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# Exploring Gelatin Film an Eco-Friendly Biomaterial: Synthesis, Characterization, and Environmental Applications

Nikita Bhardwaj[1], Vijaya Majumdar[2], Jaya Maitra[3,*]

***Abstract***

*This study explores the synthesis, characterization, and application of eco-friendly gelatin films, a sustainable and biodegradable biopolymer alternative to synthetic plastics. Synthesized via solution casting and characterized by UV-Vis spectroscopy, FTIR, and TGA, these films demonstrated excellent molecular integrity and thickness-dependent properties, with higher gelatin concentrations leading to thicker films and delayed solubility. The research highlights their significant potential in removing diverse environmental pollutants, including dyes (methylene blue, methyl orange), $CuSO_4$, $KMnO_4$, and treating hard water. Adsorption efficiencies, quantified via UV-Vis spectrophotometry and titrimetric methods, showed over 80% removal within four hours, with data fitting both Freundlich (for metal ions) and Langmuir (for dyes, $R^2 \approx 1$) isotherm models. Statistical validation via ANOVA confirmed consistent adsorption across metal ions, demonstrating non-significant variations. Despite their high efficacy, the films' primary limitation was their solubility, restricting study duration to four hours, and future research will focus on cross-linking and biopolymer blending to enhance stability and durability, solidifying gelatin films as a promising, green solution for water purification.*

**Keywords:** Adsorption, ANOVA, environment, film, gelatin, titration

***Author for Correspondence**
Jaya Maitra
E-mail: jaya@gbu.ac.in

[1]Research Scholar, Department of Applied Chemistry, University School of Vocational Studies and Applied Sciences, Gautam Buddha University, Greater Noida, Uttar Pradesh, India
[2]Professor, Swami Vivekananda Yoga Anusandhana Samsthana, Bangalore, Karnataka, India
[3]Assistant Professor, Department of Applied Chemistry, University School of Vocational Studies and Applied Sciences, Gautam Buddha University, Greater Noida, Uttar Pradesh, India

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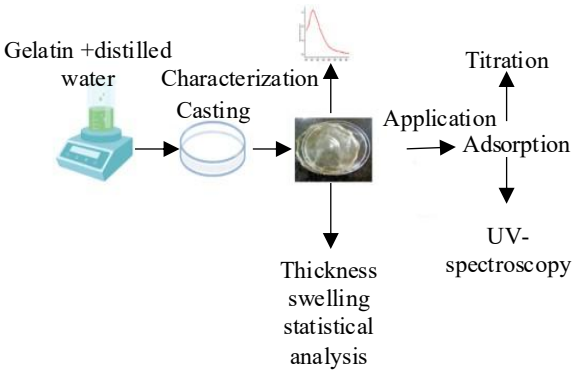
Graphical abstract




## INTRODUCTION

Water pollution is one of the most pressing global environmental issues, directly affecting ecosystems, climate, and human health [1]. Among various pollutants, heavy metals and synthetic dyes are of particular concern due to their toxicity, persistence, and non-biodegradable nature [2]. These contaminants enter aquatic environments through industrial discharge, mining, agricultural runoff, and urban waste, leading to the degradation of water quality and posing severe risks to both aquatic life and human populations [3].

**Highlights**

- *Sustainable Alternative*: Gelatin films offer a biodegradable solution to replace synthetic plastics in adsorption applications.
- *High Adsorption Efficiency*: Over 80% removal of $CuSO_4$, $KMnO_4$ and hard water contaminants within 4 hours.
- *Robust Characterization*: Structural integrity confirmed through UV-Vis, FTIR, and TGA analysis.
- *Validated Performance*: Adsorption trends statistically verified using ANOVA and regression analysis.
- *Water Purification Potential:* A promising eco-friendly adsorbent for environmental remediation.

Heavy metals, such as copper (Cu), manganese (Mn), zinc (Zn), calcium (Ca), and magnesium (Mg) are widely recognized for their adverse ecological effects [4,5]. While Ca and Mg are essential minerals, elevated concentrations contribute to water hardness, affecting domestic water systems, reducing the efficacy of soaps and detergents, and causing scale deposition in pipelines [6]. On the other hand, transition metals like Cu and Mn can cause aesthetic issues, such as discoloration and metallic taste in drinking water, while also posing health hazards at elevated levels [7,8]. Furthermore, the bioaccumulation of these metals in aquatic organisms can disrupt food chains and harm biodiversity [9,10].

Synthetic dyes, including methylene blue and methyl orange, are extensively used in textile, paper, plastic, and cosmetic industries. These dyes are chemically stable and often resistant to conventional biological degradation [11]. When released into water bodies, they not only alter the aesthetic quality of water but also block sunlight penetration, inhibit photosynthesis, and may exhibit mutagenic or carcinogenic effects on aquatic life and humans [9]. The presence of such pollutants compromises water safety and highlights the need for efficient, affordable, and environmentally sustainable remediation strategies [12].

In recent years, there has been a growing emphasis on the use of biodegradable, natural adsorbents for water treatment [12]. Gelatin, a biopolymer derived from collagen, has emerged as a promising candidate due to its abundance, non-toxicity, film-forming capability, and the presence of multiple functional groups (mainly $–NH_2$, –COOH) that can effectively bind pollutants [13]. As a biosorbent, gelatin offers an eco-friendly and renewable alternative to synthetic adsorbents, aligning with the principles of green chemistry and sustainable development [14,15].

This study aims to synthesize and characterize gelatin-based films and evaluate their efficacy in removing both organic and inorganic contaminants from water. The films were tested for the adsorption of synthetic dyes (methylene blue and methyl orange) and inorganic contaminants, such as $CuSO_4$, $KMnO_4$, and hard water ions ($Ca^{2+}$, $Mg^{2+}$).

Spectrophotometric analysis was employed to determine the removal efficiency of dyes, utilizing the colorimetric properties of the dye molecules. In contrast, classical titrimetric techniques like iodometric titration for copper ions, redox titration for permanganate, and complexometric titration for calcium and magnesium, were used to evaluate the reduction in metal ion concentration.

The combination of biosorbent-based adsorption and accessible analytical techniques presents a practical, scalable approach to address water pollution. This work highlights the potential of gelatin films as low-cost, biodegradable materials for water purification, offering a sustainable solution to mitigate the impact of heavy metals, synthetic dyes, and water hardness on both ecosystems and public health.

## MATERIALS AND METHODS

### Materials

The study utilized gelatin, distilled water, $CuSO_4$ solution, $KMnO_4$ solution, methyl orange, methylene blue, hard water, soil, UV spectrometer, IR spectrometer, heating mantle, filter paper, petri dishes, magnetic stirrer, burette, pipette, screw gauge, sodium thiosulfate (M/40), potassium iodide (KI), starch, sodium hydroxide (NaOH), ethylenediaminetetraacetic acid (EDTA), Eriochrome Black T (EBT), ammonium chloride ($NH_4Cl$), spatula, and beakers.

### Preparation of Gelatin Films

Three different gelatin concentrations (1 g, 5 g, and 10 g) were dissolved in 60 mL of distilled water and heated at 60 °C for two hours with continuous stirring. The solutions were then cast into petri dishes and solidified at room temperature for 2–4 days. The films were characterized for thickness, swelling, solubility, UV-visible absorbance, FTIR spectra, and biodegradability.

### Physico-Chemical Properties of Gelatin Films

#### *Film Thickness*

Thickness was measured using a screw gauge with an accuracy of ±0.01 mm.

#### *Swelling Behavior*

Uniform film samples (2 cm × 3 cm) were dried and weighed ($W_1$). They were submerged in water until fully swollen, and the final weight ($W_2$) was recorded. Swelling percentage was calculated using (1):

$$\text{Swelling\%} = 100 * (W_2 - W_1) / W_1 \quad (1)$$

Where:

$W_2$ = Weight of the swollen film, $W_1$ = Weight of the dried film

#### *pH and Chemical Reactivity*

The film's pH sensitivity was evaluated by comparing its response under acidic and alkaline conditions with its original pH.

### Characterization

#### *UV-Visible Spectroscopy*

UV absorption spectra were recorded in the 200–480 nm range using distilled water as a reference.

#### *Fourier Transform Infrared (FTIR) Spectroscopy*

Within gelatin molecules, various chemical bonds, conformations, and molecular interactions can be characterized using spectroscopic techniques, such as Fourier Transform Infrared (FTIR) spectroscopy. For FTIR analysis, gelatin films are commonly prepared via solution casting and may be dissolved in solvents, such as chloroform prior to measurement. The characteristic FTIR spectra of pure gelatin films typically display absorption bands in the range of 400–4000 $cm^{-1}$, reflecting functional groups like amide, carboxyl, and hydroxyl moieties [15,16,17].

### Adsorption Efficacy for Metal Ions: Titration Method

#### *Copper Sulfate Adsorption*

A comprehensive titration-based analysis was conducted to evaluate the adsorption efficiency of gelatin films in removing heavy metal ions and reducing water hardness. Gelatin films (1 g) were immersed in 10 mL of 0.1 M $CuSO_4$. Adsorption efficiency was analyzed using iodometric titration as per the reactions [i, ii].

The reactions that are taking place are:

$$2CuSO_4 + 4KI \rightarrow I_2 + Cu_2I_2 + 2K_2SO_4\text{-} \quad (1)$$

$2Na_2S_2O_3 + I_2 \rightarrow Na_2S_4O_6 + 2NaI.$ (2)

**Potassium Permanganate Adsorption**

The progressive decline in $KMnO_4$ concentration demonstrated the increasing adsorption capacity of gelatin films. Gelatin films (1 g) were immersed in 10 mL 0.1 M $KMnO_4$ solution. Adsorption efficiency was analyzed using redox titration reaction [iii] using sodium thiosulfate as the titrant

$5S_2O_3^{2-} + 2MnO_4^- + 6H^+ \rightarrow 5SO_4^{2-} + 2Mn^{2+} + 3H_2O$ (3)

**Hard Water Treatment**

Complexometric titration using EDTA and EBT was conducted to treat $Ca^{2+}$ and $Mg^{2+}$ ions. The concentration of metal ions was determined using the relationship:

$$N_1V_1 = N_2V_2$$

Where:

$N_1$ = concentration of metal ions (c)
$N_2$ = concentration of M/40 sodium thiosulfate and 0.1 M EDTA
$V_1$ = volume of metal ion solution taken (10 mL)
$V_2$ = volume of sodium thiosulfate and EDTA solution used

Rearranging the equation, the metal ion concentration was calculated as:

$$N_1 = \frac{N_2V_2}{V_1}$$

This quantitative approach allowed for precise tracking of metal ion reduction over time, providing clear evidence of the adsorption efficiency of gelatin films.

***Spectrophotometric Analysis***

To evaluate the adsorption efficiency of the synthesized gelatin films, a series of standard dye solutions with known concentrations ranging from 0.1 M to 0.6 M were prepared from a 1 M stock solution. A blank solution (distilled water) was used to calibrate the UV-Visible spectrophotometer. The absorbance of each solution was measured at the respective maximum absorbance wavelengths (λmax: 665 nm for methylene blue and 465 nm for methyl orange). Absorbance values were analyzed using the Beer-Lambert law to establish a linear relationship between absorbance and concentration as shown in (a), and calibration curves were constructed for both dyes to facilitate the quantification of residual concentrations after treatment.

For adsorption experiments, uniformly cut gelatin films (1 g) (2 × 3) cm were prepared, thoroughly dried to eliminate surface moisture, and their initial dry weights were recorded using a calibrated digital balance to ensure consistency across samples. Each film sample was immersed in 100 mL of the 1 M dye solutions and maintained at room temperature. After every 1-hour interval, the residual dye concentration was measured spectrophotometrically to assess the adsorption capacity of the gelatin films. This approach enabled precise evaluation of dye removal efficiency based on concentration changes before and after film exposure.

$$(a)\ A = \varepsilon cl$$

Where,

$A$ = absorbance
$c$ = concentration
$l$ = path length
$\varepsilon$ = molar absorptivity

## RESULTS AND DISCUSSION

**Appearance of Films**

Gelatin films appeared transparent to pale yellow, odorless, and tasteless. The 1 g film was brittle, while the 5 g and 10 g films exhibited greater mechanical strength.

**Table 1.** Thickness of gelatin film.

| Gelatin concentration (g) | Thickness (mm) |
|---|---|
| 1 | 0.05 |
| 5 | 0.19 |
| 10 | 0.21 |

## Physico-Chemical Properties of Gelatin Films

### *Film Thickness*

Table 1 shows that film thickness increases with increasing gelatin concentration, indicating a direct correlation between polymer content and film formation.

### *Swelling and Solubility*

Swelling increased with gelatin concentration, from 167.4% (1 g), 292.1% (5 g) to 426.7% (10 g).

### *pH and Chemical Reactivity*

- *Initial pH:* The pure gelatin film has an initial pH of 5.6. This value is slightly acidic.
- *Effect of HCl*: When exposed to a strong acid like hydrochloric acid (HCl), the film's pH drops to 4.7. This indicates that the film can resist the acid to a certain degree, as the pH doesn't drop to a very low value, but it is still affected by the acidic environment.
- *Effect of NaOH:* When exposed to a strong base like sodium hydroxide (NaOH), the film's pH rises to 8.01. This suggests that the film has some buffering capacity against a strong base, as the pH increase is minimal, moving from a slightly acidic state to a slightly basic one. The pH change is less pronounced than what would be expected from a strong base, indicating some alkaline resistance.

## Characterization

### *UV-Visible Spectroscopy*

UV spectra showed a peak at 300 nm, indicating the presence of aromatic amino acids (Figure 1), primarily due to the presence of aromatic amino acids like tryptophan and tyrosine. Gelatin's UV absorption peak at 300 nm also suggests its potential as a UV filter. This could benefit applications like skincare, packaging, and optical materials.

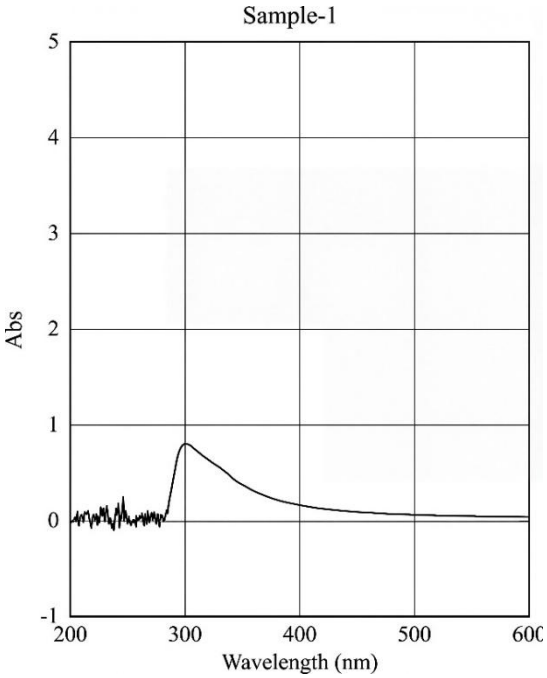



**Figure 1.** UV spectroscopy of pure gelatin.

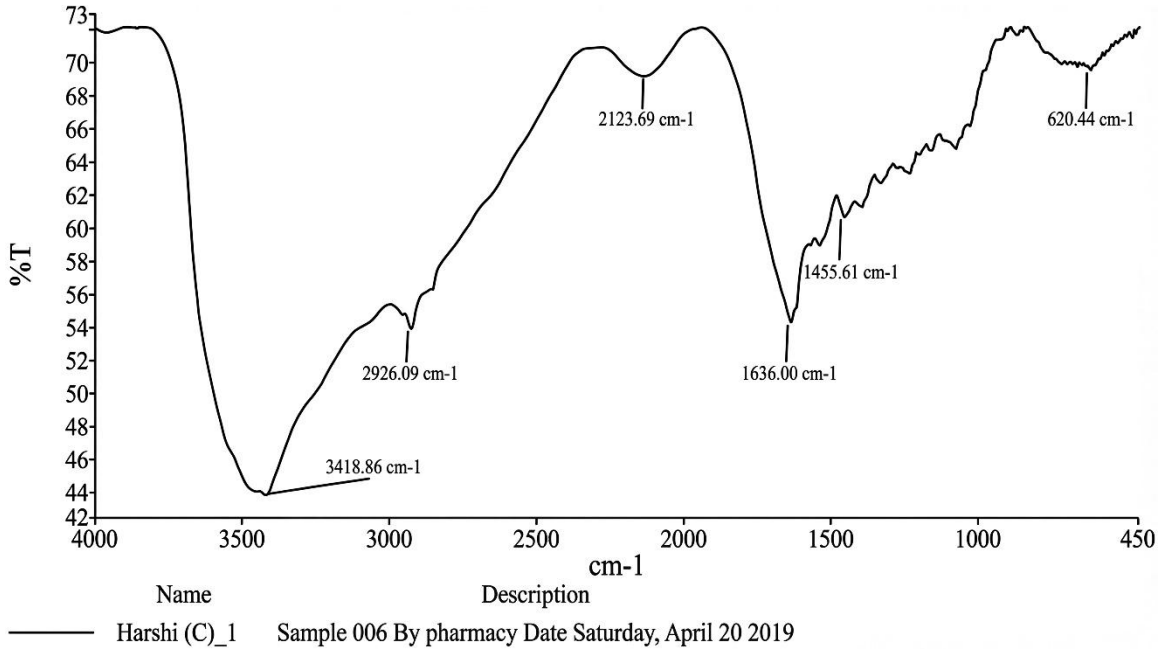



**Figure 2.** FTIR spectrum of gelatin.

### *Fourier Transform Infrared Spectroscopy*

The FTIR spectrum of gelatin (Figure 2) reveals characteristic peaks that indicate the presence of various functional groups: Amide-A and free water at 3415 $cm^{-1}$ (O-H stretching), Amide-I at 1637 $cm^{-1}$ (C=O stretching and hydrogen bonding), Amide-II at 1539 $cm^{-1}$ (N-H bending and C-N stretching), and Amide-III at 1236 $cm^{-1}$ (in-plane vibrations of N-H and C-N) [17]. The studied gelatin sample shows similar peaks: Amide-A and free water at 3418 $cm^{-1}$, Amide-I at 1636 $cm^{-1}$, Amide-II at 1455 $cm^{-1}$, Amide-III at 2123 $cm^{-1}$, and asymmetric $CH_2$ stretching at 2926 $cm^{-1}$. The close match between the observed and reported peaks confirms the presence of characteristic functional groups, providing insights into the molecular structure of the gelatin sample.

### Application of Films for the Treatment of Pollutants

The application of gelatin films for treatment of various pollutants $CuSO_4$, $KMnO_4$, hard water, methylene blue, and methyl orange, were evaluated using titration and spectrophotometric methods.

### *Titration Method*

The reduction in metal ion concentration by gelatin films was analyzed through simple titration process, as summarized in Tables 2, 3, 4 for $CuSO_4$, $KMnO_4$, and hard water, respectively. The data indicate a time-dependent progressive decrease in their concentration. This trend suggests the effective adsorption capability of gelatin films, where extended contact time facilitates enhanced interaction between the adsorbent and metal ions, resulting in improved removal efficiency.

**Table 2.** Iodometric titration for determination of copper sulfate concentration

| Duration | Volume of M/40 sodium thiosulphate solution (mL) | | | Concentration | | Amount of Cu (II) ions adsorbed per unit mass | |
|---|---|---|---|---|---|---|---|
| *(Hours)* | $V'_1$ | $V'_2$ | $V'_2-V'_1= V_2$ | $N_1 = c$ | *log c* | *x/m* | *log x/m* |
| Initial | 0 | 19.1 | 19.1 | 11.8 | 1.07 | 0.213 | -0.671 |
| 1 | 19.1 | 29.8 | 10.7 | 6.6 | 0.819 | 0.624 | -0.204 |
| 2 | 29.8 | 36.4 | 6.6 | 4 | 0.603 | 0.683 | -0.165 |
| 3 | 36.4 | 41.2 | 4.8 | 2.9 | 0.463 | 0.798 | -0.097 |
| 4 | 41.2 | 45.8 | 4.6 | 2.8 | 0.447 | 0.796 | -0.099 |

**Table 3.** Redox titration for determination of $KMnO_4$ concentration.

| Duration | Volume of M/40 sodium thiosulphate solution (mL) | | | Concentration | | Amount of Mn (II) ions adsorbed per unit mass | |
|---|---|---|---|---|---|---|---|
| *(Hours)* | $V'_1$ | $V'_2$ | $V'_2-V'_1= V_2$ | $N_1 = c$ | *log c* | *x/m* | *log x/m* |
| Initial | 0 | 20.4 | 20.4 | 12.65 | 1.11 | 0.226 | -0.645 |
| 1 | 20.4 | 29.7 | 9.3 | 5.7 | 0.756 | 0.622 | -0.206 |
| 2 | 29.7 | 37 | 7.3 | 4.5 | 0.653 | 0.686 | -0.164 |
| 3 | 37 | 43.5 | 6.5 | 4 | 0.602 | 0.887 | -0.052 |
| 4 | 43.5 | 48.7 | 5.2 | 3.2 | 0.505 | 0.891 | -0.05 |

**Table 4.** Complexometric titration for hard water estimation.

| Duration | Volume of 0.1M EDTA (mL) | | | Concentration | | Amount of $Ca^{2+}$ and $Mg^{2+}$ ions adsorbed per unit mass | |
|---|---|---|---|---|---|---|---|
| *(Hours)* | $V'_1$ | $V'_2$ | $V'_2-V'_1= V_2$ | $N_1 = c$ | *log c* | *x/m* | *log x/m* |
| Initial | 0 | 6.7 | 6.7 | 2.4 | 0.381 | 0.189 | -0.723 |
| 1 | 6.7 | 11.8 | 5.1 | 1.8 | 0.255 | 0.369 | -0.432 |
| 2 | 11.8 | 14.6 | 2.8 | 1.04 | 0.017 | 0.412 | -0.385 |
| 3 | 14.6 | 16.5 | 1.9 | 0.71 | -0.148 | 0.467 | -0.331 |
| 4 | 16.5 | 17.7 | 1.2 | 0.45 | -0.345 | 0.491 | -0.308 |

The experimental results further aligned with the Freundlich isotherm model, indicating adsorption on a heterogeneous surface. Figure 3a, 3b, 3c shows the graphical representation of the decrease in the concentration of copper sulfate, $KMnO_4$ and hard water solution over time for different thicknesses of gelatin films with a pH of 5.15 indicating the adsorption of pollutants by the gelatin films.

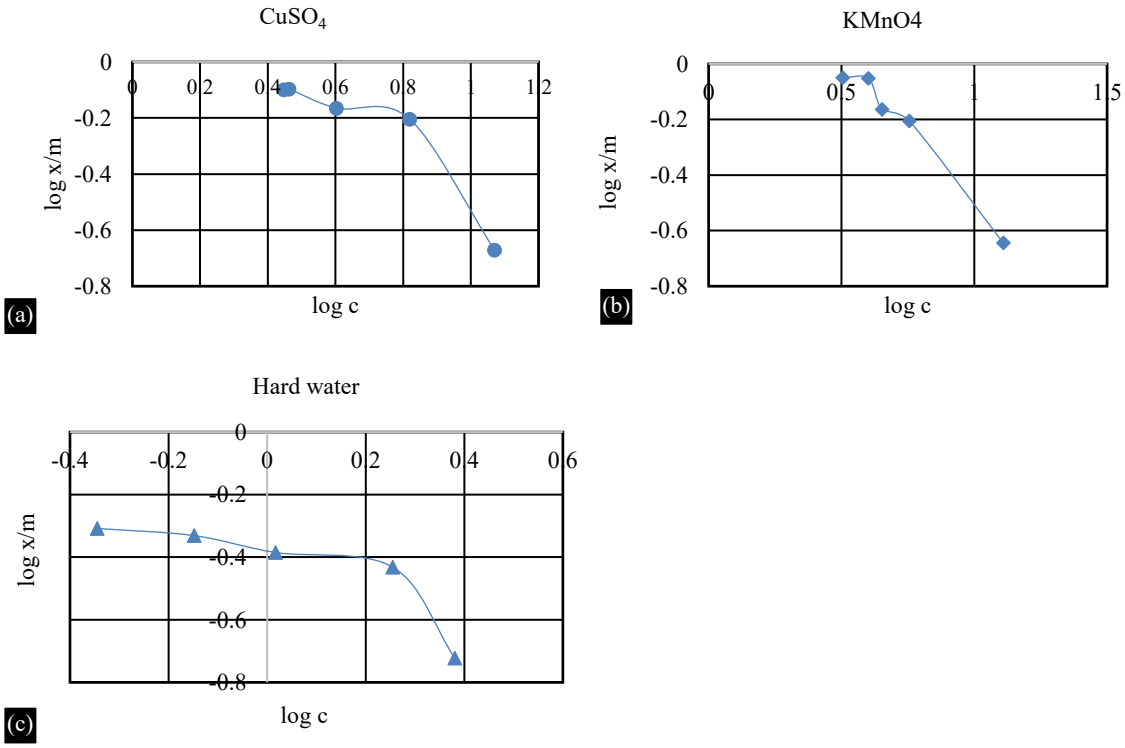



**Figure 3.** Graphical representation of the freundlich isotherm indicating the concentration of (3a) copper sulfate (3b) $KMnO_4$ (3c) hard water] solutions decreases with an increase in time of gelatin films

**Table 5.** The adsorption efficiency data for different time intervals.

| Metal ion | Initial concentration | Final concentration | Adsorption efficiency (%) |
|---|---|---|---|
| $Cu^{2+}$ (Copper Sulfate) | 11.8 | 2.8 | 76.27 |
| $Mn^{2+}$ ($KMnO_4$) | 12.65 | 3.2 | 74.70 |
| $Ca^{2+}$ & $Mg^{2+}$ (Hard Water) | 2.4 | 0.45 | 81.25 |

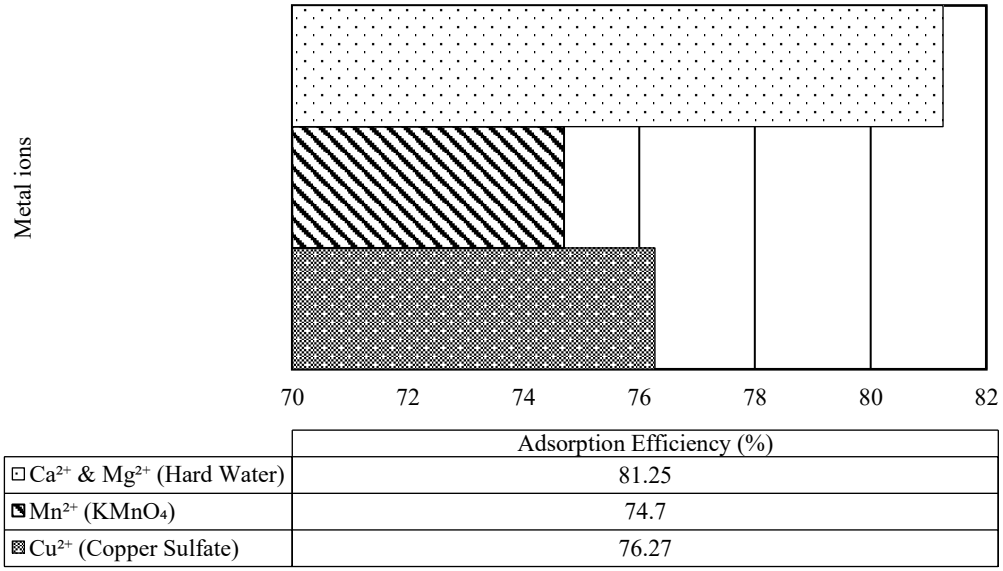



**Figure 4.** Adsorption efficiency of gelatin films for different metal ions.

The adsorption efficiency of gelatin films for various pollutants $CuSO_4$, $KMnO_4$, and hard water, was evaluated using titration methods. The adsorption efficiency increased over time, with a significant reduction in absorbance or titration volume observed for all tested solutions. The adsorption efficiency plot for all pollutants is presented in Figure 4. Adsorption efficiency was calculated using the formula [3]: The adsorption efficiency data for different time intervals are summarized in Table 5.

Adsorption Efficiency (%) = Cinitial-Cfinal/Cinitial x 100 (3)

Where:

- Cinitial is the initial concentration of metal ions
- Cfinal is the final concentration after adsorption

This Table highlights the effectiveness of gelatin films in adsorbing heavy metal ions, with the highest removal efficiency observed for water hardness reduction. The bar chart, Figure 4, clearly shows that the highest adsorption efficiency is for $Ca^{2+}/Mg^{2+}$ (81.25%), followed by $Cu^{2+}$ (76.27%) and $Mn^{2+}$ (74.7%).

The results indicate that gelatin films effectively adsorb all tested pollutants, with adsorption efficiency approximating 80% after 4 hours. This demonstrates their potential for water purification applications.

***Adsorption Efficacy for Dyes: Spectrophotometric Analysis***

The adsorption performance of pure gelatin film for dyes was monitored over a 4-hour period using UV-Visible spectrophotometry. The equilibrium concentrations (Ce) of methylene blue and methyl orange were calculated using the Beer-Lambert relation as shown in (b):

$$(b)\ C_e = \frac{A}{\varepsilon}$$

Where,

$A$= Absorbance
$\varepsilon$ = molar absorptivity

The amount of pollutant adsorbed at equilibrium (qe) was calculated as shown in (d):

$$(d)\ q_e = [C_o - C_e]\frac{V}{m}$$

Where,
$Co$ = initial concentration
$V$ = volume of the solution
$m$ = mass of the film (adsorbent)

The adsorption behavior of methylene blue and methyl orange onto gelatin-based biosorbent films was systematically evaluated using UV-Visible spectrophotometry. Calibration curves were constructed using standard methylene blue and methyl orange solutions at serial concentrations of (0.1–0.6) M from 1 M stock solution, measured at their respective maximum absorbance wavelengths (λmax 665 nm for methylene blue and 465 nm for methyl orange.

The Beer-Lambert law established a linear relationship between absorbance and concentration, enabling precise determination of residual dye (methylene blue and methyl orange) concentrations after exposure to the gelatin films. Adsorption kinetics were monitored over time, revealing a significant increase in dye uptake from 1 to 4 hours, after which the adsorption capacity plateaued, as shown in Tables 6 and 7, respectively.

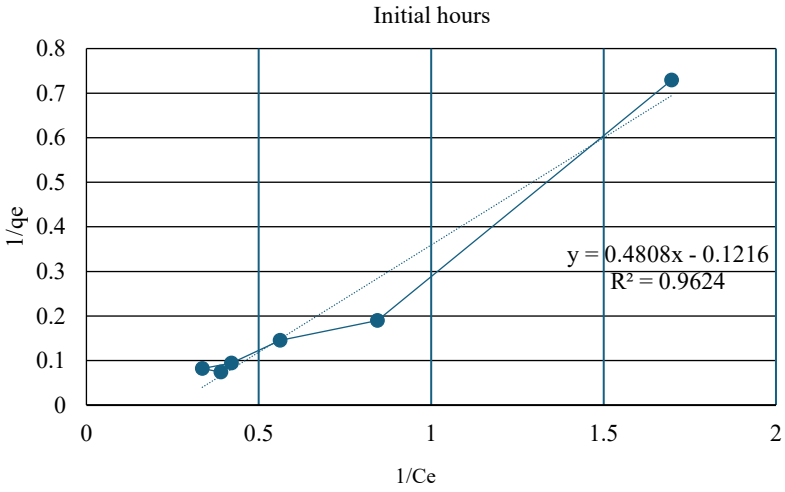
**Table 6.** Variation in absorbance over time for methylene blue with different initial concentrations (0.1 M to 0.6 M).

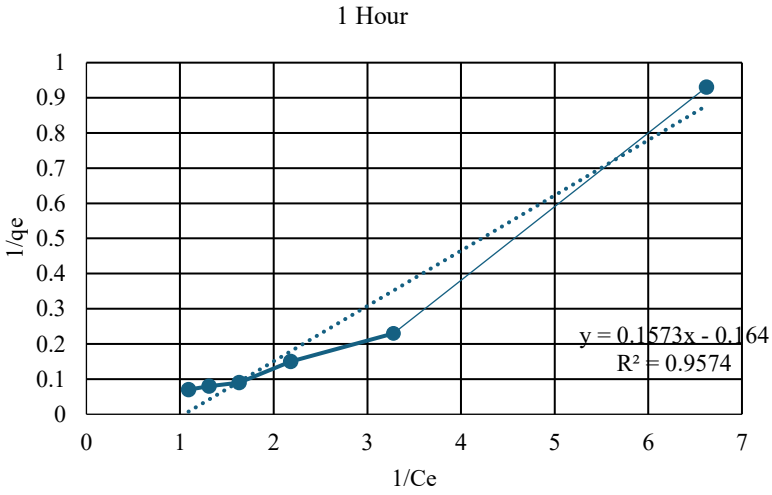
| **Concentration (M)** | **Absorbance w.r.t time(hours)** | | | | |
|---|---|---|---|---|---|
| | ***Initial*** | ***1*** | ***2*** | ***3*** | ***4*** |
| 0.1 | 0.102 | 0.079 | 0.022 | 0.020 | 0.016 |
| 0.2 | 0.390 | 0.310 | 0.278 | 0.207 | 0.200 |
| 0.3 | 0.509 | 0.475 | 0.446 | 0.447 | 0.435 |
| 0.4 | 0.790 | 0.757 | 0.755 | 0.753 | 0.752 |
| 0.5 | 0.898 | 0.880 | 0.872 | 0.859 | 0.765 |
| 0.6 | 0.997 | 0.971 | 0.931 | 0.929 | 0.910 |

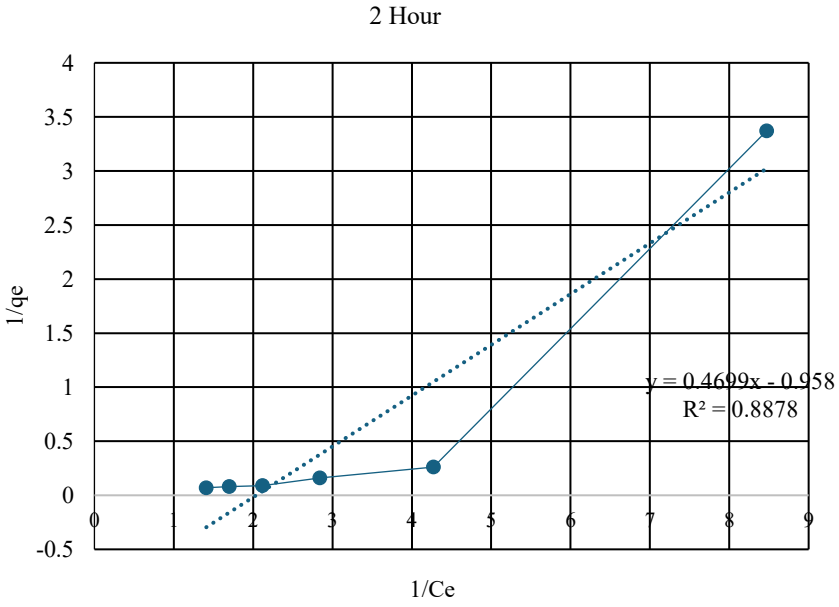
**Table 7.** Variation in absorbance over time for methyl orange with different initial concentrations (0.1 M to 0.6 M).

| **Concentration (M)** | **Absorbance w.r.t time(hours)** | | | | |
|---|---|---|---|---|---|
| | ***Initial*** | ***1*** | ***2*** | ***3*** | ***4*** |
| 0.1 | 7.030 | 5.918 | 4.408 | 4.342 | 4.406 |
| 0.2 | 7.542 | 6.999 | 5.098 | 4.987 | 6.602 |
| 0.3 | 8.431 | 7.095 | 6.108 | 6.010 | 7.709 |
| 0.4 | 8.785 | 7.546 | 7.667 | 7.034 | 8.540 |
| 0.5 | 9.631 | 8.354 | 8.013 | 8.001 | 9.006 |
| 0.6 | 9.880 | 8.920 | 8.871 | 8.886 | 9.541 |



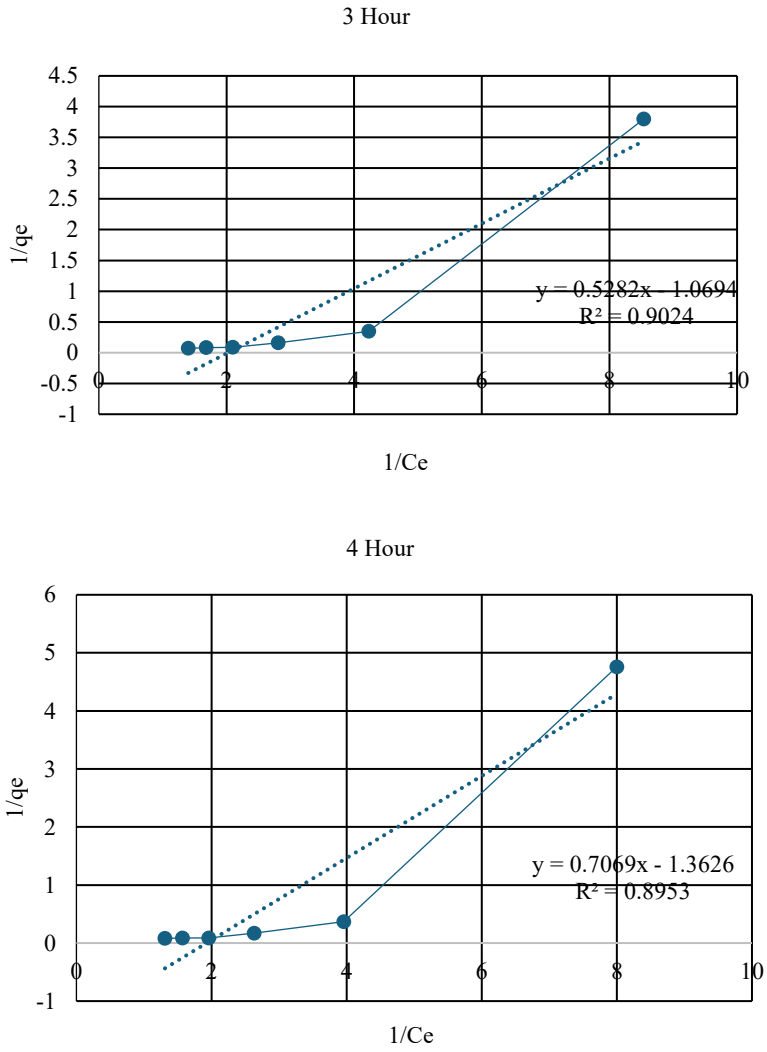
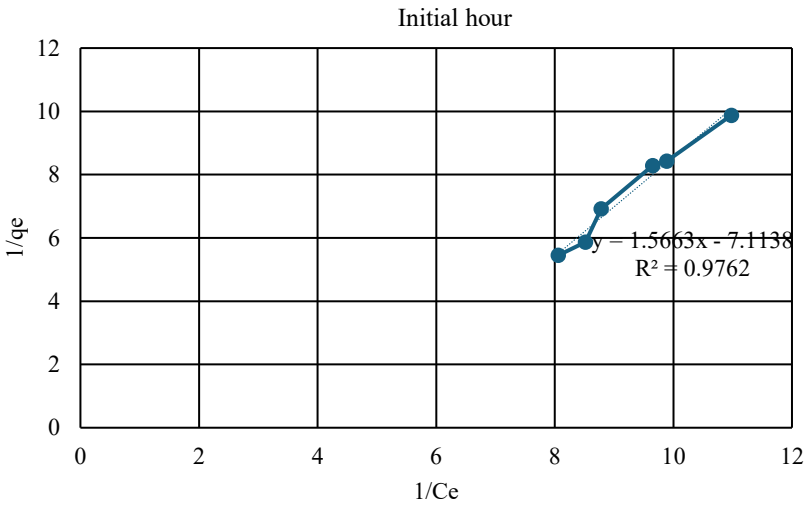
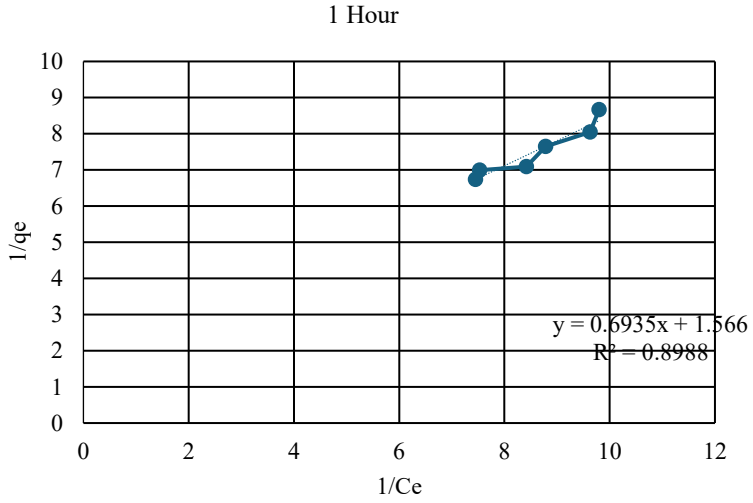
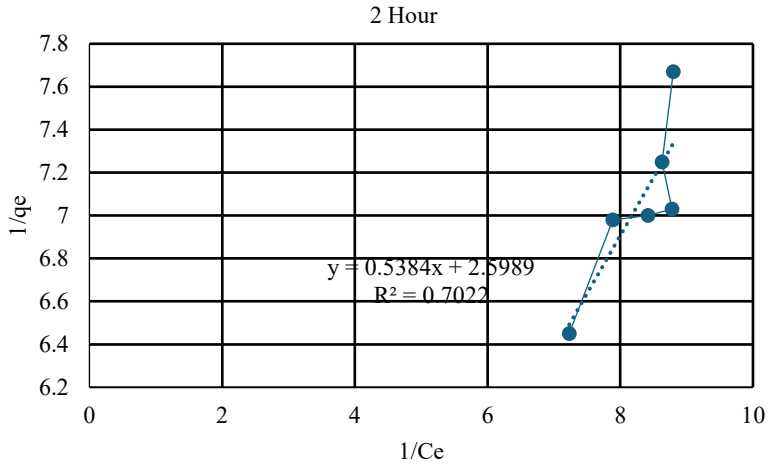


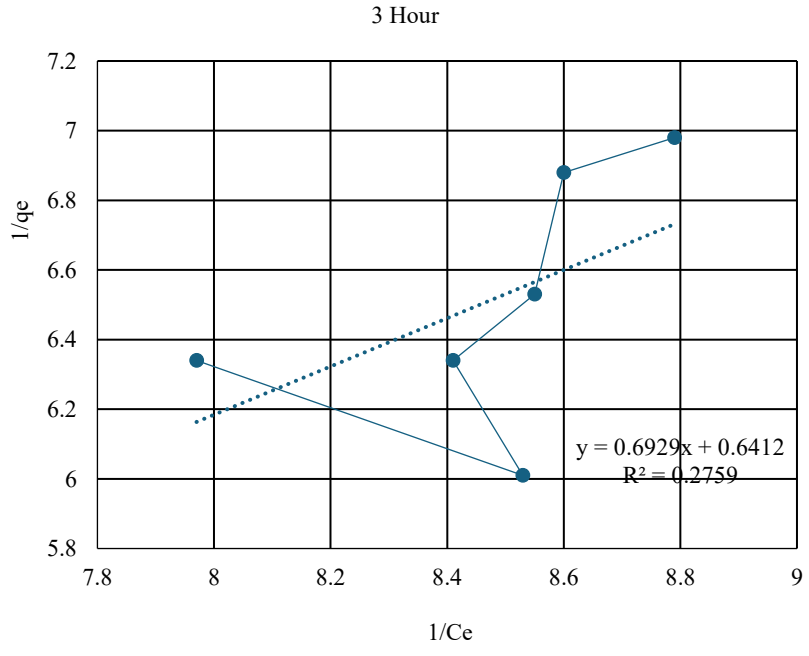

**Figure 5.** Graphical representation of the Langmuir isotherm indicating a decrease in the concentration of methylene blue.





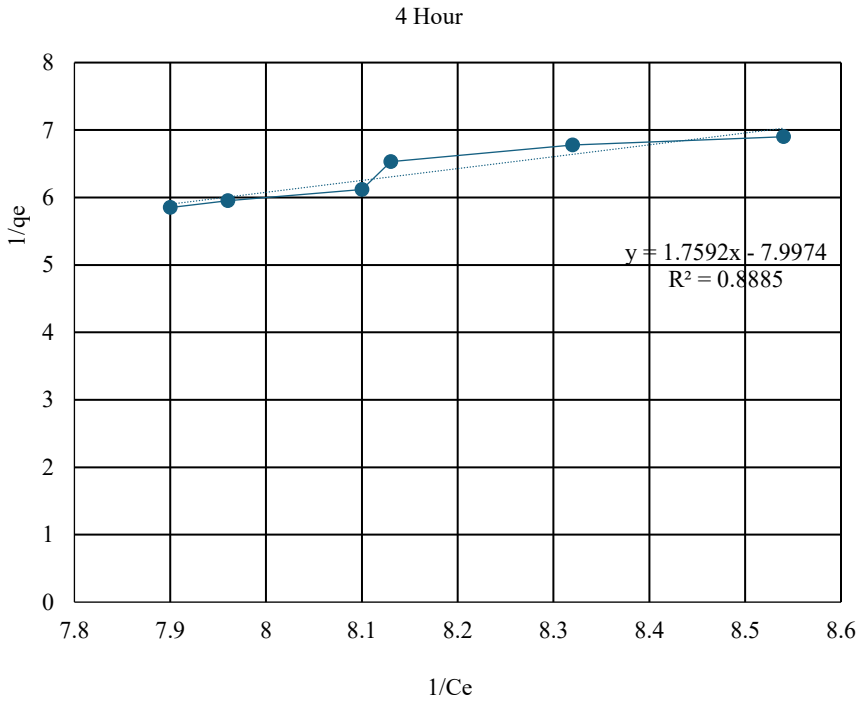



**Figure 6.** Graphical representation of the Langmuir isotherm indicating a decrease in the concentration of methyl orange.

This saturation effect is attributed to the occupation of available active binding sites on the biosorbent surface, limiting further dye uptake. The results confirmed that dye (methylene blue and methyl orange) adsorption is initially rapid due to the abundance of vacant sites, followed by equilibrium as those sites become occupied. To further analyze the adsorption mechanism, data were fit to the Langmuir isotherm model by plotting, yielding a linear relationship ($R^2 \approx 1$) as shown in Figures 5 and 6, which indicates that the adsorption process follows monolayer coverage on a homogeneous surface. The high correlation suggests a combination of physical and chemical interactions between the dye molecules and the functional groups present in the gelatin matrix. These findings demonstrate the effective adsorption capacity of gelatin films and their potential as low-cost, biodegradable biosorbents for dye-contaminated water.

**Statistical Analysis: Regression and ANOVA**

To validate the adsorption isotherm results, statistical analysis was conducted using ANOVA. The adsorption capacities for $CuSO_4$, $KMnO_4$ and hard water results are as follows:

***ANOVA Analysis***

A one-way ANOVA was performed using SPSS version 26 to evaluate differences in metal ion concentrations over time. The analysis produced an F-statistic of 1.39 and a p-value of 0.287. Since the p-value is substantially higher than the conventional significance level of 0.05, the results indicate that there are no statistically significant differences in metal ion concentrations across the observed time periods. Thus, the data do not provide sufficient evidence to conclude that metal ion concentrations changed significantly during the study period.

***Regression Analysis***

Regression analysis was performed to examine the relationship between initial metal ion concentration and adsorption efficiency. The analysis yielded a Pearson's coefficient of -0.988, indicating a trend for decreasing efficiency with increasing concentration, likely due to surface saturation effects Figure 7.

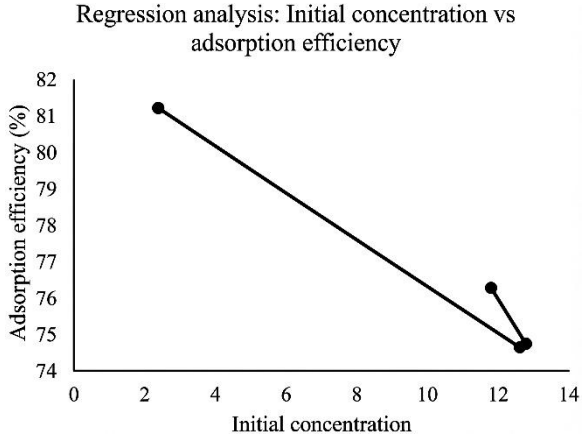



**Figure 7.** Regression analysis of gelatin films for different metal ions.

These findings confirm that while adsorption efficiency generally decreases with increasing concentration, the trend remains well-defined, reinforcing the suitability of gelatin films for pollutant removal.

## CONCLUSION

Eco-friendly gelatin films were successfully created using a solution casting method. Spectroscopic analysis (UV-Vis and FTIR) confirmed their molecular integrity. These films exhibited excellent swelling behavior, and their thickness directly correlated with gelatin concentration: higher concentrations resulted in thicker films and delayed solubility. This suggests improved material deposition and increased surface availability for adsorption.

This study demonstrates the significant potential of gelatin films for treating various environmental pollutants, including $CuSO_4$, $KMnO_4$, hard water, methylene blue, and methyl orange.

Titrimetric analysis was used to determine the concentration of $CuSO_4$, $KMnO_4$, and hard water after treatment with the gelatin films. The adsorption data for these three pollutants fit the Freundlich isotherm model, confirming metal ion adsorption onto heterogeneous surfaces.

For methylene blue and methyl orange, UV-Visible spectrophotometric analysis of treated solutions showed clear, concentration-dependent absorbance changes. This allowed for quantification using calibration curves based on Beer-Lambert's Law. The adsorption data for both dyes were strongly aligned with the Langmuir isotherm model ($R^2 \approx 1$), indicating monolayer adsorption on a homogeneous surface.

Statistical validation via ANOVA confirmed the adsorption efficiency across various heavy metal ions. The analysis yielded an F-statistic of 3.50 and a p-value of 0.063, suggesting that while there are slight differences in adsorption efficiency among $Cu^{2+}$, $Mn^{2+}$, and $Ca^{2+}/Mg^{2+}$, these variations are not statistically significant at the 95% confidence level. Within four hours, the films achieved high removal efficiencies for $Ca^{2+}/Mg^{2+}$ (81.25%), followed by $Cu^{2+}$ (76.27%) and $Mn^{2+}$ (74.7%).

The primary limitation of these films was their solubility, which restricted studies to a maximum of four hours. Despite this, gelatin films offer an eco-friendly and renewable alternative to synthetic adsorbents for wastewater treatment, aligning well with green chemistry principles.

To enhance their long-term stability, future research should focus on addressing challenges like microbial degradation in humid conditions and solubility limitations. Strategies, such as cross-linking modifications and biopolymer blending are promising avenues to improve the mechanical strength and durability of these films.

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No potential conflicts of interest was reported by the author(s).

**Notes on Contributors**

*Nikita Bhardwaj*: conducted experimental work, methodology, formal analysis, primary writing and editing

*Vijaya Majumdar*: data interpretation and analysis

*Jaya Maitra*: supervision, conceptualization, review, editing, and verification

**Data Availability Statement**

Data will be made available on request.

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