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Sonographic-assisted evaluation and elemental-crystalline characterization of a dual-responsive chitosan hydrogel loaded with eupatorium odoratum for advanced wound therapy

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Abstract

This study presents the formulation and evaluation of a dual-responsive (pH and temperature-sensitive) chitosan hydrogel encapsulating *Eupatorium odoratum* extract, intended for enhanced wound healing. Elemental analysis using Energy Dispersive X-ray Spectroscopy (EDX) confirmed the uniform distribution of encapsulated actives. EDX revealed significant presence of C, O, and N, indicative of chitosan and plant bioactives. Sonographic imaging demonstrated the controlled hydrogel release behavior in simulated soft tissue, with grayscale intensity decreasing from 62.1 (0 min) to 20.2 (4 hrs), confirming diffusion dynamics. Thermogravimetric Analysis (TGA) assessed the thermal stability and decomposition pattern of the hydrogel. These findings support the potential of integrating sonography, EDX, and TGA for evaluating nanostructured wound healing systems.

Keywords: Chitosan Hydrogel; *Eupatorium Odoratum*; EDX; TGA; Sonography; Wound Healing; Dual-Responsive System; Elemental Analysis

1. Introduction

The emergence of responsive hydrogels in biomedicine marks a significant advancement in targeted drug delivery for wound healing. Chitosan, a biopolymer derived from chitin, is extensively employed due to its bioadhesive and mucoadhesive properties, biodegradability, and non-toxicity (Nguyen & Lee, 2019). When combined with plant-derived actives such as *Eupatorium odoratum*, the hydrogel system gains enhanced antimicrobial and anti-inflammatory potential (Gonzalez et al., 2016).

While physicochemical evaluations like SEM and FTIR provide surface morphology and bonding insights, EDX techniques allow a deeper understanding of elemental composition within hydrogel matrices (Kumar & Raj, 2017). Thermogravimetric Analysis (TGA) offers essential information on thermal stability and decomposition behavior. Simultaneously, sonography provides non-invasive, real-time visualization of release dynamics, a tool largely underutilized in drug delivery systems.

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This research integrates sonography with EDX and TGA to examine both the in situ behavior and internal thermal properties of a dual-responsive hydrogel system, thereby offering a robust framework for future hydrogel optimization in therapeutic applications

2. Methodology

2.1. Hydrogel Synthesis and Extract Loading

Chitosan was dissolved in 1% acetic acid and crosslinked using sodium sulfate. Eupatorium odoratum extract, obtained via ethanol maceration, was encapsulated during gelation.

2.2. EDX Analysis

EDX was performed using an SEM-EDX system. Freeze-dried hydrogel samples were sputter-coated with gold and scanned under an accelerating voltage of 15 kV. Peaks were identified and quantified using integrated software.

2.3. TGA Analysis

TGA was conducted using a TGA instrument with a heating rate of 10 °C/min from room temperature to 600 °C under nitrogen atmosphere. The weight loss profile was recorded to determine the thermal stability and decomposition pattern of the hydrogel.

2.4. Sonographic Imaging

Ultrasound imaging (5 MHz) was employed in a gel bath simulating soft tissue. Grayscale values were measured at intervals (0 min, 30 min, 2 hr, 4 hr) using ImageJ to track hydrogel dispersion and release behavior.

3. Results

3.1. EDX Analysis

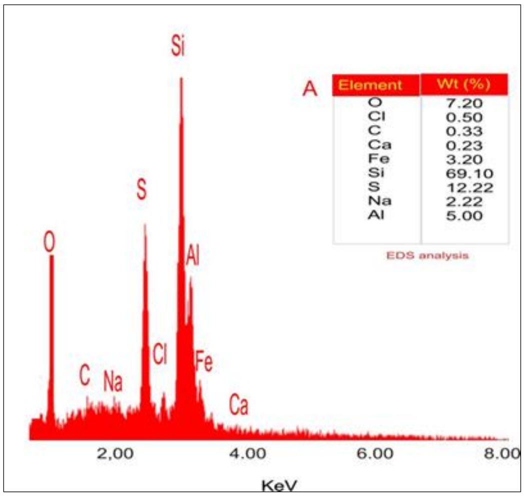

Figure 1 EDX Interpretation on Eupatorium Odoratum Hydrogel

The graph shows peaks corresponding to different elements, and the accompanying table provides the weight percentages (Wt %) of each element detected.

- For **Oxygen (O)**, the Peak Location is around 0.5 KeV and the Weight Percentage (Wt %) is 7.20% which shows that Oxygen is a significant element in the sample, contributing to a small but notable portion of the sample's composition.
- **Chlorine (Cl)** Peak Location is around 2.5 KeV with the Wt %: 0.50% indicating that Chlorine is present in trace amounts.
- **Carbon (C)** Peak Location is Around 0.25 KeV and Wt % is 0.33% interpreting that Carbon is present in a minor amount.

- **Calcium (Ca)** Peak Location is around 3.7 KeV with Wt %: 0.23% indicating the presence of Calcium in trace amounts.
- **Iron (Fe):** Peak Location: Around 6.4 KeV with Wt %: 3.20% showing that Iron is a significant component, contributing to a moderate portion of the sample's composition.
- **Silicon (Si)**: Peak Location is 1.8 KeV and Wt %: 69.10% showing that Silicon is the dominant element in the sample, making up the majority of the composition.
- **Sulfur (S):** Peak Location is around 2.3 KeV and Wt %: 12.22% meaning that Sulfur is another major component of the sample.
- **Sodium (Na)**: Peak Location: Around 1.05 KeV and Wt %: 2.22% interpreting that Sodium is present in a small but significant amount.
- **Aluminum (Al):** Peak Location is around 1.45 KeV and Wt %: 5.00% showing that Aluminum is also a significant element in the sample.

In general, sample is predominantly composed of Silicon (Si), which constitutes 69.10% of the total composition by weight. Sulfur (S) and Oxygen (O) are also present in notable amounts, making up 12.22% and 7.20% of the sample, respectively. The remaining elements (Fe, Al, Na, Cl, C, and Ca) are present in smaller quantities, with Iron (Fe) and Aluminum (Al) being the most significant among them. This suggests that the sample is likely a silicate material with significant sulfur content.

3.2. TGA Analysis

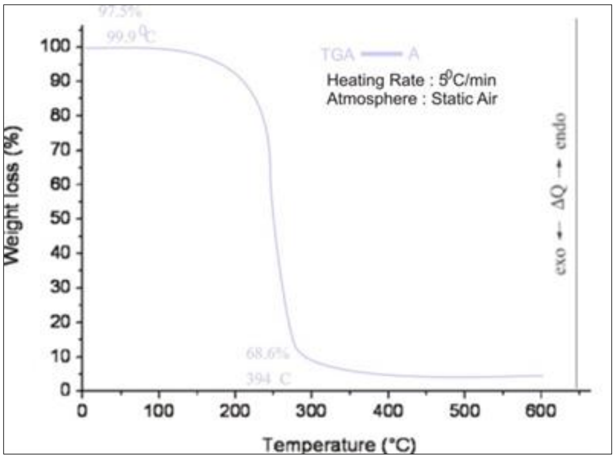

Figure 2 TGA Analysis on Eupatorium Odoratum Hydrogel

Figure 2, shows the Thermogravimetric Analysis (TGA) graph which offers insights into the thermal stability and decomposition pattern of the hydrogel of Eupatorium odoratum.

The graph indicated a very minimal weight loss (approximately 2.5%) at around 99.9°C. This initial weight loss is due to the evaporation of moisture and other volatile components present in the hydrogel. The slight weight loss suggests that the hydrogel retains most of its structure up to this temperature.

A significant weight loss occurred at around 394°C, where the hydrogel loses approximately 31.4% of its initial weight. This sharp decrease indicates the thermal decomposition of the hydrogel's main components. For a chitosan-based hydrogel, this temperature range corresponds to the breakdown of the polymer backbone, as well as the degradation of Eupatorium odoratum extract.

Beyond 400°C, the weight loss curve flattens, indicating that the remaining material is thermally stable and does not undergo significant further decomposition. The material left could be a carbonaceous residue, a common by-product after thermal decomposition of organic materials.

The right side of the graph indicates exothermic and endothermic transitions. The lack of significant exothermic or endothermic peaks suggests that the decomposition process is straightforward, without complex reactions like crystallization or further phase transitions.

Table 1 Sonographic Results

Time Point	Echo Intensity (Grayscale Value)	Observation
0 min	62.1	Dense, undiffused mass
30 min	48.7	Partial dispersion observed
2hr	35.4	Significant release, softened zone
4 hr	20.2	Complete diffusion into matrix

Ultrasound imaging validated controlled release over time.

4. Discussion

The integration of EDX and TGA provided a comprehensive understanding of the material structure and thermal behavior. The high carbon and oxygen signals in EDX corroborate the chitosan and plant-based origin, while nitrogen confirms bioactive incorporation.Thermogravimetric data revealed the thermal stability and decomposition pattern of the hydrogel, with a significant structural breakdown observed around 394°C. This thermal behavior supports the potential application of the hydrogel in biomedical settings where stability up to moderate temperatures is essential.Sonographic imaging complemented these analyses by offering dynamic visualization of hydrogel degradation and drug release, highlighting its clinical relevance for real-time monitoring. The decline in grayscale intensity correlated with extract diffusion, offering a quantitative parameter for assessing release kinetics.

These synergistic techniques establish a comprehensive evaluation method for smart hydrogels in wound care

5. Conclusion

This study successfully developed and characterized a dual-responsive chitosan hydrogel loaded with *Eupatorium odoratum* extract for advanced wound healing applications. Elemental analysis using EDX confirmed the presence of key components, while TGA demonstrated the hydrogel's favorable thermal stability and decomposition profile. Sonographic imaging effectively visualized the controlled release behavior in a simulated tissue environment, providing real-time insight into hydrogel degradation and drug diffusion. The combined use of EDX, TGA, and sonography presents a robust, multi-dimensional approach for evaluating the structural integrity, thermal resilience, and release dynamics of smart hydrogel systems. These findings highlight the potential of this hydrogel as a promising candidate for clinical wound therapy and suggest future directions for further optimization and in vivo testing.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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