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Synthesis and Characterization of Hydrogel from *Gongronema latifolia* for Potential Drug Delivery

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Abstract

This study reports the synthesis and characterization of a plant-based hydrogel derived from *Gongronema latifolium* leaf extracts for potential drug delivery applications. Bioactive components, including alkaloids, flavonoids, terpenoids, and saponins, were extracted from the leaves using standard procedures, after which a biocompatible hydrogel was synthesized from poly(vinyl alcohol) (PVA) and polyethylene glycol (PEG) and characterized using UV–visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), scanning electron microscopy (SEM), and X-ray diffraction (XRD). The results confirmed the successful incorporation of the plant extracts, revealing a porous, interconnected three-dimensional polymer matrix. TGA data showed that the hydrogel is thermally stable, bioactive, and possesses semicrystalline porous structures with high entrapment capacity, making it suitable for drug delivery, water retention, and solute diffusion. FTIR analysis confirmed the presence of hydroxyl, carbonyl, and other functional groups, indicating strong hydrogen bonding and extensive polymeric crosslinking. SEM images revealed a rough, heterogeneous surface morphology with interconnected pores, while XRD patterns indicated slight crystalline features within an overall amorphous

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structure. Collectively, these findings demonstrate the successful development of a structurally robust and bioactive hydrogel with promising applications in drug delivery and agriculture. The hydrogel's properties position it as an attractive alternative to synthetic petrochemical-based materials that pose environmental risks and highlight the potential of *Gongronema latifolium* leaf-extract-based hydrogels for future therapeutic and drug delivery applications.

Keywords: *Gongronema latifolium*; Plant-Based Hydrogel; Drug Delivery; Polyvinyl Alcohol; Polyethylene Glycol; Porous Polymer Matrix

INTRODUCTION

Over the centuries, humans have faced numerous diseases and ailments, initially relying on traditional remedies like herbs and plant parts (Ozioma and Chinwe, 2019). With scientific advancements, particularly in nanotechnology, hydrogels have emerged as a revolutionary tool in drug delivery systems (DDS) (Pushpamalar *et al.*, 2021). Conventional drug administration often suffers from inefficiencies such as poor bio-distribution and lack of selectivity, but controlled DDS addresses these issues by targeting specific sites, minimizing side effects, and enhancing drug stability (Kumar *et al.*, 2023). This approach reduces dosage requirements, lowers toxicity, and improves patient compliance, making it a promising alternative to traditional methods. Scientists are actively exploring ideal in nano-vehicles, such as hydrogels, to optimize drug absorption and delivery.

A topical drug delivery system is highly favoured for localized administration of therapeutic agents, particularly in the management of pain and inflammation, hormonal therapy, and treatment of cardiovascular and central nervous system disorders (Stanos, 2020). This route offers convenience and affordability while minimizing drug loss due to first-pass metabolism, thus optimizing therapeutic effects and avoiding interference from factors such as pH, enzymes, and intestinal bacteria (Jeong *et al.*, 2021).

In recent decades, biomaterials like liposomes, hydrogels, solid lipid nanoparticles, and polymeric micelles have advanced drug carrier systems (Joy *et al.*, 2022). These nano-carriers can encapsulate drugs, enabling precise delivery to previously inaccessible sites while ensuring biocompatibility, non-toxicity, and biodegradability (Shinde *et al.*, 2021). Such innovations have significantly improved drug efficacy and safety, offering targeted

therapies that outperform conventional methods. Hydrogel stands out as a semi-solid topical dosage form characterized by cross-linked three-dimensional networks of hydrophilic polymer chains, enabling it to retain a significant amount of water (Parhi, 2020). There has been a notable surge in interest surrounding the biomedical utilization of hydrogels constructed from natural polysaccharides, driven by their outstanding attributes, including superb biocompatibility, biodegradability, hydrophilicity, and bio-functionality (Tavakol *et al.*, 2016).

A hydrogel is formed through the crosslinking of polymer chains, either from a single monomer or through interactions such as hydrogen bonds and strong van der Waals forces (Catoira, 2019). These interactions result in the formation of a three-dimensional network structure, achieved by introducing intermolecular cross-links between linear polymer chains. These cross-links may be established through covalent bonds, as well as electrostatic, hydrophobic, or dipole-dipole interactions (Singh and Mahto, 2017). Hydrogels offer several advantages over other types of topical drugs, including enhanced biocompatibility, a porous structure, adjustable biodegradability, and appropriate mechanical strength (Chai *et al.*, 2017). Among hydrogels, in situ forming ones have attracted increasing attention in the drug delivery and tissue engineering fields.

Despite the vast variety of polysaccharides in nature, only a small collection of naturally occurring polysaccharides has been investigated in the preparation of hydrogels for biomedical applications. Natural polymers such as polysaccharides and proteins have been used as raw materials for preparing hydrogels. Moreover, hydrogels can be derived from plants (Fathi *et al.*, 2022).

Gongronema latifolium, commonly known as Amaranth globe, is a tropical rainforest plant belonging to the family Asclepiadaceae and genus Gongronema (Balogun *et al.*, 2016). It is native to West Africa and is referred to as "Utasi" by the Ibibios, Quas, and Efiks; "Utazi" by the Igbos in the Southeast; and "Arokeke" by the Yorubas in the Southwest of Nigeria. This plant features edible green leaves, yellow flowers, and stems that release milky latex when cut. Its flavour is characterized by a sharp bitterness with subtle sweetness, especially noticeable when consumed fresh. *Gongronema latifolium* is highly valued for its nutritional and medicinal benefits. Its leaves are rich in fats, proteins, vitamins, minerals, and essential amino acids (Eleyinmi, 2007). Common culinary uses include adding the leaves to soups, drying and grinding them into a spice, or using them in salads (Morebise *et*

al., 2002; Ugochukwu *et al.*, 2003). In Sierra Leone, the root and stem are used as chewing sticks or processed into liquor. This liquor, obtained by boiling sliced plant parts with lime juice or infusing them in water for several days, serves as a remedy for colic, stomach pains, and worm infections (Onike, 2010). *Gongronema latifolium* is also believed to possess medicinal properties due to its diverse array of active chemicals, some of which have been scientifically validated (Balogun *et al.*, 2016).

In recent years, there has been growing interest in utilizing medicinal plant extracts for hydrogel production due to their inherent bioactive properties, cost-effectiveness, and minimal toxicity. Medicinal plants such as *Gongronema latifolium* is traditionally used for treatment, yet their application in advanced drug delivery systems has not been thoroughly investigated. There is a need to assess compatibility in hydrogel production and evaluate their potential for controlled drug release. Therefore, this study seeks to address these gaps by developing and characterizing plant-based hydrogels from *Gongronema latifolium* leaf extracts.

Statement of Problem

The production of effective and biocompatible drug delivery systems remains a critical challenge in modern medicine. Conventional drug delivery methods often face limitations, including poor bioavailability, rapid drug degradation, and systemic side effects (Sultana *et al.*, 2022; Homayun *et al.*, 2019). Hydrogels have emerged as promising candidates for targeted and sustained drug delivery due to their high water content, tunable physicochemical properties, and ability to provide controlled drug release. However, many synthetic hydrogels lack biocompatibility and biodegradability, necessitating the exploration of natural, plant-based alternatives that offer improved safety and therapeutic efficacy.

There is a need to assess compatibility in hydrogel production and evaluate their potential for controlled drug release. Therefore, this study seeks to address these gaps by developing and characterizing plant-based hydrogel from *Gongronema latifolium* leaf extract.

Justification of the Study

The production of plant-based hydrogels presents a significant opportunity to overcome the limitations of conventional synthetic systems, such as poor biocompatibility, high toxicity, and environmental concerns. Natural polymers derived from medicinal plants offer a sustainable and cost-effective alternative, with inherent bioactive properties that can enhance therapeutic efficacy. Many existing hydrogels rely on synthetic materials, which

may pose biocompatibility challenges. This study aimed to produce a safer, biodegradable and plant-based drug delivery system

Aim and Objectives of the Study

The aim of the study is to produce hydrogel of *Gongronema latifolium* plant extracts, characterize and determine the entrapment efficiency

The aim of the study was achieved by the following objectives;

i. Carry out extraction on Gongronema Latifolia plant using ethanol, methanol and disttle water.
ii. Characterize the plant extract and produce hydrogel using FTIR, SEM, XRD, TGA and UV-VISIBLE SPECTROSCOPY
   Synthesize hydrogel using plant extracts and PVA
iii. Determine the entrapment efficiency and drug loading of the synthesized hydrogel.

MATERIALS AND METHODS

Materials Used

All reagents were of analytical grade and procured from certified suppliers. They include Polyethene glycol, Poly (vinyl alcohol), Magnesium ion (Mg^{2+}), Ethanol, Methanol, Distilled water and Potassium persulphate (KPS). The plant material was *Gongronema latifolium.*

Collection of Plant Material

The *Gongronema latifolium* leaves were obtained from Wukari Local Government Area, Taraba State, Nigeria. The leave was identified in the Biological Science Department at Federal University Wukari, Taraba State. The leave was properly cleaned with distilled water, cleaned of debris and air-dried under shade at room temperature. The dried material was coarsely pulverized using a mortar and pestle into fine powder. The powdered sample was sealed in an air-tight plastic container, labelled appropriately and stored at room temperature until ready for extraction.

Extraction of Compound from the Plant

Extraction was done by first weighing three portions of 60g (a portion for each solvent) of the pulverized leave sample using a sensitive weighing balance. It was macerated

in 500 ml of methanol, ethanol and distilled water in separate jars for 24 h under repeated stirring. Thereafter, the mixture was filtered using Whatman filter paper No. 1, while the ensuing residues were macerated again twice for the same duration in similar solvents (Cannell, 2006). Filtrates from the three rounds of maceration of each solvent portion were combined and evaporated at 45 °C to get a concentrated solution using a rotary evaporator. The extracts were then preserved under refrigerated conditions in air-tight glass containers until further use.

Preparation of the Hydrogel

The method described by AttahDaniel *et al.* (2023) was used to prepare the hydrogel. Polyvinyl alcohol (PVA) (10.0 g) was dissolved in 100 mL of double-distilled water in a 250 mL beaker at a temperature of 90 °C on a hot plate while stirring. The solution was left to cool down to room temperature. Polyethylene glycol (PEG) (5 ml) was added to the reaction mixture. The plant extract (100 ml) was mixed with the reaction. Magnesium sulphate (10 ml) was added as a cross-linking agent. The pH of the mixture was adjusted to neutral (pH 7.0) using a 0.1M sodium hydroxide solution. Potassium persulpate (KPS) (1g) was added to the mixture as an initiator to begin the polymerization process. The solution was stirred for 15 minutes at 60 °C on a hot plate to ensure uniform mixing and activation of the initiator. The solution was transferred into a mould or petri dish where it was allowed to cool and solidify at room temperature for 72 hours, forming a cross-linked hydrogel.

Characterization of Hydrogel

Swelling Ratio Determination

The swelling study of the hydrogel was determined using dry sample in distilled water. The pre-weighed hydrogel sample was immersed in different solutions at 27 °C and 37°C for swelling. The wet mass of the swollen sample was removed at particular time intervals, and the surface water was absorbed with filter paper to eliminate excess outer surface droplets (Madhusudana *et al.*, 2021). The swelling ratio of the hydrogel was determined from Equation (1).

$$\text{Swelling ratio } (\%) = \frac{W_2 - W_1}{W_1} \text{ x } 100 \qquad (1)$$

Where, W_1 and W_2 are the dry and swollen weights of the hydrogel.

Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

The FTIR spectra of the hydrogel were obtained using a Fourier Transform Infrared Spectroscopy (FTIR) instrument. The wave numbers ranged between 4000 and 800 cm^{-1}. Each sample was scanned 40 times for spectrum integration. The scanning resolution was 2 $cm^{-1,}$ and the spectras were recorded in transmittance.

Scanning Electron Microscopy (SEM) Analysis

The hydrogel was examined by scanning electron microscopy using a Scanning Electron Microscope (SEM). Sample was observed using an accelerating voltage of 15 kV. Hydrogel sample was initially treated with magnesium and ethyl alcohol (98°), dried up to the critical point and stored at 25°C on a desiccator with silica gel. The samples were mounted on bronze stubs and coated with gold-palladium alloy.

Thermogravimetric Analysis

The thermogravimetric analysis (TGA) of the synthesized hydrogel was carried out in a thermogravimetric analyzer. This was carried out by increasing the heat flow rate under the nitrogen atmosphere to 20°C/minute (Madhusudana *et al.*, 2021).

X-ray diffraction Analysis

Sample was analyzed for their crystalline phase using an X-ray powder diffractometer (XRD). The Ni-filtered Cu Kα radiation (λ = 0.15418 nm, 45 kV, 112 mA) was used in the range of 5–70° (2θ) with a step size of 0.01° (2θ) and scan rate of 20°/min (Dharmalingam and Anandalakshmi, 2019).

Determination of Entrapment Efficiency and Percent Drug Loading

A very important parameter to judge the suitability of a drug carrier system is its loading capacity and entrapment efficiency. The loading capacity is generally expressed in percent related to its hydrogel phase (hydrogel + drug). The entrapment efficiency and drug loading percent of hydrogel dispersion were determined by the centrifugation method as described by Agrawal *et al.* (2022). The precipitate of drug-hydrogel was dispersed in 100ml of double distilled water and was allowed for 3 min to dissolve the free drugs. The resulting dispersion was centrifuged for 3 min at 3,000 rpm. The drug content in the supernatant after centrifugation was measured by the UV-Spectroscopy method at 326 and 232 nm. The drug entrapment efficiency (EE) and drug loading (L) of the hydrogels were calculated using the following equations:

$$\%EE = \frac{W_a - W_s}{W_a} \times 100 \quad (2)$$

$$\%L = \frac{(W_a - W_s)}{(W_a - W_s + W_l)} \times 100 \quad (3)$$

Where W_a, W_s and W_l are: the weight of the drug added in the system, analyzed weight of the drug in supernatant and the weight of the lipid added in the system, respectively.

Preparation of Standard Curve for reference drug

One tablet of reference drug (Diabetmin) was weighed using an analytical weighing balance, and the weight was 0.5609g. The drug was crushed using a mortar and pestle, before 0.0263g of the drug was weighed and dissolved in 100ml of distilled water. 0.0430g, 0.0643g, 0.0827g, 0.1085g and 0.1204g were all dissolved separately in 100ml distilled water as well, and then used to prepare the calibration curve. One tablet of Diabetmin contains 500mg of the active ingredient metformin HCl. The absorbances of the different solutions were all determined using a UV-6300PC Spectrophotometer at 232nm and 326nm, and the values were recorded.

Drug Application to Hydrogel before Centrifugation

1g of the hydrogel was weighed into a beaker, 100ml of distilled water was added, and the solution was kept for 48hours to dissolve. 100ml of the solution was measured into a beaker while 0.0647g of the crushed drug was introduced. Another 100ml of the dissolved hydrogel was measured into a different beaker while 0.1206g of the crushed drug was added, and the solution was mixed by stirring, then the absorbance was taken using a UV-6300PC Spectrophotometer at 326nm, respectively, and the values were recorded.

Drug Application to Hydrogel after Centrifugation

The mixture was centrifuged using a Heraeus Megafuge 16R centrifuge at 3,000 revolutions per minute(rpm) for 3 minutes, the upper layer was decanted the absorbance of supernatant was determined using a UV-6300PC Spectrophotometer at 326nm.

RESULTS AND DISCUSSION

Swelling Ratio, Entrapment Efficiency and Percentage Drug Loading of the Hydrogel

The swelling ratios of PVA-PEG hydrogel and *Gongronema latifolium* leaf hydrogel, entrapment efficiency and percent drug loading of the hydrogels are shown in Table 1. The swelling ratio of hydrogels is a critical parameter that indicates their water absorption capacity, which is essential for applications such as drug delivery, wound healing, and tissue engineering. The *Gongronema latifolium* leaf hydrogel exhibited a high swelling ratio of 298.39%, indicating superior water absorption compared to the PVA-PEG hydrogel formulation. This high swelling capacity may be attributed to the presence of hydrophilic functional groups in the bioactive compounds of *G. latifolium*, which enhance water uptake by increasing the hydrogel's porosity and hydrophilicity (Fathi *et al.*, 2022). The hydrogel formulations exhibited excellent entrapment efficiency of 98.7% (Table 1), indicating highly effective incorporation of *Gongronema latifolium* bioactive compound into the polymer matrix. The PVA-PEG hydrogel exhibited entrapment efficiency of 98.5% (Figure 4), suggesting that the polymer matrix itself has a strong inherent capacity for encapsulation, which was further enhanced by the synergistic inclusion of both plant extracts (Ren *et al.*, 2022). The high entrapment efficiencies observed in this study may be due to strong phytoconstituent-matrix interactions. These interactions are crucial for minimizing compound loss during hydrogel formation and ensuring controlled drug release. The porous structure of the hydrogel, likely facilitated efficient entrapment, by providing ample space for extract incorporation while maintaining structural stability (Fathi *et al.*, 2022).

The value observed in this study was higher than the entrapment efficiency of cubosomal formulation (86.4%) reported by Archana *et al.* (2015). Reddy and Thakur (2019) reported that silver nanocomposite hydrogel had an entrapment efficiency of 58.7%. Dharmalingam and Anandalakshmi (2019) observed that citric acid-crosslinked hydrogels demonstrated controlled drug release profiles influenced by crosslinking density but exhibited lower entrapment efficiency compared to the *G. latifolium*-loaded hydrogels in this study.

The drug loading capacity of the *Gongronema latifolium* leaf hydrogel was observed at 88.5% (Table 1). This high loading efficiency is critical for ensuring therapeutic drug

concentrations are maintained over prolonged periods (Liu *et al.*, 2020). The negligible difference between the PVA-PEG hydrogel (91.4%) and the *Gongronema latifolium* (88.5%) suggests near-complete saturation of the matrix. The efficient retention of plant extracts without significant leaching during loading confirms the hydrogel's structural stability (Pelin *et al.*, 2023).

Table 1: Swelling ratio, entrapment efficiency and percentage drug loading of *Gongronema latifolium* leaf hydrogel

Swelling ratio (%)	Entrapment efficiency	Percentage drug loading
298.39	95.6±0.21	88.5±0.17

FTIR Spectra of *Gongronema latifolium* Leaf Extract and its Leaf Hydrogel

The FTIR spectra of *Gongronema latifolium* leaf extract and its leaf hydrogel are shown in Table 2. The leaf extract showed a band at 3435 cm^{-1} (O-H stretching) (Figure 2), and the hydrogel displayed a similar peak at 3479 cm^{-1} (Figure 2). The leaf extract also features sharp free hydroxyl peaks at 3785 cm^{-1} and 3704 cm^{-1}, which are absent in the hydrogel, suggesting that the hydrogel's polymeric matrix may restrict free hydroxyl groups through interactions or encapsulation. Both spectra show strong C=O stretching vibrations (1651 cm^{-1} in the leaf extract and 1641 cm^{-1} in the leaf hydrogel) (Thippeswamy *et al.*, 2021). The C-H stretching region in the leaf extract, with peaks at 2959 cm^{-1} and 2836 cm^{-1}, corresponds to aliphatic hydrocarbons, while the hydrogel lacks these distinct peaks. The hydrogel shows a prominent C–O stretch at 1083 cm^{-1}, which is absent in the extract, confirming the presence of the hydrogel's polymeric structure.

The peaks at 1466 cm^{-1} (C-H bending) and 1376 cm^{-1} (COO^- symmetric stretch) suggest organic acids or phenolics in the *Gongronema latifolium* leaf extract (Figure 1), whereas lower-frequency peaks (804 cm^{-1} and 456 cm^{-1}) were observed in the leaf hydrogel (Figure 2), implying C-H bending and metal-oxygen interactions. In the fingerprint region (<1500 cm^{-1}), the leaf extract displays multiple peaks (1248 cm^{-1} for phenolic C-O stretching), while the leaf hydrogel's spectrum is comparatively simpler. The absence of certain extract peaks (2647 cm^{-1} and 2354 cm^{-1}, possibly from S-H or $N-H^+$

vibrations) in the hydrogel suggests that some leaf components may not be fully incorporated or are altered during hydrogel formation.

Table 2. FTIR Spectral Data of *Gongronema latifolium* Leaf Extract and its Leaf Hydrogel

Samples	OH	C-H	N-H or S-H	C≡N or S-C≡N	C=O	COO^-	C-O	sC-H	M-O or S-S
Gongronema latifolium leaf extract	3785.00, 3704.00, 3550.32, 3435.00, 3083.00,	2959.89, 2836.44	2647.00, 2354.00	2038.23, 1887.36	1651.38,	1583.09, 1505.32, 1466.65, 1420.64, 1376.27, 1296.57	1248.48, 1176.73, 1120.45, 1065.72, 1015.19	863.19, 812.78, 732.65, 678.84	513.47, 407.61, 371.41
Gongronema latifolium leaf synthesized hydrogel	3479.00	-		-	1641.52		1083.00	804.07	456.00

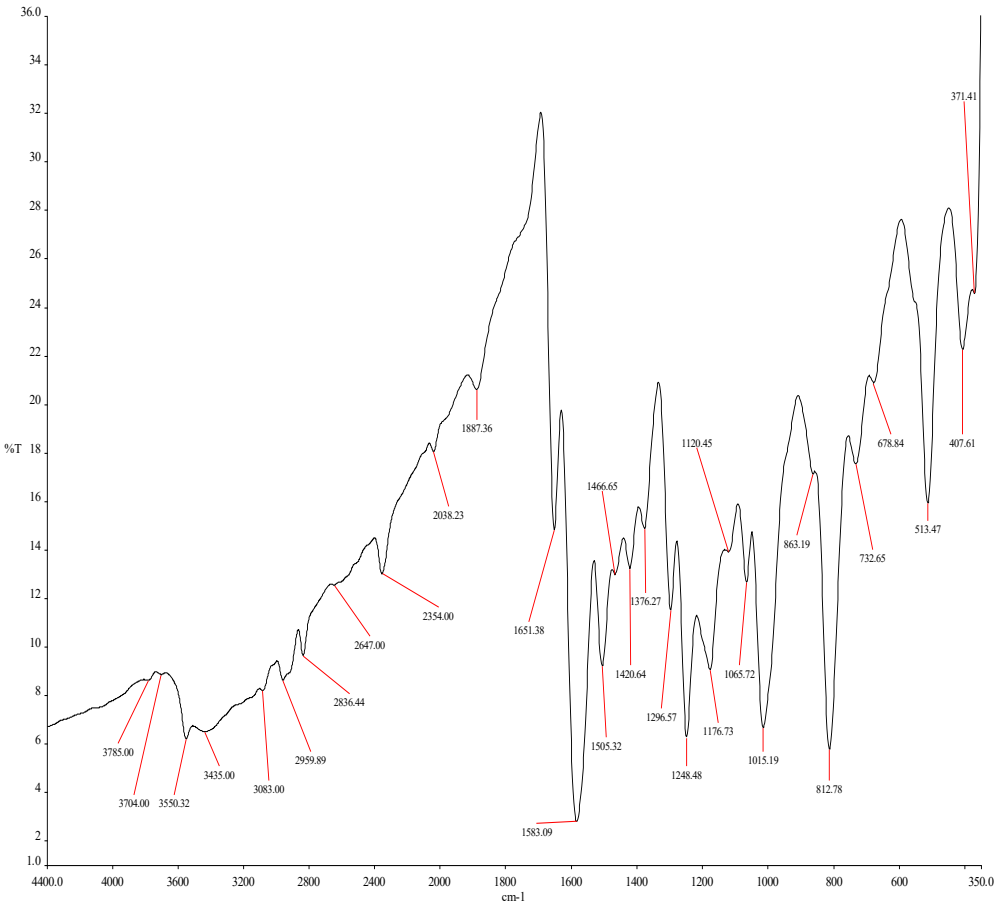

Figure 1. FTIR spectrum of *Gongronema latifolium* leaf extract

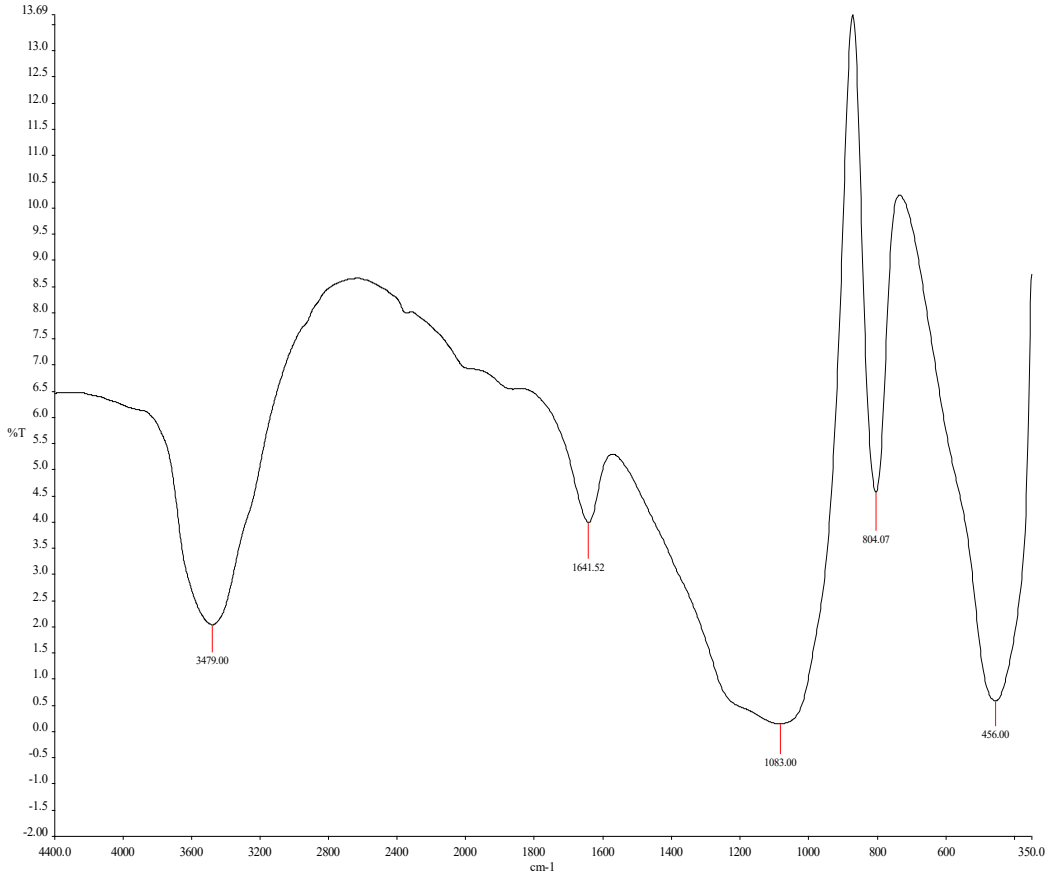

Figure 2. FTIR spectrum of *Gongronema latifolium* leaf hydrogel

Scanning Electron Microscopy (SEM) of the Hydrogel

The SEM micrographs of the hydrogel revealed a highly porous and interconnected three-dimensional network structure, critical for drug delivery applications (Figures 3 and 4). The hydrogel showed spherical and irregular pores. The particulate aggregates observed resemble the moisture-extrusion pores in PEO-LaBDC (AttahDaniel *et al.*, 2023), suggesting analogous syneresis-driven pore formation. The structural integrity and pore uniformity of the hydrogels showed its suitability for nutrient diffusion and cellular interactions. Musa *et al.* (2019) reported that the polyacrylic acid hydrogel exhibited a smooth surface morphology before drug loading, which became noticeably rougher after the incorporation of DPH. *Gongronema latifolium* Leaf-Loaded Hydrogel appears flaky and porous, with distinct crystal clusters. It exhibit more dispersed texture than unmodified hydrogel. Some levels of micropore formation are visible, indicating effective loading and dispersion of plant extract into the hydrogel. The increased porosity may support better nutrient/drug diffusion or biological interactions. The *Gongronema latifolium* leaf hydrogel

exhibits a homogeneous pore distribution, with lower magnifications revealing a honeycomb-like architecture.

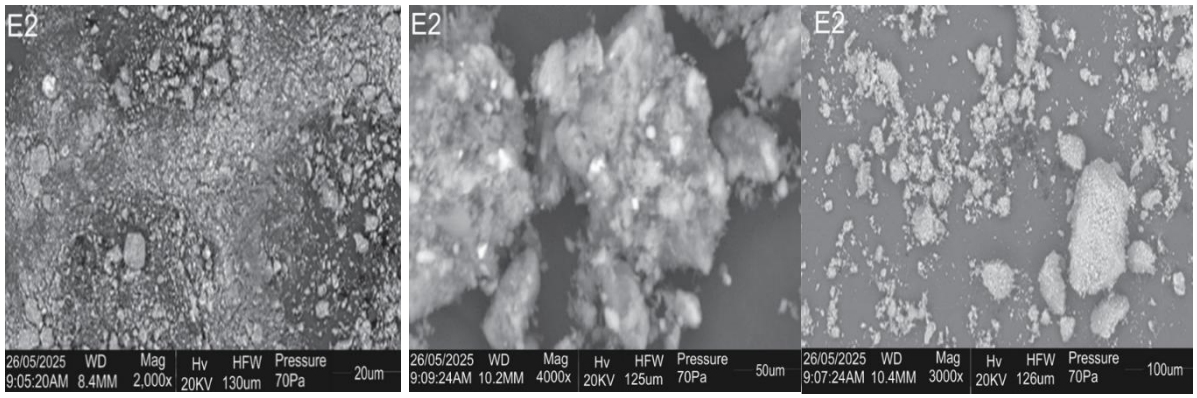

Figure 4. SEM image of PVA-PEG hydrogel

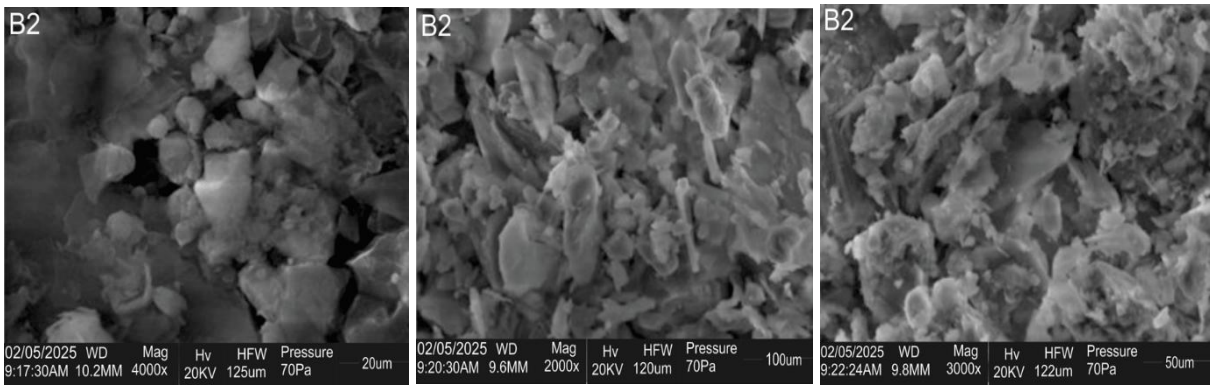

Figure 5. SEM images of *Gongronema latifolium* leaf hydrogel.

XRD Pattern of the Hydrogels

The XRD pattern of the *Gongronema latifolium* leaf hydrogel is shown in Figure 6. *Gongronema latifolium* leaf hydrogel has a prominent peak at the (111) plane (Figure 6), suggesting the presence of ordered domains. The peak broadening and low intensity indicate small crystallite sizes or lattice strain, possibly due to interactions between plant metabolites and the polymer network. The absence of sharp peaks at higher 2θ angles confirms the dominance of amorphous phases, typical of hydrogels, while the detectable crystallinity may arise from bioactive compounds or crosslinking complexes.

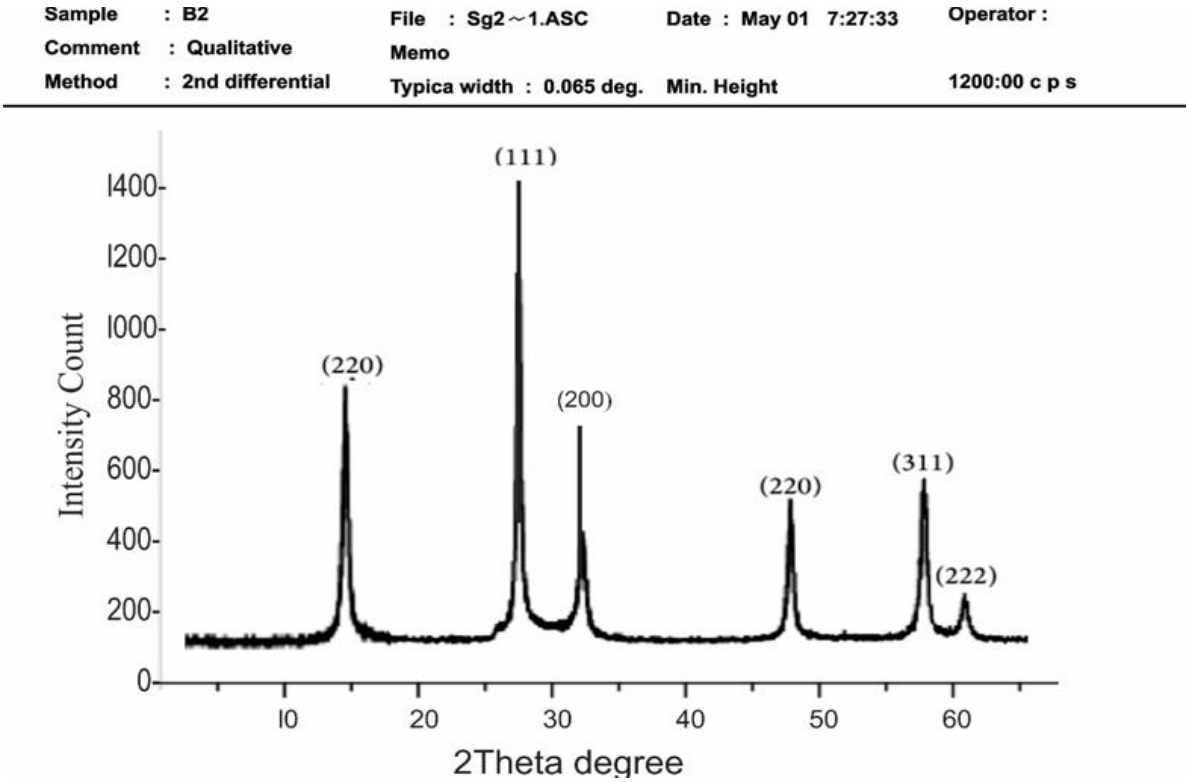

Figure 6. XRD image of *Gongronema latifolium* leaf hydrogel.

Thermogravimetric Analysis Graph of the Hydrogels

Thermogravimetric analysis (TGA) was used to analyse the thermal stability of the *Gongronema latifolium* leaf hydrogel, and the result shown in Figure 7. Thermogravimetric analysis revealed that the *Gongronema latifolium* leaf hydrogel exhibited significant degradation around 332°C, which indicates its suitability for applications requiring sterilization or exposure to elevated temperatures. The analysis provided insights into the moisture content and structural integrity of the hydrogel, with initial minor weight losses below 100°C attributed to water evaporation, followed by major degradation due to polymer matrix breakdown. When heating the sample up to 100 °C, weight losses due to water (moisture content) was observed. The Figure 4 shows that *Gongronema latifolium* leaf hydrogel had an initial minor weight loss (~1.3%) below 100°C. The major degradation step (70.5% mass loss) was observed at 332°C after an initial weight loss of 12.46%.

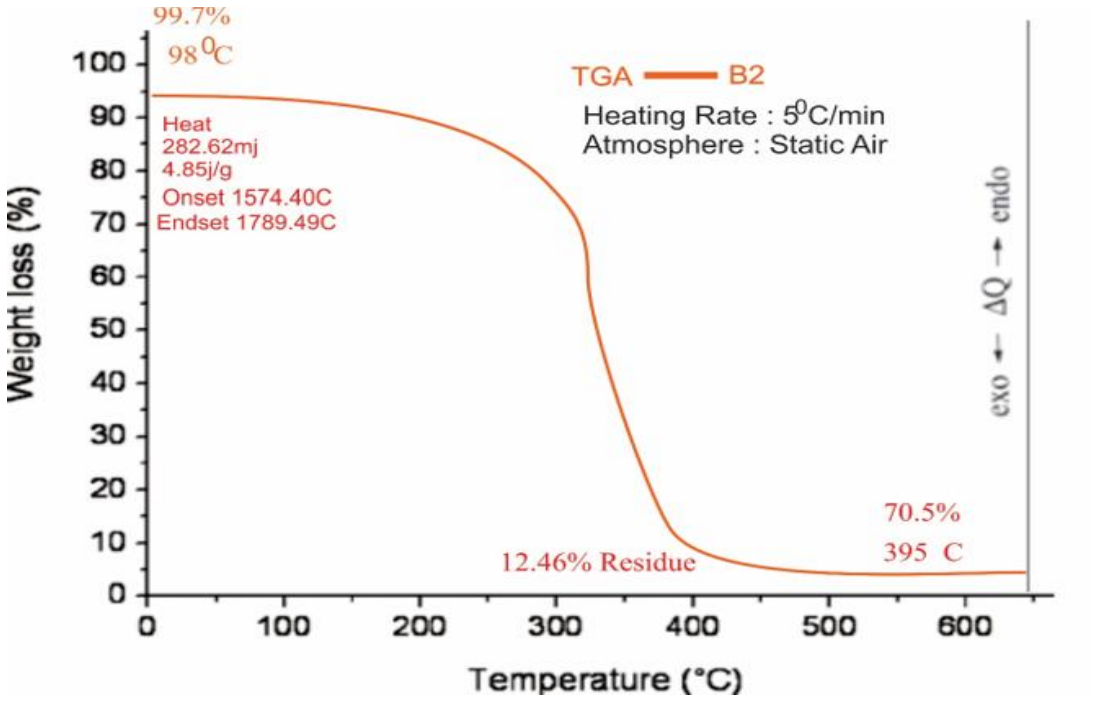

Figure 7. *Gongronema latifolium* leaf hydrogel TGA graph.

CONCLUSION

The study synthesized and characterized hydrogel from *Gongronema latifolium* leaf extracts. The *G. latifolium* leaf hydrogel exhibited a high swelling behaviour. Structural analyses, including FTIR and SEM, confirmed the successful incorporation of plant extracts while further characterization through XRD and TGA revealed that the hydrogel was semi-crystalline. The hydrogel also demonstrated excellent entrapment efficiency and high drug-loading capacity, indicating strong interactions between the bioactive compound and the polymer matrix. These properties are crucial for minimizing compound loss and enabling sustained drug release. The formulated hydrogel exhibits tuneable swelling, structural integrity, thermal stability, and high drug-loading capacity, making it a promising candidate for biomedical applications. The ability to support controlled drug delivery, wound healing, and tissue engineering highlights its versatility and potential for future therapeutic use.

Recommendations

To further develop and optimize the hydrogels for practical applications, the following recommendations are proposed:

i. *In vitro* drug release experiments should be conducted under varying pH and temperature conditions to assess the hydrogels' responsiveness and suitability for targeted drug delivery.

ii. Cytotoxicity and cell viability assays should be performed to ensure the hydrogels are safe for biomedical use, particularly in wound healing and tissue engineering.

iii. Further studies should test the hydrogels against common pathogens to validate their antimicrobial potential.

iv. Advanced characterization techniques like NMR, LC-MS, or DSC should be employed to further analyze phytochemical-hydrogel interactions and identify key bioactive compounds responsible for functional enhancements.

v. Further studies should be done to assess hydrogel performance in animal models to validate efficacy before clinical trials.

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