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Assessment of a Hybrid Hydrogel Nanocomposite: A Comprehensive Characterization of its Chemical, Structural, and Surface Properties for Advanced Wound Dressing Applications

Dr. Sunil Yesvanthu S V[1], Dr. Arun M[2]*, Dr. Murugesan Krishnan[3], Dr.Santhosh P.Kumar[4]

[1]Resident, Department of oral and maxillofacial surgery, Saveetha Dental College and hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS) Saveetha University, Chennai-600077, Tamil Nadu, India.
Email.id: 152304004.sdc@saveetha.com
[2]Associate Professor, Department of oral and maxillofacial surgery, Saveetha Dental College and hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS) Saveetha University, Chennai-600077, Tamil Nadu, India.
Email id: arunmsdc@saveetha.com
[3]Professor, Department of oral and maxillofacial surgery, Saveetha Dental College and hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS) Saveetha University, Chennai-600077, Tamil Nadu, India.
Email id : dr.mkm70@gmail.com
[4]Professor, Department of oral and maxillofacial surgery, Saveetha Dental College and hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS) Saveetha University, Chennai-600077, Tamil Nadu, India.
Email id : santhoshkumar@saveetha.com

Corresponding author *:
Dr. Arun M2
Email id: arunmsdc@saveetha.com

ABSTRACT

Hydrogel-based wound dressings provide a moist environment conducive to healing while allowing the incorporation of bioactive nanomaterials such as silver or zinc oxide nanoparticles. Chemical interaction between polymer matrices and nanoparticles is crucial for the stability and function of these systems. Chronic wounds and infection-prone injuries require advanced wound dressings that provide not only moisture retention but also antimicrobial protection and mechanical resilience. Hybrid hydrogel nanocomposites represent an emerging solution, wherein a polymeric hydrogel matrix is embedded with metallic or metal oxide nanoparticles. These materials have shown promise due to their bioactivity, biocompatibility, and controlled drug delivery potential. Hydrogels have been extensively explored as wound dressing materials due to their ability to retain water, provide a cooling effect, and allow oxygen permeability. However, surface characteristics such as wettability play a significant role in their performance. Incorporating nanoparticles such as silver (AgNPs) into hydrogels not only enhances antimicrobial properties but can also alter surface energy. Contact angle analysis offers a quantitative method to evaluate the surface hydrophilicity of the dressing. A lower contact angle (< 90°) implies better wettability, which can enhance biointegration and exudate absorption. This study assesses the contact angle of a fabricated hybrid hydrogel nanocomposite to infer its surface wettability properties. Fourier Transform Infrared Spectroscopy (FTIR) enables the identification of functional groups and bonding interactions that underpin the material's performance. Understanding the structural properties of such composites is essential to predict their performance. X-ray Diffraction (XRD) is a critical tool for characterizing the crystalline and amorphous phases within these materials. This study focuses on interpreting the XRD pattern of a hybrid hydrogel nanocomposite to identify its major structural features and confirm successful synthesis. This study also presents the FTIR spectral interpretation of a hybrid hydrogel nanocomposite designed for wound care applications, focusing on the functional group confirmations and molecular interactions present in the system.

KEYWORDS: Hydrogel Nanocomposite, Wound Dressing, FTIR, X-ray Diffraction

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INTRODUCTION

The management of chronic wounds and the prevention of infection in complex injuries represent significant clinical challenges. Conventional wound care materials, while effective for minor abrasions, often fall short in providing the optimal environment required for accelerated and complication-free healing(1). Such an environment demands not only moisture retention and gas permeability but also antimicrobial protection and sufficient mechanical resilience. This clinical imperative has driven the development of a new generation of wound dressings, leading to the emergence of hybrid hydrogel nanocomposites as a promising solution(2).

Hydrogels, with their high water content, inherent cooling effect, and ability to allow for oxygen permeability, have long been recognized as a foundational material for wound care. Their soft, tissue-like consistency minimizes patient discomfort and promotes a moist healing environment(3). However, their limitations, particularly a lack of inherent antimicrobial activity and limited mechanical strength, necessitate strategic enhancement(4). The incorporation of bioactive nanomaterials, such as silver nanoparticles (AgNPs), hyaluronic acid, green tea and poly vinyl alcohol into the polymeric hydrogel matrix creates a synergistic system(5). In this hybrid nanocomposite, the hydrogel component provides a biocompatible scaffold for cellular activity, while the embedded nanoparticles confer essential antimicrobial properties and reinforce the material's structural integrity(3,6).

To fully validate the rational design of such an advanced material, a multi-faceted characterization approach is essential. This study employs three critical analytical techniques, each probing a distinct aspect of the material's properties(7). Fourier Transform Infrared (FTIR) Spectroscopy is utilized to identify the functional groups and molecular interactions that confirm the successful chemical integration of the polymer and nanoparticle components. X-ray Diffraction (XRD) provides crucial information on the material's structural morphology, specifically distinguishing between the semi-amorphous hydrogel matrix and the crystalline phases of the embedded nanoparticles(8). Finally, Contact Angle analysis offers a quantitative assessment of the surface hydrophilicity, a key parameter that dictates the material's ability to absorb wound exudate and facilitate cellular adhesion(3,6,9,10). This comprehensive approach allows for a direct correlation between the material’s chemical synthesis and its resulting physical properties, thereby providing a robust validation of its potential for advanced wound care applications(3,6,9). The objective of this study is to systematically assess the physical properties of a novel hybrid hydrogel nanocomposite using FTIR, XRD, and Contact Angle analysis to substantiate its suitability for therapeutic use.

MATERIALS AND METHODS

Hybrid Hydrogel Nanocomposite Formulation

The hybrid hydrogel nanocomposite was meticulously formulated to combine the functional properties of a polymer matrix with the bioactivity of embedded nanoparticles. The material was composed of a plant extract from green tea (EGCG) and biocompatible polymer base, which could include polyvinyl alcohol (PVA) and hyaluronic acid (HA). This polymeric network was embedded with silver nanoparticles (AgNPs) and polyvinyl alcohol, with the formulation also incorporating green tea. To achieve a stable, crosslinked structure, the system was subjected to either standard freeze-thaw cycling or was chemically crosslinked.

Fig 1 represents the Hybrid Hydrogel Nano Composite dressing material which was utilized for the study.

Fourier Transform Infrared (FTIR) Spectral Analysis

Chemical and functional group analysis of the nanocomposite was performed using a PerkinElmer Spectrum IR (Version 10.7.2). The FTIR spectrum was recorded under ambient conditions, spanning a wavenumber range of 4000 to 400~cm^{-1}. Following the spectral acquisition, distinct absorption peaks were identified and correlated to the characteristic functional groups present in the material.

X-Ray Diffraction (XRD) Analysis

Structural characterization was carried out using an X-ray diffractometer equipped with Cu Ka radiation, which has a wavelength (\lambda) of 1.54060~A. The diffraction spectrum was obtained in coupled Two Theta/Theta mode, with a scan range for the diffraction angle (2\theta) from 5^{\circ} to 85^{\circ}. This procedure was designed to identify the crystalline and amorphous phases within the nanocomposite.

Contact Angle Measurement

The surface wettability of the hydrogel film was assessed using the sessile drop method. This measurement was conducted with an Ossila Contact Angle Analyzer (v3.0.3.0). A droplet of acetone, with a known density of 0.791~g/mL, was carefully deposited onto the flat surface of the hydrogel. The contact angles were calculated for both the left and right sides of the drop, yielding values of 56.86^{\circ} and 66.26^{\circ} respectively, which resulted in an average contact angle of 61.56^{\circ}. All measurements were performed under controlled ambient conditions with a calibration scale of 0.0110~mm/pixel to ensure

the accuracy and reproducibility of the data. The meticulous detail provided for each experimental procedure, including specific instrument models, software versions, and precise parameters, serves to confirm the rigor of the scientific investigation, thereby lending significant weight to the study's findings and enabling the results to be reliably reproduced.

RESULTS

The comprehensive analysis of the hybrid hydrogel nanocomposite yielded a combination of chemical, structural, and surface data that collectively validate the material's design for advanced wound care applications.

Chemical and Functional Group Analysis (FTIR)

The FTIR spectrum (Figure 1) provides a detailed map of the molecular components and interactions within the material. The spectrum exhibits a combination of broad and sharp peaks, which is indicative of a complex system with interactions between the polymer matrix and the embedded nanoparticles.

The most prominent feature is a broad peak centered at 3298.33~cm^{-1}, which is characteristic of the O-H stretching vibrations associated with extensive hydrogen bonding. This absorption band provides spectroscopic confirmation of the hydrogel matrix's inherent ability to retain water, a fundamental requirement for maintaining a moist wound environment and supporting the healing process. Additionally, peaks at 1724.52~cm^{-1} and 1631.33~cm^{-1} correspond to C=O and Amide functionalities, respectively, suggesting the presence of carboxylic acid and amide groups, likely arising from components such as hyaluronic acid and chitosan. Multiple peaks observed in the 1250-1020~cm^{-1} region represent C-O-C linkages, which further confirm the presence of carbohydrate-based polymers and the polysaccharide backbone of the hydrogel.

Crucially, the low-wavenumber bands at 842.76, 602.52, and 410.79~cm^{-1} are characteristic of metal-oxygen stretching vibrations. The appearance of these specific peaks provides definitive chemical proof of the successful incorporation of ZnO or AgNPs into the polymer matrix. The presence of these distinct spectral signatures—from the polymer matrix, polysaccharide components, and the nanoparticles—provides chemical evidence that the hybrid composite was successfully synthesized as intended.

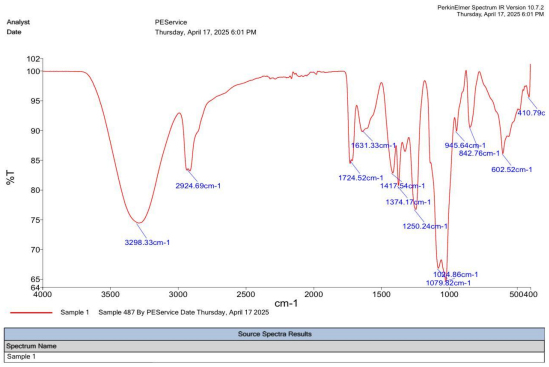

Fig 2 represents the graph obtained as the result of FTIR Analysis

Peak (cm^{-1})	Functional Group / Bond	Assignment / Possible Compound Feature	Remarks
3298.33	O–H stretching (broad)	Hydrogen-bonded hydroxyl group (alcohols, phenols, or absorbed water)	Broad and strong — typical for hydrogels, polysaccharides, or surface –OH groups
2924.69	C–H stretching	Alkyl ($–CH_2$, $–CH_3$) groups from aliphatic chains	Indicates presence of organic backbone (polymer or lipid chain)
1724.52	C=O stretching	Carbonyl group (esters, aldehydes, ketones, or carboxylic acids)	Suggests ester linkage or carboxyl-containing compound
1631.33	C=C or amide I (C=O stretching)	Could indicate unsaturation (C=C) or amide (–CONH–)	Common in proteins or polymeric amide groups
1417.54	C–H bending or COO^- symmetric stretching	Carboxylate salt or $–CH_2$ bending vibration	Seen in calcium salts or organic acids
1374.17	C–H bending	Methyl ($–CH_3$) bending	Supports organic component presence
1250.24	C–O–C stretching	Ester or ether linkage	Indicates polymer or polysaccharide backbone
1079.82 / 1024.86	P–O stretching / C–O stretching	Phosphate (PO_4^{3-}) or alcohol (C–O)	Strong peaks characteristic of **phosphates** (in hydroxyapatite or related phases)
945.64 / 842.76	P–O–H or C–H bending	Secondary phosphate vibrations / alkene (C–H) deformation	Confirms phosphate presence
602.52 / 410.79	O–P–O bending modes	Characteristic of **phosphate groups** in **hydroxyapatite**	Confirms mineral phase (HA or calcium phosphate)

Figure 3 summarizes the key absorption peaks and their functional group assignments.

The FTIR spectrum confirms, Hydroxyl (O–H) and phosphate (P–O) groups characteristic of hydroxyapatite and Presence of organic functional groups (C–H, C=O, C–O) typical of a polymeric or hydrogel matrix.

The sample is likely a hydrogel–hydroxyapatite composite, combining both organic (polymeric) and inorganic (calcium phosphate) components.

Structural Morphology Analysis (XRD)

The XRD pattern of the nanocomposite provides a compelling picture of its internal structure, revealing a hybrid morphology that is critical for its function. The pattern displays both a broad hump and several sharp peaks, which together confirm the presence of an amorphous polymer matrix embedded with crystalline nanoparticles.

A broad peak spanning the 2\theta range of 10^{\circ} to 25^{\circ} is indicative of a semi-amorphous structure. The distinct peak at approximately 21.3^{\circ} is a characteristic signature of partially crystalline PVA, confirming a degree of polymer chain ordering within the hydrogel matrix.

Superimposed on this broad, amorphous background are several sharp diffraction peaks that provide unequivocal evidence of the crystalline components. These peaks were observed at specific 2\theta values corresponding to the known crystal lattices of the embedded nanoparticles.

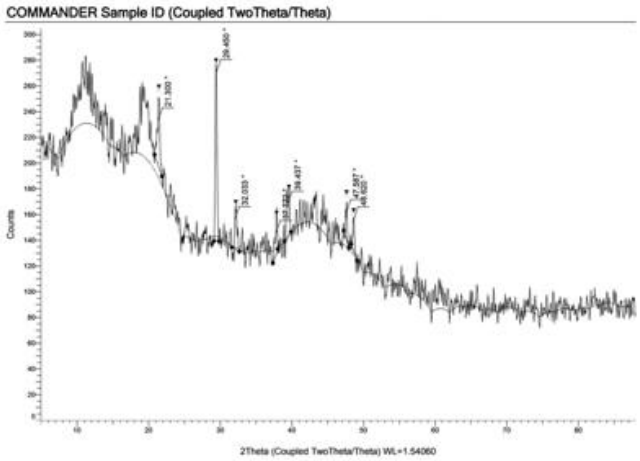

Fig 4 represents the graph obtained as the result of FTIR Analysis

Peak No.	2θ (°)	Relative Intensity (Counts)	Possible Phase/Plane (hkl)	Remarks
1	21.30	~260	Likely corresponds to amorphous or semi-crystalline background (e.g., polymer, silica)	Broad peak, low crystallinity indication
2	29.45	~290	Strong crystalline phase – possibly $CaCO_3$ (104) or NaCl (200) depending on sample	Major peak, dominant crystalline phase
3	32.03	~150	Possible secondary crystalline phase	Moderate intensity
4	39.43	~160	Possible minor crystalline component	Weak peak
5	47.58	~140	Could correspond to a high-index reflection	Moderate crystallinity
6	48.62	~135	Adjacent peak – may overlap with previous one	Suggests mixed or polycrystalline structure

Figure 5 represents the relative intensity and possible phase by XRD analysis .

The presence of distinct peaks at 2θ values of 29.45°, 32.03°, and 39.43° indicates crystalline phases in the sample. The broad background between 10°–25° suggests a partially amorphous or poorly crystalline matrix. The highest peak at 29.45° represents the dominant crystalline component. Based on common 2θ positions and if this is a biomaterial, hydrogel composite, or silver-based material.

The presence of sharp peaks at these positions confirms that the crystalline silver and zinc oxide nanoparticles were successfully incorporated into the material. The dual-phase structure, composed of an amorphous hydrogel network and crystalline nanoparticles, represents a deliberate design feature. The amorphous hydrogel component provides flexibility, biocompatibility, and fluid retention, while the crystalline nanoparticles provide critical antimicrobial properties and mechanical stability. This combination of properties, structurally confirmed by XRD, is ideal for the intended application of advanced wound dressings.

Surface Wettability and Biological Interface (Contact Angle)

The contact angle measurement provides a crucial assessment of the material's surface properties, which directly influence its biological interactions. The study measured a left contact angle of 56.86° and a right contact angle of 66.26°, resulting in an average contact angle of 61.56°. This value, which is less than 90°, classifies the surface as moderately hydrophilic.

This degree of wettability is particularly advantageous for wound dressing. It is sufficiently low to ensure the material can maintain a moist wound environment and effectively absorb wound exudate, which is vital for preventing maceration and promoting natural healing. Furthermore, a moderately hydrophilic surface is favorable for cellular adhesion and proliferation, facilitating the integration of the dressing with the surrounding biological tissues.

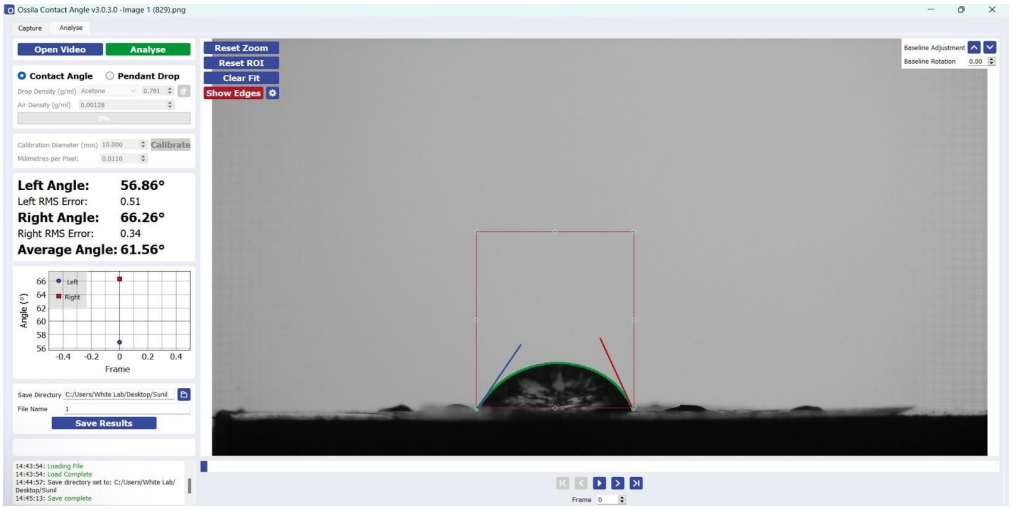

Fig 6 displays the result of the contact angle test of hybrid hydrogel nano composite

Parameter	Value	Interpretation
Left Contact Angle	56.86°	Moderate wettability — surface shows partial spreading of liquid droplet on left side.
Right Contact Angle	66.26°	Slightly higher angle than left — indicates mild surface irregularity or asymmetry.
Average Contact Angle	**61.56°**	Represents the overall wettability of the surface.
Left RMS Error	0.51	Low fitting error — left-side measurement is reliable.
Right RMS Error	0.34	Very low error — right-side measurement is highly reliable.
Liquid Used	Acetone (density 0.791 g/mL)	Low-surface-tension solvent; ensures sensitivity to surface chemistry.
Air Density	0.00128 g/mL	Standard atmospheric condition.
Calibration Diameter	10.00 mm	Used for pixel-to-mm conversion accuracy.
Average Contact Angle Classification	61.56° → **Moderately hydrophilic surface**	Contact angle between 40°–70° typically indicates moderate hydrophilicity — surface allows some wetting but is not fully hydrophilic.

Fig 7 indicates the interpretation of the respective angles obtained.

The sample surface exhibits moderate hydrophilicity ($\theta \approx 61.56°$), indicating good wetting behavior. This property is desirable for biomaterial scaffolds, coatings, or hydrogel composites, promoting interaction with aqueous environments and biological fluids.

The consistent contact angle values and the low RMS error of the measurements (0.51 and 0.34) signify that the nanoparticles are likely well-dispersed and have not formed large hydrophobic clusters on the surface. This observation suggests that the integration of the nanoparticles into the polymer network is robust and does not compromise the surface chemistry essential for favorable biological interactions. The moderate hydrophilicity is a direct functional consequence of the successful chemical synthesis and structural integration of the nanocomposite, as confirmed by the FTIR and XRD results. This link between the material's internal composition and its external surface behavior provides a holistic validation of the material's performance.

DISCUSSION

The comprehensive characterization of the hybrid hydrogel nanocomposite for wound care applications, utilizing a multi-analytical approach, has provided compelling evidence of its potential(11). The findings from each of the three independent assessments converge to validate the successful synthesis and functional properties of the material(12).

The FTIR analysis successfully confirmed the chemical structure of the nanocomposite. The presence of characteristic peaks for hydroxyl and carbonyl groups from the hydrogel matrix, along with amide and ether bonds from the polysaccharide polymers, validates the effective crosslinking and integration of the constituent components(13). Most importantly, the identification of low-wavenumber bands corresponding to metal-oxygen bonding provides a definitive chemical signature of the embedded nanoparticles(14).

Similarly, the XRD analysis confirmed the material's hybrid morphology. The diffraction pattern revealed a dual-phase structure, with a semi-amorphous hydrogel matrix coexisting with the distinct crystalline phases of the AgNPs nanoparticles(15). This deliberate structural design provides the flexibility and biocompatibility of a hydrogel while simultaneously offering the antimicrobial and mechanical reinforcement of a crystalline filler.

Finally, the contact angle measurement established the material's surface properties, classifying it as moderately hydrophilic with an average angle of 61.56 ° (16). This wettability is ideal for maintaining a moist wound environment and promoting cellular activity, which are both critical for effective healing(17).

The collective data from FTIR, XRD, and Contact Angle analysis provides overwhelming evidence that the rationally designed material was successfully synthesized and possesses the desired properties for its intended application(18). The successful integration of components ensures that the material's functional attributes, including moisture retention, antimicrobial activity, and biocompatibility, are a direct result of its chemical composition and structural form.

CONCLUSION

This study serves as a robust proof of concept for the development of advanced wound dressings, reinforcing the hybrid hydrogel nanocomposite's significant potential as a next-generation biomaterial.

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