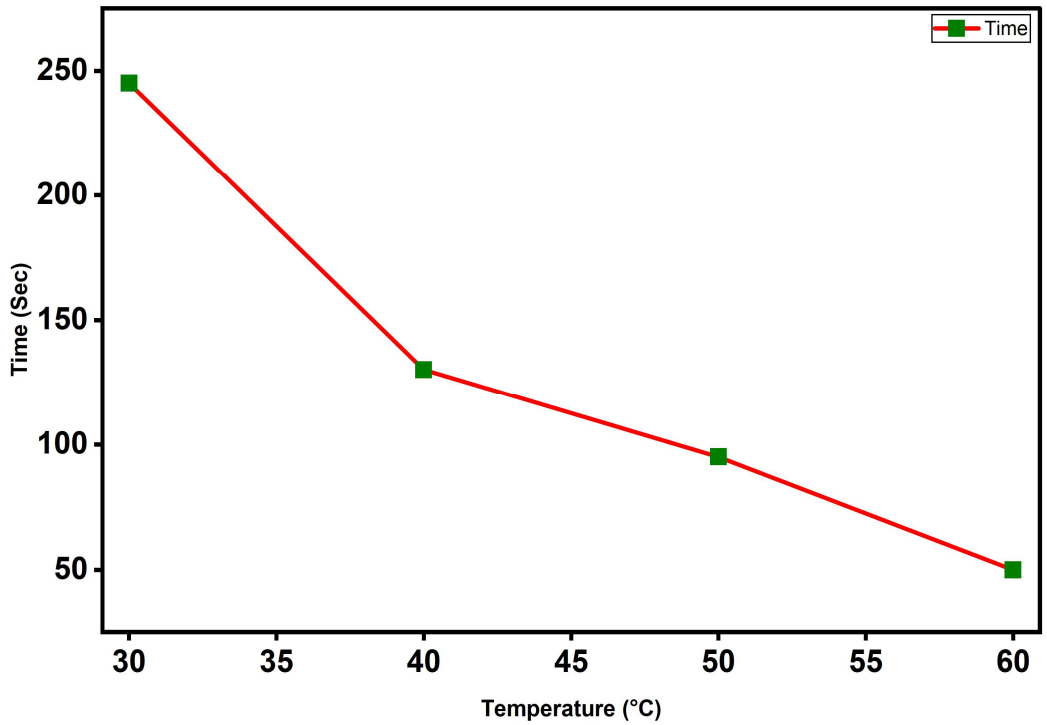


Figure 6. Plots of (a) concentration vs time (b) temperature vs time

4.2.3 SELECTIVITY AND COEXISITING IONS INTEFERANCE STUDIES

Additionally, research was conducted to determine how the concentration of metal salts affected the synthesized sensor. Metal salts were generated in an aqueous solution at varying concentrations (50 ppm to 500 ppm) in order to carry out this investigation. The time needed for sensing reduces as metal ion concentration rises from 50 ppm to 500 ppm, indicating an inverse relationship between metal ion concentration and sensing time. A preset quantity of metal salt solution (50 mg L-1) was employed to examine color change in the hydrogel in order to clarify interference caused by alkaline, alkali, and other metal ions. In order to examine the produced hydrogel, a number of heavy metal ions, such as Cu+2, Ni+2, K+, Cd+2,

Mg+2, and Mn+2, were added to the aqueous solution. There will be no change in the color of ferric ions as shown in figure 7.

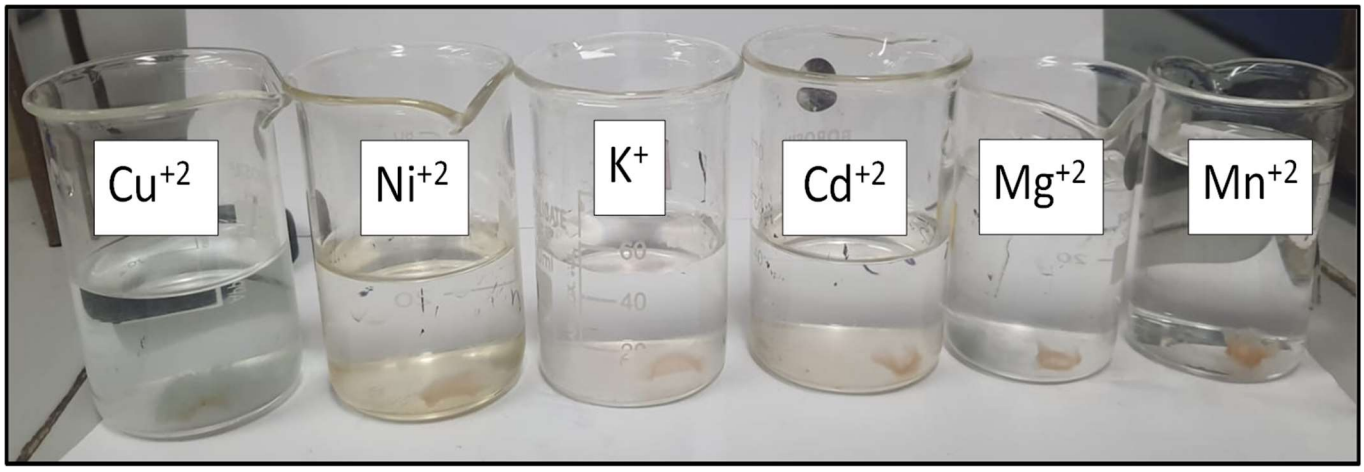
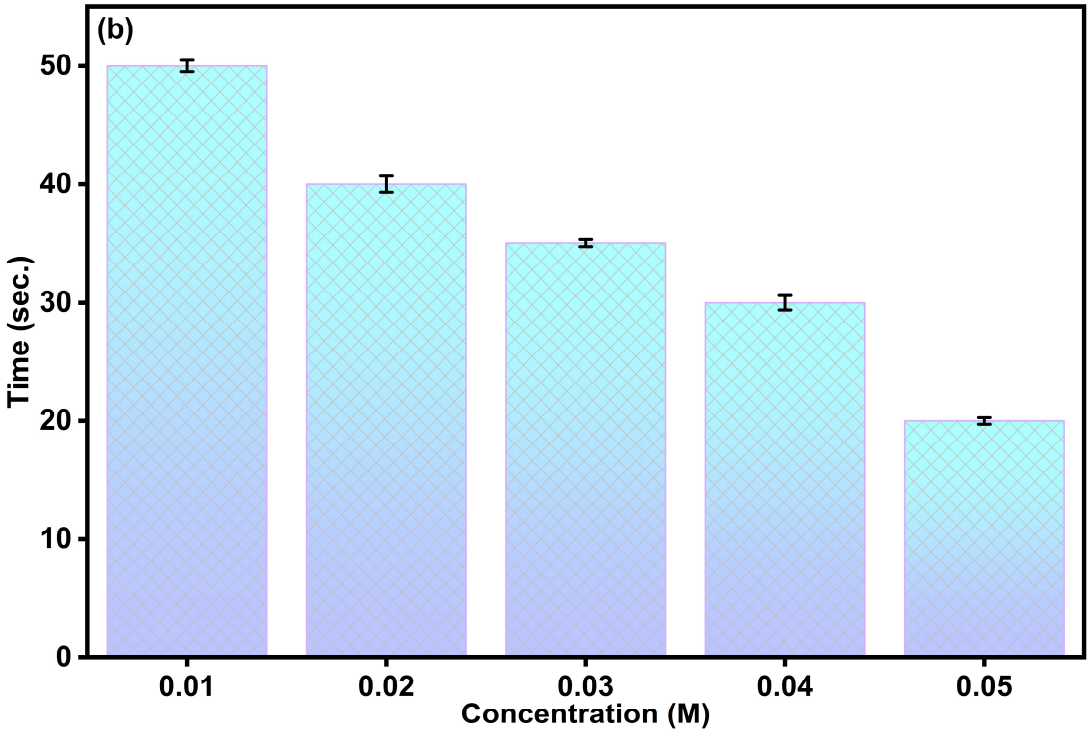


FIGURE 7. DIFFERENT IONS INTERFEANCE STUDIES

4.2.4 IMPACT OF PH AND CONCENTRATION OF METAL ION

The research was carried out to check the effect of pH on the probe. Several pH solutions were made between the range of pH 2 and 10. The effect of the colorimetric response of the hydrogel in metal salt solutions (ferric ions) at various pH 2-10 solutions was then examined using the synthetic hydrogel as a probe. A change in color was observed in all the pH solutions, but the results were somewhat better at around pH 5-7. This could be attributed to the absence of protonation of the acidic groups in the hydrogel matrix and the absence of hydroxides formation for the metal ions in this pH range. Additionally, a research was conducted to determine how the concentration of metal salts affected the synthesized sensor. Metal salts were generated in an aqueous solution at varying concentrations (50 ppm to 500 ppm) in order to carry out this

investigation. The time needed for sensing reduces as metal ion concentration rises from 50 ppm to 500 ppm, indicating an inverse relationship between metal ion concentration and sensing time.



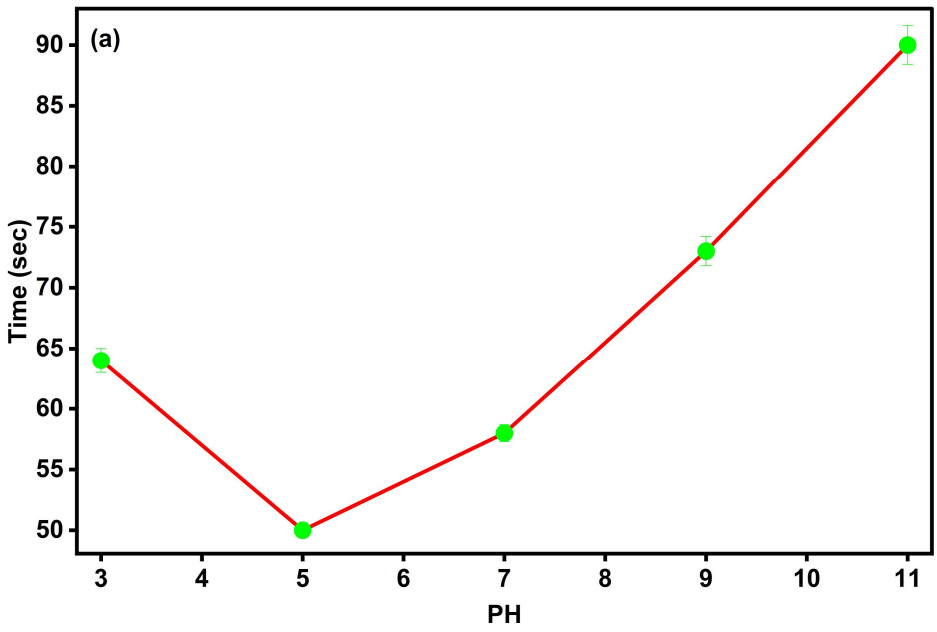


Figure 8. Impact of metal ion PH and concentration

4.3 MECHANISM

In this research article, we aim to sense Fe^{+2} in aqueous media using a Phenanthroline-based hydrogel matrix. Phenanthroline is an organic moiety that is insoluble in water and is responsible for sensing of Fe^{+2} [29].To overcome the insolubility constraint of phenanthroline, a CMTKG/PAM hydrogel matrix was used. Using a free radical process, the Biopolymer CMTKG offers a hydrogel matrix that is both affordable and biocompatible. As shown in Figure 2, the CMTKG is made up of the D-form of xylose, galactose, and glucose units in a ratio of 2:1:3. It has hydrophilic groups in its structure that are in charge of water retention, PAM gives the matrix strength, and phenanthroline is an organic moiety used as a filler in the hydrogel matrix. The N group in the phenanthroline ring bonds with the metal in solution (Fe+2) when the phenanthroline-embedded CMTKG/PAM is immersed in a salt solution, changing the color from pale yellow to red.

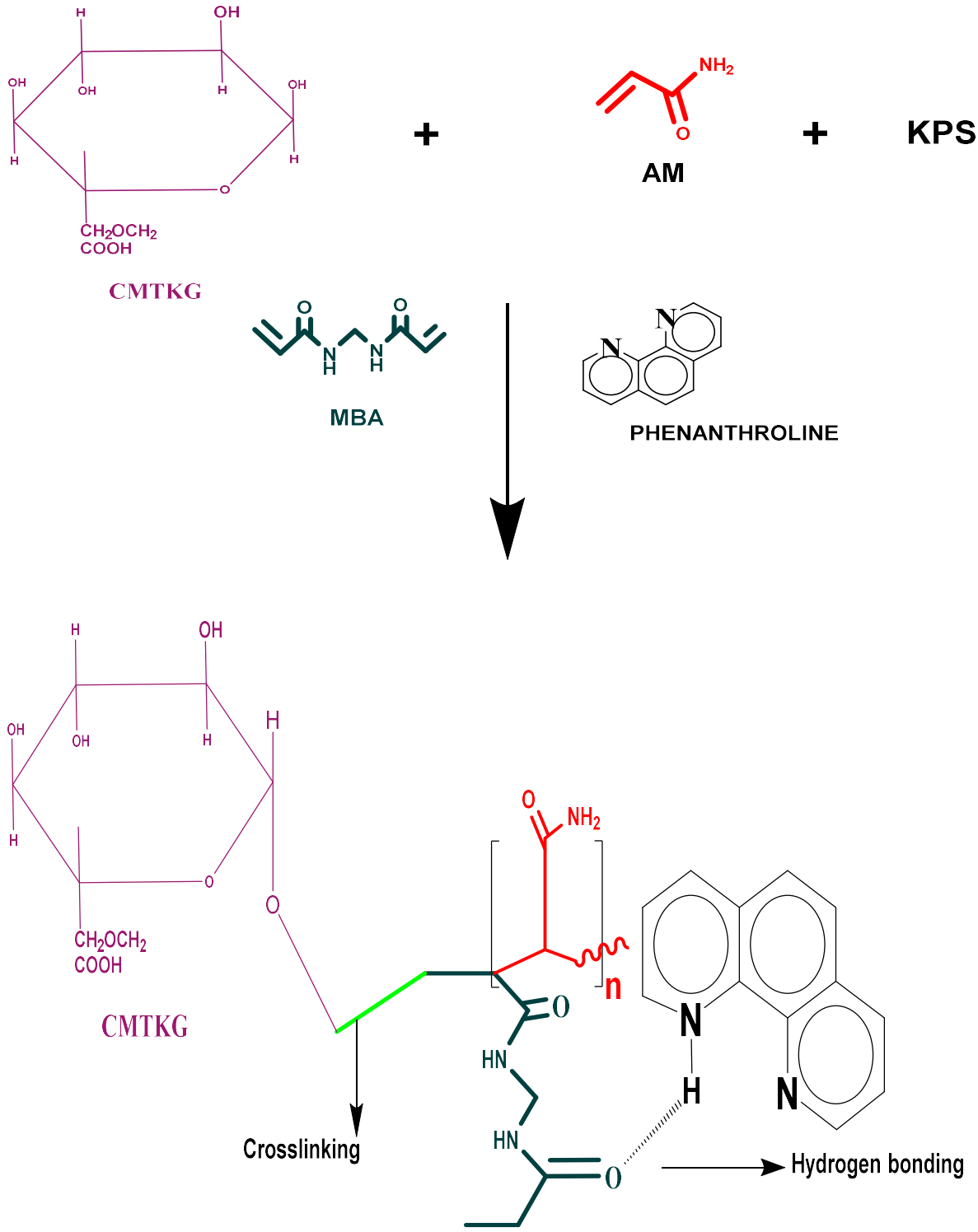


Figure 9. Probable mechanism for Phen/CMTKG/PAM hydrogel composite

CONCLUSION

The current work effectively produced a Phen-modified CMTKG/PAM hydrogel composite as a simple and efficient colorimetric sensor for the identification of iron ions from aqueous solutions. Phenanthroline was incorporated into the CMTKG/PAM hydrogel network to provide active binding sites for iron, while the CMTKG/PAM matrix offered a hydrophilic, stable, and biopolymer-based platform for sensing in water. The hydrogel composite showed a clear colorimetric response in the presence of iron ions due to the formation of an iron–phenanthroline complex, confirming its potential as a visual sensing probe.

The sensing performance was found to be more effective under lower pH conditions, where iron ions remain more soluble and easily available for interaction with phenanthroline. The hydrogel sensor showed good sensitivity, selectivity, and practical applicability for detecting iron ions in aqueous samples. Overall, the Phen/CMTKG/PAM hydrogel composite can be considered a cost-effective, eco-friendly, and easy-to-use biopolymer-based sensing platform for the colorimetric detection of iron ions in aqueous media. The combination of biopolymer-supported hydrogel structure, good water retention ability, and strong iron–phenanthroline interaction makes this hydrogel composite as a promising material for environmental monitoring and water quality analysis.

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