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DEVELOPMENT AND CHARACTERIZATION OF CELLULOSE-BASED HYDROGEL PATCHES AS A TOPICAL DELIVERY SYSTEM FROM AGRICULTURAL WASTE, INFUSED WITH *Aloe vera* AND COLLOIDAL OATMEAL FROM *Avena sativa.*

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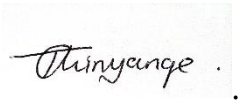
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DEVELOPMENT AND CHARACTERIZATION OF CELLULOSE- BASED HYDROGEL PATCHES AS A TOPICAL DELIVERY SYSTEM FROM AGRICULTURAL WASTE, INFUSED WITH *Aloe vera* AND COLLOIDAL OATMEAL FROM *Avena sativa.*

Submitted By: CHINYANGE TADIWANASHE **REG NO: B222251B**

In partial fulfillment of the requirements of the BACHELOR OF SCIENCE HONORS DEGREE IN CHEMICAL TECHNOLOGY.

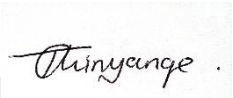
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DECLARATION

I, CHINYANGE TADIWANASHE, declare to Bindura University of Science Education that this dissertation is my original work and that all material and academic sources of information have been properly acknowledged. This work has not been submitted to any other academic institution for academic consideration.

Signed  Date: 30/05/2026

DEDICATION

For my parents, Atiel and Grace Chinyange, who have always supported me in everything, big or small. Without you, I would be nothing and have achieved nothing.

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I would like to express my profound gratitude to my project supervisor, Professor P Dzomba. Thank you for your invaluable knowledge, support, patience and encouragement. Your constructive feedback was of great importance to the success of this project. I am also deeply thankful to Dr Machingauta and the entire staff of the Department of Chemistry and the Chemistry Laboratory of Bindura University of Science Education for providing me with the necessary facilities and academic resources to complete this research and project.

LIST OF ABBREVIATIONS

FTIR	Fourier-Transform Infrared Spectroscopy
HPLC	High-Performance Liquid Chromatography
UV–Vis	Ultraviolet–Visible Spectroscopy
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
DSC	Differential Scanning Calorimetry
NaOH	Sodium hydroxide
NaOCl	Sodium hypochlorite
HCl	Hydrochloric acid
w/v	Weight per volume
v/v	Volume per volume
a.u.	Absorbance units
cm^{-1}	Wavenumber (reciprocal centimetres)
F1	Formulation 1 — 2% cellulose, 5% citric acid
F2	Formulation 2 — 3% cellulose, 7.5% citric acid (optimum)
F3	Formulation 3 — 4% cellulose, 10% citric acid
NF-κB	Nuclear Factor Kappa B
IκB-α	Inhibitor of Nuclear Factor Kappa B alpha
IL-8	Interleukin-8
SD	Standard Deviation
%CV	Percentage Coefficient of Variation
SR	Swelling Ratio
ANOVA	Analysis of Variance

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Abstract

Despite 20% of the world population being afflicted with allergic skin diseases such as urticaria and eczema, oral antihistamines are still most commonly prescribed despite their drawbacks; (e.g., first-generation agents, are blood-brain barrier-crossing while causing drowsiness). Long-term use could result in gastrointestinal disturbances and interactions. Topical drug delivery allows localized application of active ingredients at the site of the irritation, limiting systemic absorption. In this study, biodegradable cellulose-based hydrogel patches incorporated with *Aloe vera* and colloidal oatmeal extracts were prepared from maize cob as a source of sustainable cellulose. Cellulose was prepared by alkaline treatment and bleaching whilst *Aloe vera* and oatmeal extracts were prepared by aqueous and hydro-alcoholic extraction, respectively. The patches prepared were skin compatible with pH values ranging between 4.87 and 5.21, high swelling ratios (91.2–141.5%), low moisture contents (9.26–10.90%) and excellent flexibility (214-312 folds). FTIR spectra showed successful crosslinking of cellulose by citric acid, with effective incorporation of the active principles into the hydrogel network. The progressive increase in intensity of the C=O ester band at 1726 cm^{-1}, from F1 to F3, and the presence of a characteristic phenolic C-O stretching band at 1028 cm^{-1} confirmed the interaction between the components of the patches. The release of phenolics and flavonoids from the extracts into the formulation, was confirmed by UV-visible spectroscopy. The optimum patch (F2, composed of 3% cellulose and 7.5% citric acid) was identified with better physicochemical properties. This study revealed that agricultural waste in low-resource countries like Zimbabwe can be utilized effectively to form sustainable biodegradable hydrogel patches loaded with natural bio-actives for topical application on the skin.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Skin allergies are far more common than many people realize. Conditions such as atopic dermatitis, urticaria and eczema affect roughly one in five people worldwide - a striking figure that places allergic skin disease among the most prevalent chronic conditions seen in clinical practice (Dierick et al., 2020). What makes these conditions particularly difficult to manage is the nature of the immune response driving them: the body reacts to otherwise harmless substances, triggering itching, redness and inflammation that can significantly reduce quality of life. The standard management approach has long relied on oral antihistamines such as loratadine, cetirizine and diphenhydramine, which work by competitively blocking histamine receptors and thereby blunting the allergic cascade (Fonacier et al., 2010). These drugs are effective - but they come with a cost.

Although oral antihistamines are widely used and effective, their administration may be associated with several side effects. First-generation antihistamines easily penetrate the blood-brain barrier and bind to histamine receptors in CNS, causing hallucinations, drowsiness, restlessness, insomnia and other adverse CNS reactions(Fonacier et al., 2010). In some cases, prolonged oral administration may also lead to systemic side effects such as gastrointestinal discomfort and drug interactions. These limitations have encouraged researchers to find other ways for managing localized skin irritation and allergic reactions.

Topical delivery systems provide a promising alternative because they allow active compounds to act directly at the site of irritation while minimizing systemic exposure. Currently, topical drug delivery systems are getting more attention among researchers due to their promising therapeutic outcomes for the treatment of local and systemic diseases (Khan et al., 2022). The topical delivery of drugs has many advantages over other dosage forms because it minimizes systemic side effects, prevents metabolism of drugs by the liver, avoids gastrointestinal disorders associated with oral forms and avoids the inconvenience of parenteral forms(Khan et al., 2022).Among these topical drug delivery systems, hydrogels have attracted significant interest in biomedical and pharmaceutical research. Hydrogels are three-dimensional (3D) cross-linked molecular networks,

generally polymers, capable of holding large amounts of water(Bahram et al., 2016). The network of a hydrogel is established via covalent bonds or noncovalent interactions. Noncovalent interactions mainly include physical entanglements, hydrogen bonds, hydrophobic interactions, supramolecular interactions, electrostatic interactions and coordination interactions. A range of natural polymers (e.g., polypeptides, polysaccharides and DNA) and synthetic polymers (e.g., polyacrylamide and poly (vinyl alcohol)) have been widely explored to synthesize hydrogels with attractive properties(Ho et al., 2022). Their high water content, flexibility and biocompatibility make them suitable for applications such as wound dressings, transdermal patches and skin-soothing formulations.

Natural polymers are particularly suitable for making hydrogels because they are biodegradable and environmentally friendly(Yustira et al., 2021). Cellulose, the most abundant natural polymer in plant biomass, can be recovered from agricultural residues such as maize cobs and husks, which are plentiful in farming regions like Zimbabwe. Converting these wastes into cellulose creates an opportunity to transform agricultural by-products into useful biomaterials.

Incorporating plant extracts into the polymer matrix can further enhance a hydrogel's therapeutic effects. *Aloe vera* has long been used in traditional and contemporary medicine for its anti-inflammatory, moisturizing and wound-healing properties(Elferjane et al., 2023). Likewise, oats (*Avena sativa*) contain phenolic compounds, especially avenanthramides, that help reduce itching, inflammation and skin irritation(Xochitl et al., 2021).

1.2 Statement of the Problem

Anyone who has taken an antihistamine before a long drive knows the problem - the drowsiness arrives before the itch does. Medications like loratadine and cetirizine are effective at managing allergic skin conditions such as atopic dermatitis and urticaria but their systemic administration means the entire body is affected, not just the skin that needs treatment Ali (2018). For a localized rash on the arm, a pill that crosses the blood-brain barrier and causes fatigue is, at minimum, an inconvenient trade-off.

Meanwhile, a walk through any farming area in Zimbabwe after the maize harvest reveals something striking – maize residues piled in heaps, drying in the sun, waiting to be burned or left

to rot. These residues are rich in cellulose, a polymer with well-documented potential in biomaterial development, yet they are almost universally discarded. The gap between what these materials could become and what they are currently used for is considerable.

Plants like *Aloe vera* and oats (*Avena sativa*) have been applied to irritated skin for centuries - long before anyone knew what avenanthramides or acemannan were. Science has since caught up with the tradition but the research combining these plant extracts with agricultural waste-derived cellulose in a topical delivery system is sparse therefore, this study.

1.3 Hypothesis

Cellulose extracted from maize cob agricultural waste can be successfully formulated into biodegradable hydrogel patches incorporating *Aloe vera* and colloidal oatmeal extracts and the resulting patches will exhibit physicochemical and spectroscopic properties consistent with effective skin-soothing topical delivery systems.

1.4 Significance of the Study

The significance of this work operates on several levels simultaneously, making it worthwhile to pursue.

Environmentally, turning waste into useful products is definitely encouraged. Maize cobs are generated in enormous quantities across Zimbabwe each season and the vast majority are discarded. If even a fraction of that cellulose could be redirected into biomaterial production, the waste valorization argument alone would justify the research.

From a healthcare perspective, according to the Dermal Drug Delivery from Innovation to Production (2016), the case for developing topical alternatives to oral antihistamines is straightforward. Oral drugs like cetirizine and loratadine work systemically - they travel through the entire body to reach a localized problem. A patch applied directly to irritated skin bypasses this inefficiency entirely, delivering bioactive compounds precisely where they are needed while reducing the risk of systemic side effects.

Scientifically, the novelty lies in the combination. Cellulose hydrogels are well studied. *Aloe vera* in skincare is well studied. Colloidal oatmeal in dermatology is well studied. What has not been

studied is the three-way integration of all of them - using locally sourced agricultural waste as the polymer base - in a resource-limited African context. That specificity is where this study contributes something genuinely new.

Finally, there is a practical argument that matters particularly in Zimbabwe. The characterization methods used here - FTIR and UV-Vis spectroscopy alongside standard physicochemical tests - can be accessible in most university chemistry laboratories. If the results are promising, this is a study that could realistically be followed up, scaled and built upon without requiring equipment that does not exist in this environment.

1.5 Limitations

This study may be subject to several limitations. The most fundamental limitation is the natural variability of the raw materials. Maize cobs are not a standardized reagent - their cellulose content shifts with variety, growing conditions and post-harvest handling. The same is true of *Aloe vera* and oat composition, which vary with season, geography and how long the raw material has been stored. This study worked with what was locally available at a specific time and that introduces a degree of batch variability that more tightly controlled synthetic materials would not.

The analytical toolkit was deliberately limited to what is available at Bindura University - UV-vis spectroscopy and standard physicochemical tests. Techniques like scanning electron microscopy, X-ray diffraction, DSC and HPLC would have added structural and quantitative depth to the characterization. Their absence is not a flaw in the research design so much as a reflection of what is practically achievable in this setting - which is, in fact, part of the point of the study.

The extracts used are crude - aqueous and hydroalcoholic mixtures containing multiple compounds, not isolated pure avenanthramides or acemannan. This is appropriate for the study's aims but means that specific compound concentrations are estimated rather than precisely quantified.

Finally, the patches were not tested on living tissue. Everything reported here is physicochemical and spectroscopic. Whether these patches would perform as intended on human skin - whether the anti-inflammatory and anti-pruritic effects actually materialize in practice - remains an open question for future work.

1.6 Delimitations

This study focused specifically on the development of hydrogel patches using cellulose extracted from selected agricultural waste materials**,** such as maize cobs and did not consider other potential polymer sources. The formulation was limited to the incorporation of extracts from *Aloe vera* and colloidal oatmeal derived from *Avena sativa,* excluding other possible plant-based additives.

The extraction methods employed were simple and laboratory-scale procedures using safe and readily available solvents, rather than advanced industrial or highly specialized extraction techniques. Similarly, the characterization of the hydrogel patches were restricted to accessible analytical and physicochemical methods, including pH measurement, swelling studies, moisture content determination and spectroscopic analysis.

The study was also limited to evaluating the physical and chemical properties of the hydrogel patches and did not extend to large-scale production, commercialization or detailed pharmacological testing.

1.7 Aim

The aim of this study was to develop and characterize biodegradable hydrogel patches from maize cob-derived cellulose incorporating *Aloe vera* and colloidal oatmeal extracts and to evaluate their physicochemical and spectroscopic properties for potential skin-soothing applications.

1.8 Objectives of the Study

1. To formulate cellulose-based hydrogel patches incorporating *Aloe vera* extract and colloidal oatmeal.
2. To characterize the developed hydrogel patches using UV-visible spectroscopy and the FTIR**.**
3. To evaluate the physicochemical properties of the prepared hydrogel patches, including parameters such as pH, swelling capacity, moisture content and thickness.

1.9 Organization of the Study

This study is organized into five chapters. Chapter One presents the introduction to the study, including the background, problem statement, aim, objectives, hypothesis, justification, significance and the limitations and delimitations of the research.

Chapter Two reviews relevant literature on the extraction and properties of cellulose**,** the application of hydrogels in biomedical and cosmetic fields and the role of natural products such as *Aloe vera* and oats derived from *Avena sativa* in skin-related applications. It also discusses the bioactive compounds present in oats, including avenanthramides and their functional significance.

Chapter Three outlines the methodology employed in the study, including materials, apparatus, instruments, extraction procedures, preparation of hydrogel patches and the characterization techniques used, such as UV-visible spectroscopy and Fourier-transform infrared spectroscopy**.**

Chapter Four presents and discusses the results obtained from the experimental work, including physicochemical properties and analytical findings of the hydrogel patches.

Chapter Five provides a summary of the findings, conclusions drawn from the study and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a comprehensive review of literature relevant to the development of cellulose-based hydrogel patches incorporating natural extracts from *aloe vera* and oats derived from *Avena sativa*. The focus is on the structure, properties and extraction of cellulose, as well as the principles and applications of hydrogels. The chapter further explores the phytochemical composition of *aloe vera* and oats, particularly compounds responsible for skin-soothing and anti-inflammatory effects.

In addition, extraction methods for bioactive compounds and analytical techniques for characterization are discussed. The aim is to establish a strong scientific foundation for the study and highlight existing research gaps.

2.2 Definition of Key Terms

Cellulose
A naturally occurring polysaccharide composed of β-(1→4)-linked glucose units forming the structural framework of plant cell walls.

Hydrogel
A three-dimensional polymeric network capable of absorbing and retaining significant amounts of water without dissolving.

Cross-linking
A process that connects polymer chains through chemical or physical bonds, forming a stable network structure.

Lignocellulosic biomass
Plant-derived material composed of cellulose, hemicellulose and lignin, commonly obtained from agricultural waste.

Colloidal oatmeal

Finely ground oat powder derived from *Avena sativa* used for dermatological applications.

Avenanthramides

Phenolic compounds unique to oats that exhibit antioxidant, anti-inflammatory and anti-pruritic properties.

2.3 Cellulose

2.3.1 Structure of Cellulose

Cellulose is, at its core, a linear polymer - individual β-D-glucose units joined end-to-end through β-(1→4)-glycosidic bonds, forming the repeating disaccharide unit known as cellobiose (Kadimi et al., 2016). That single structural detail - the β-linkage - explains almost everything about how cellulose behaves. Unlike starch, which uses α-linkages and curls into helical coils, cellulose lies flat. Its chains adopt a ribbon-like configuration that stacks efficiently, chain against chain, held together by extensive hydrogen bonding.

Those hydrogen bonds are what give cellulose its reputation for toughness. The individual chains pack into microfibrils - long, thread-like assemblies where the molecular order is so precise that the result is genuinely crystalline in places (Jarvis, 2018). This crystallinity is why cellulose does not dissolve in water despite being studded with hydroxyl groups. The hydrogen bond network is simply too dense and too organized for water to disrupt it without chemical assistance - which is exactly why alkaline pre-treatment is required before extraction (Riseh et al., 2024).

The microfibril is not uniform throughout, however. The interior is densely crystalline and essentially inert - water and reagents struggle to penetrate it. The surface chains are a different story. Less tightly constrained, exposed, rich in accessible hydroxyl groups, these outer regions are the functional heart of cellulose for hydrogel chemistry (Madhushree et al., 2024). When citric acid crosslinks cellulose or when *Aloe vera* compounds interact with the polymer matrix, it is these surface hydroxyls that are doing the work.

Native plant cellulose exists predominantly as Cellulose Iβ - parallel chain arrangement, high crystallinity, mechanically strong but chemically resistant (Riseh et al., 2024). Alkaline processing

can shift this toward Cellulose II, an antiparallel arrangement with lower crystallinity and more accessible reactive sites. For hydrogel formation, this shift is advantageous - it means more hydroxyl groups are available for crosslinking and more space is available for water uptake.

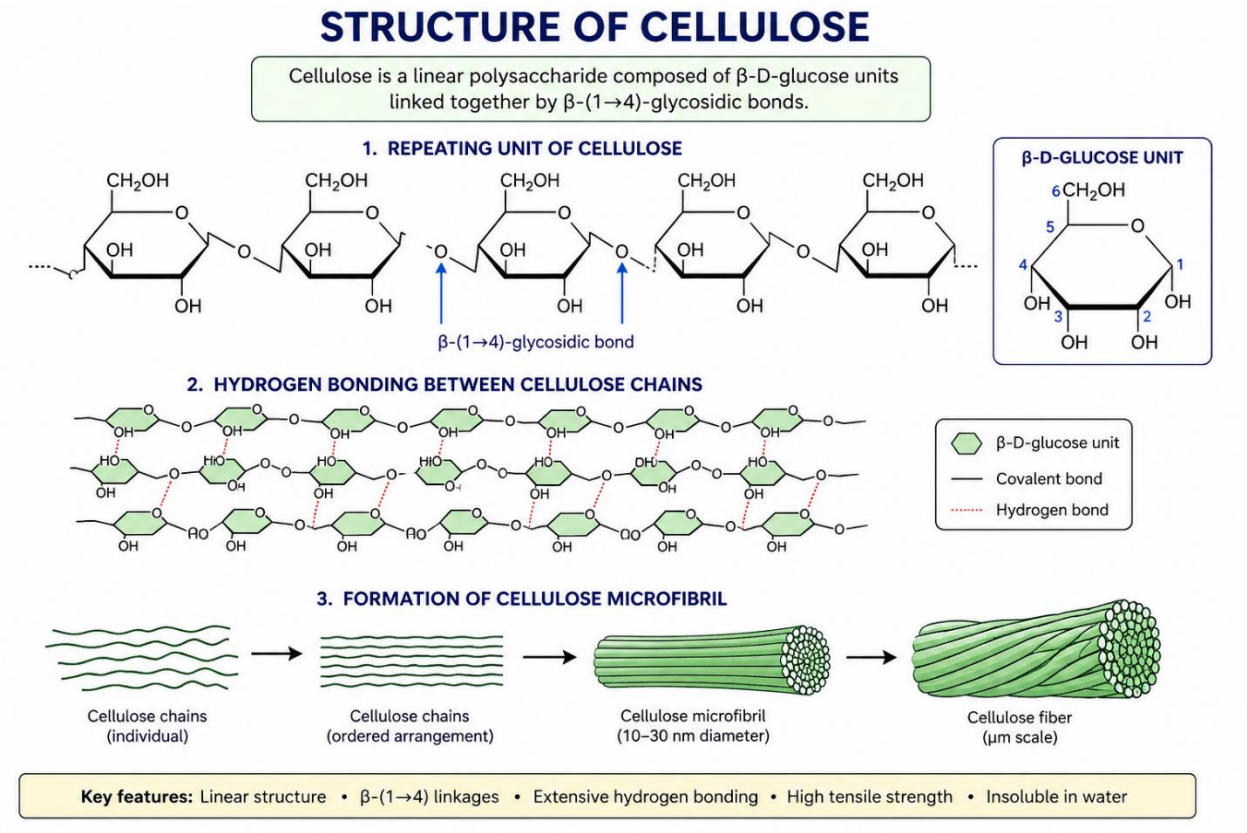


Figure 1: Structure of Cellulose

Cellulose exhibits polymorphism, existing in several crystalline forms including Cellulose I, II, III and IV, which differ in molecular arrangement and hydrogen bonding within cellulose. Native plant cellulose occurs predominantly as Cellulose Iβ, characterized by a parallel chain arrangement and high crystallinity, which contributes to its mechanical strength and resistance to chemical attack.(Riseh et al., 2024)

2.3.2 Properties of Cellulose

Cellulose is biodegradable, renewable and non-toxic. It exhibits high tensile strength and hydrophilicity due to the presence of hydroxyl groups(Riseh et al., 2024). Cellulose exhibits high tensile strength, a good elastic modulus of 130-150 GPa, low density of approximately 1.6 g/cm^3,

high biodegradability and abundant hydroxyl functional groups on its surface enabling chemical modification with high wettability. These properties make it one of the most mechanically strong natural polymers relative to its weight.(Abdelhamid & Mathew, 2022).

Cellulose has three alcoholic hydroxyl groups in each of its anhydro glucose units and chemical modifications can be performed on these hydroxyls. The primary hydroxyl group at C-6 and the two secondary ones at C-2 and C-3 can participate in classical reactions including esterification, etherification and oxidation reactions. This reactivity is what makes cellulose so versatile as a platform for hydrogel development(Qiu & Hu, 2013).

Cellulose presents an important paradox in that, despite containing numerous hydroxyl groups that make cellulose inherently hydrophilic, it is insoluble in water and most common solvents. This behavior is attributed to the extensive network of intra- and intermolecular hydrogen bonds that tightly hold the polymer chains together, particularly within the crystalline regions. These strong interactions create a highly ordered structure that prevents water molecules from penetrating and disrupting the chains, thereby limiting solubility. As a result, chemical pre-treatment such as alkaline processing is required during extraction to disrupt this hydrogen bonding network, remove surrounding lignocellulosic components and increase accessibility of reactive sites. (Riseh et al., 2024)

On another note, the most widely used synthetic hydrogels are petroleum-based, such as polyacrylamide and polyacrylic acid (Wang et al., 2022). These polymers are designed for stability and are highly resistant to environmental degradation; for instance, some synthetic gels show no significant signs of breakdown even after 3 months in physiological conditions (Hynd et al., 2007). In contrast, cellulose is a renewable natural polymer that can be fully broken down by microbial and enzymatic action (Kabir et al., 2018.). Research shows that cellulose-based superabsorbent polymers can reach up to 40% biodegradation within 54 days when subjected to soil composting, whereas acrylate-based synthetic gels remain as soil pollutants due to their non-biodegradable nature (Kabir et al., 2018; Thakur et al., 2021)

Hydrogels derived from cellulose and its derivatives (like carboxymethyl cellulose) are inherently non-toxic and biocompatible (Mondal & Rahman, 2024). Studies on cellulose-based hydrogels consistently show high cell viability (often >87-88%) when tested against human

dermal fibroblasts, making them ideal for the skin-soothing patches (Mohamad et al., 2016; Pandey et al., 2016).

2.3.3 Sources of Cellulose

Cellulose is abundant in plant biomass, particularly in agricultural residues such as maize cobs, husks and stalks. Cellulose is the most abundant natural polymer on Earth, produced annually in vast quantities through photosynthesis. It is widely distributed in plant cell walls and represents a major renewable resource for material development. A significant proportion of global cellulose is derived not only from wood but also from agricultural residues, making it highly accessible for sustainable applications(Mujtaba et al., 2023). Lignocellulosic biomass typically consists of approximately 40-60% cellulose, 20-40% hemicellulose and 10-24% lignin, indicating that a substantial fraction of plant-based waste materials can serve as a valuable source of recoverable cellulose.(Mujtaba et al., 2023)

Among agricultural residues, maize-derived materials are particularly important. The corn cob, which forms the central core of the maize ear, contains a considerable proportion of cellulose (approximately 27.71%) and hemicellulose (around 38.78%)(Alexander, 2025). Despite the large-scale global production of maize, these residues are often underutilized and are commonly discarded or burned after harvest.

In Zimbabwe, where maize is a staple crop, such agricultural by-products are generated in significant quantities but remain largely unexploited.

This presents an important opportunity for sustainable material development. The utilization of maize cobs as a feedstock for cellulose extraction aligns strongly with green chemistry principles, particularly waste valorization and the use of renewable resources. While cellulose has also been successfully extracted from other agricultural wastes such as rice straw, sugarcane bagasse, wheat straw and coconut coir, the focus on maize cobs in this study is justified by their local abundance and accessibility. This makes them an ideal, low-cost and environmentally sustainable raw material for hydrogel production in resource-limited settings.(Rajanna et al., 2022)

2.4 Lignocellulosic Biomass

The removal of hemicellulose and lignin is essential for obtaining high-purity cellulose. Residual hemicellulose can result in a gummy texture and reduced mechanical strength, while residual lignin contributes to undesirable coloration and may introduce reactive impurities that interfere with hydrogel performance.(Madhushree et al., 2024)

These challenges justify the use of a two-step extraction process involving alkaline treatment followed by bleaching, in order to isolate cellulose suitable for material applications.

2.5 Extraction and Purification of Cellulose

The pre-treatment of lignocellulosic biomass is the necessary first step for extracting Cellulose from agricultural residues. The agricultural residues such as cobs are first washed thoroughly with water to remove soil particles, dust and soluble impurities adhering on the surface that can hinder chemical treatments to be performed afterwards. The material is then dried (generally at a moderate temperature) to decrease the moisture content since abundant moisture can dilute the chemical reagents, hindering smooth chemical reaction during alkali treatment. The dried lignocellulosic biomass is then milled/ground into small particles in order to largely increase the surface area so that alkali treatment can effectively penetrate into the material, which results in enhanced cellulose isolation.(Ibrahim et al., 2015)

Alkaline treatment is a key step in the isolation of Cellulose from lignocellulosic biomass and is typically carried out using sodium hydroxide (NaOH) before bleaching. During this process, NaOH penetrates the plant matrix and disrupts the extensive hydrogen bonding within hemicellulose, making it soluble.(Gusain et al., 2026) In addition, the alkali saponifies ester linkages that connect hemicellulose to lignin, effectively breaking down the structural network that binds these components to cellulose. This results in swelling of the biomass, increased porosity and enhanced accessibility of the cellulose fibers, thereby facilitating the removal of non-cellulosic materials.

Operational conditions for alkaline treatment vary depending on the biomass source but literature commonly reports NaOH concentrations in the range of approximately 4-17.5% (w/v) and treatment temperatures between 60 and 90°C. Higher alkali concentrations and temperatures generally improve the removal of hemicellulose and partial delignification; however, excessively

harsh conditions may lead to degradation or depolymerization of cellulose chains. Therefore, careful control of these parameters is essential to achieve an optimal balance between purity and structural integrity of the extracted cellulose.(Madhushree et al., 2024).

Generally, following the alkaline treatment, a bleaching stage is conducted so as to remove the remnant of lignin and obtain purer cellulose fibers extracted. Common bleaching agents include sodium hypochlorite (NaOCl), which is an oxidant. Under oxidation from hypochlorite ions, the color-causing elements in lignin (for example, conjugated aromatic system and phenolic group, which lead to the yellow or brown color of biomass), were destructed, and they are reduced to more stable smaller products and often are soluble in water. Thus, the material turns from yellow or brown to light yellow or even white. Finally, excessive chemical and by-products were removed by washing with distilled water till the pH of washing liquor reaches the neutrality to avoid the degradation of cellulose fibers.(Thongsomboon et al., 2023) (Iqbal et al., 2024)

2.6 Hydrogels

2.6.1 Structure of Hydrogels

The defining characteristic of a hydrogel is deceptively simple: it holds enormous amounts of water without dissolving. A sponge does this mechanically; a hydrogel does it molecularly. The three-dimensional crosslinked polymer network that constitutes a hydrogel traps water within its mesh structure through a combination of hydrophilic interactions and physical confinement - the water is thermodynamically comfortable inside the network but cannot escape because of the crosslinks (Jacob et al., 2021).

Classification schemes for hydrogels abound in the literature but the distinctions most relevant to this study are three. First, ionic versus non-ionic - the hydrogels developed here are non-ionic, meaning they do not carry a net charge, which is relevant for skin compatibility. Second, natural versus synthetic origin - cellulose-based hydrogels sit firmly in the natural category, which carries advantages in biocompatibility and biodegradability that synthetic alternatives like polyacrylamide cannot easily match (Ahmad et al., 2022). Third, physical versus chemical crosslinking - and this distinction matters enormously for what happens during formulation.

Physical crosslinks - hydrogen bonds, chain entanglements, electrostatic attractions - are reversible. They give hydrogels flexibility and processability but tend to produce mechanically weaker structures. Chemical crosslinks, by contrast, are covalent - permanent under normal conditions, mechanically robust and stable in aqueous environments (Rajanna et al., 2022). In this study, citric acid provides the chemical crosslinks. Under heat, its carboxyl groups react with cellulose hydroxyl groups through esterification, forming ester bonds that lock the three-dimensional network into place. The result is a hydrogel that can absorb water, conform to skin and release bioactive compounds - without falling apart in the process (Mali, 2022).

2.6.2 Swelling Behavior

Swelling is a defining property of hydrogels and occurs when water molecules diffuse into the polymer network and occupy the free volume between chains. This leads to expansion of the network until an equilibrium state is reached between osmotic forces and the elastic resistance of the polymer matrix. The extent of swelling is governed by several factors, including crosslink density, polymer hydrophilicity and environmental conditions.(Chelu et al., 2023)

Higher crosslink density restricts chain mobility and reduces swelling capacity, while increased hydrophilicity, due to the presence of hydroxyl groups, enhances water uptake. External factors such as pH and ionic strength can also influence swelling behavior by affecting polymer-solvent interactions. For skin-related applications, a moderate swelling ratio is desirable(Ghorbani et al., 2018). The hydrogel must absorb sufficient moisture to maintain contact with the skin and provide a soothing effect but excessive swelling may compromise mechanical integrity and reduce retention of incorporated bioactive compounds.(Saeed et al., 2023)

2.6.3 Applications of Hydrogels

Hydrogels have gained widespread attention in biomedical and pharmaceutical fields due to their non-toxic nature, high water content and tunable properties. They are commonly used in applications such as wound dressings, controlled drug delivery systems, tissue engineering scaffolds, biosensors and contact lenses. Their ability to mimic the extracellular matrix makes them particularly suitable for applications involving direct contact with biological tissues.(Baldea et al., 2025)

For topical and transdermal applications, hydrogels are especially advantageous. They maintain a moist environment at the site of application, which promotes healing and reduces irritation. Hydrogel films, in particular, are thin and flexible, allowing them to conform closely to the skin surface. This enhances adhesion and ensures efficient delivery of active compounds. In this study, the hydrogel patch format enables sustained release of bioactive components from *Aloe vera* and *Avena sativa*, while simultaneously providing a cooling and soothing effect through moisture retention.(Saeed et al., 2023)

2.7 Cellulose-Based Hydrogels

Cellulose-based hydrogels combine sustainability with functionality. Cellulose-based hydrogels have attracted considerable attention due to the unique physicochemical and biological properties of Cellulose. Structurally, cellulose is composed of linear chains of β-(1→4)-linked glucose units arranged into fibrous networks. This configuration provides high mechanical strength and structural stability, while the abundance of hydroxyl (-OH) groups along the polymer backbone imparts strong hydrophilicity. These hydroxyl groups enable extensive hydrogen bonding and interaction with water molecules, making cellulose highly suitable for hydrogel formation. In addition, cellulose is inherently biocompatible, biodegradable and non-toxic, which makes it particularly advantageous for biomedical and cosmetic applications compared to many synthetic polymers.(Rumon, 2025)

The formation of cellulose-based hydrogels involves the development of a three-dimensional polymer network through crosslinking. The hydroxyl groups present on cellulose chains act as reactive sites for crosslinking agents such as citric acid. Under thermal conditions, the carboxyl groups of citric acid undergo esterification reactions with the hydroxyl groups of cellulose, forming covalent ester linkages that stabilize the hydrogel network. This crosslinking process enhances the structural integrity of the material while maintaining its capacity to absorb water. Analytical techniques such as Fourier Transform Infrared (FTIR) spectroscopy have been widely used to confirm the formation of these ester bonds, typically indicated by the appearance of characteristic carbonyl (C=O) stretching bands. Furthermore, studies have shown that increasing the concentration of crosslinking agents leads to a higher degree of network formation, resulting

in improved mechanical strength but reduced swelling capacity, highlighting the need for careful optimization.(Mahmoudi et al., 2024)

Modifications and additives play a crucial role in tailoring the properties of cellulose hydrogels for specific applications. In particular, glycerol is commonly used as a plasticizer to improve flexibility and reduce brittleness. Glycerol molecules insert themselves between cellulose chains, reducing intermolecular hydrogen bonding and increasing chain mobility. This results in a softer, more flexible material that can conform to irregular surfaces such as human skin. However, excessive glycerol content may reduce tensile strength and structural integrity, necessitating a balance between flexibility and durability in the final formulation.

In the present study, the hydrogel system is designed by combining cellulose extracted from agricultural waste with bioactive components derived from *Aloe vera* and *Avena sativa*. The cellulose matrix provides a structural scaffold and moisture-retaining environment, while the incorporated plant extracts contribute functional properties such as anti-inflammatory, antioxidant and soothing effects. Similar studies have demonstrated the successful incorporation of plant-derived bioactive compounds into cellulose-based hydrogels for topical applications, supporting the feasibility of this approach even when different combinations of materials are used.(Mo et al., 2025)

2.8 *Aloe vera*: Composition and Applications

Aloe vera has been applied to human skin for at least four thousand years, which is an unusually long clinical trial. The fact that it is still used - and still recommended - suggests the outcomes have generally been positive. The plant (*Aloe barbadensis Miller*, family Asphodelaceae) is a succulent whose inner leaf gel has become one of the most widely used ingredients in topical dermatological products globally (Matei et al., 2025).

The chemistry behind this reputation is genuinely complex. *Aloe vera* gel contains polysaccharides, proteins, enzymes, vitamins, minerals and an extensive array of secondary metabolites including anthraquinones, chromones, flavonoids and tannins (Abid et al., 2025). The gel fraction is dominated by hydrophilic polysaccharides, which give it its characteristic texture and moisture-retaining capacity.

One compound stands out above the others: acemannan. This β-(1→4)-acetylated polymannose is the principal bioactive polysaccharide in *Aloe vera* and is responsible for much of its immunomodulatory, antioxidant and wound-healing activity (Liu et al., 2019). It supports collagen synthesis, promotes tissue regeneration and modulates inflammatory signaling - properties that make it directly relevant to the skin-soothing application pursued in this study (Abid et al., 2025).

At the molecular level, *Aloe vera*'s anti-inflammatory action involves downregulation of pro-inflammatory mediators, support for fibroblast proliferation and promotion of cell migration - the core processes of tissue repair (S.-H. Kim et al., 2023). These are not subtle effects; they represent a genuine pharmacological mechanism, not just traditional medicine optimism.

For this formulation, *Aloe vera* serves a dual purpose. The cellulose provides the structural scaffold - the architecture of the patch. The *Aloe vera* extract adds the therapeutic payload. Together they form a system where structure and function reinforce each other rather than competing.

2.9 Oats and Avenanthramides

Oats have been used on skin since before written records. Roman physicians documented oat baths for irritated skin; Egyptian and Arabian healers used similar preparations centuries earlier (Maliarova et al., 2015a). This is worth noting - not as a substitute for scientific evidence but because the persistence of a remedy across cultures and millennia is itself a form of data. Something was working. Modern chemistry has identified what. Colloidal oatmeal - finely ground *Avena sativa* - contains a mixture of carbohydrates, proteins, lipids, β-glucans and, most significantly, avenanthramides (Sur et al., 2008). The β-glucans form a film on the skin surface that retains moisture and physically soothes. The proteins and lipids support barrier function. But avenanthramides are the most pharmacologically interesting component - a class of phenolic alkaloids found almost exclusively in oats, with antioxidant, anti-inflammatory and antipruritic properties that have now been characterized at the molecular level.

The mechanism is specific. Avenanthramides inhibit the activation of NF-κB - the transcription factor that acts as a master switch for inflammatory signaling in skin cells. They do this by

preventing degradation of IκB-α, the protein that normally keeps NF-κB inactive. With NF-κB suppressed, downstream expression of pro-inflammatory cytokines like interleukin-8 is reduced and the result at the skin surface is measurably less redness, less itching, less irritation (Reynertson et al., 2015). This is not a vague soothing effect - it is a defined molecular pathway. One clarification is necessary. This study uses colloidal oatmeal - a crude extract - rather than isolated avenanthramides.

Isolating pure avenanthramides requires chromatographic equipment that was not available for this work. Colloidal oatmeal is the practical alternative and it is a legitimate one: it retains the full spectrum of oat bioactives, is accepted by regulatory bodies as a safe and effective skin protectant and has decades of clinical use behind it. The trade-off is reduced precision in terms of exact compound concentration - acknowledged here as a limitation.

2.10 Extraction of Bioactive Compounds

The selection of an appropriate solvent is a critical factor in the extraction of bioactive compounds from plant materials, as it directly influences both the efficiency and specificity of the process. Extraction is fundamentally governed by the principle of solubility, where the polarity of the solvent must correspond to the polarity of the target compounds. Polar solvents such as water are particularly effective for extracting hydrophilic compounds, including polysaccharides and glycoproteins. This is especially relevant for *Aloe vera*, where the primary bioactive component, acemannan, is a highly polar polysaccharide that is readily extracted using aqueous systems. In contrast, phenolic compounds such as avenanthramides found in *Avena sativa* exhibit intermediate polarity and are more efficiently extracted using mixtures of ethanol and water. The use of ethanol-water systems enhances the solubility of these compounds while maintaining a relatively safe and environmentally friendly extraction medium suitable for biomedical applications.(Liu et al., 2019)

The extraction strategies employed in this study are therefore guided by both chemical principles and practical considerations. Aqueous extraction is selected for *Aloe vera* to efficiently recover hydrophilic polysaccharides, while an aqueous-ethanolic system is used for oat-based materials to enhance the recovery of phenolic compounds such as avenanthramides. These approaches are not only effective but also safe, cost-efficient and accessible, making them particularly suitable for implementation in resource-limited laboratory settings. Furthermore, the use of mild extraction

conditions helps to preserve the biological activity of the compounds, ensuring that the resulting extracts retain their functional properties for incorporation into hydrogel-based topical formulations.(Pratinthong et al., 2024)

2.11 Characterization Techniques

2.11.1 Physicochemical Characterization

Physicochemical characterization is one important test to investigate the efficacy of a hydrogel patch for topical applications under simulated condition. Usually physicochemical parameters included in evaluating hydrogel patch are: visual appearance, thickness, weight change, tensile strength, surface pH, swelling property, water content, water vapor transmission rate, folding endurance etc. These parameters all explain how structural, stable and functional is hydrogel and it determines whether the formulation can remain comfortable to skin, guarantee controlled release of drug, survive from handling etc.(Fiorati et al., 2021a)

The surface pH value is considered an important feature in any material that is applied directly to the skin. Normal skin pH is found to be around 4.5-5.5 which may cause disturbance to the acid mantle of the skin thus giving it a negative effect on sensitive skin and changing the microbial balance. The pH is usually performed by hydrating a small piece of the sample in distilled water, measured by using pH electrode. For the skin to tolerate it will be of physiological pH. Other than its skin compatibility, pH also affects the stability and release property of *Avena sativa* and *Aloe vera*'s incorporated active principles from the gel patch.(Zamora-Mendoza et al., 2023)

. Hydrogels are known to swell by absorbing water when exposed to an aqueous environment and water is incorporated into the reaction medium, causing expansion of the system as the chains of the polymer matrix are separated. The weight of the hydrogel following immersion in appropriate media is subtracted from the initial weight (dry weight) and the resulting value is reported as a swelling ratio. The higher the crosslink density of the hydrogels, the lower the swelling they tend to exhibit and therefore reach a steady state quite quickly whereas systems with a lower crosslink density show swelling over a much longer period. When applied to the skin, as we intend the hydrogel patches to be, it is desirable for the swelling to be as controlled as possible, allowing for moisture uptake from the skin and provide close contact without losing integrity, this will have a

major influence on the retention of the drugs and their subsequent release from the dressing. (Fiorati et al., 2021b)

Moisture content refers to the amount of residual water retained within the hydrogel after drying. This parameter plays a dual role in determining both storage stability and mechanical behavior. Low moisture content may lead to brittleness and reduced flexibility, whereas excessive moisture can promote microbial growth and compromise structural integrity. Therefore, an optimal moisture level must be maintained to ensure both durability during storage and functionality during application.(Navarra et al., 2015)

2.11.2 FTIR Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy is a powerful analytical technique used to identify functional groups and monitor chemical interactions within polymer systems. It operates in the infrared region of the electromagnetic spectrum, where absorbed radiation induces vibrational transitions in molecular bonds. These vibrations are associated with specific functional groups and their corresponding absorption bands provide a molecular fingerprint of the material. FTIR is particularly useful for studying modifications in cellulose during extraction and hydrogel formation.(Haque et al., 2016)

In cellulose-based systems, characteristic absorption bands appear in well-defined regions of the spectrum. The broad band observed between approximately 3200 and 3500 cm^{-1} corresponds to O-H stretching vibrations, reflecting the extensive hydrogen bonding present in polysaccharides. Peaks near 2900 cm^{-1} are associated with C-H stretching, while the region between 1630 and 900 cm^{-1} contains multiple bands related to C-O, C-C and glycosidic linkages. These spectral features confirm the presence and structural integrity of cellulose before modification.(Haque et al., 2016)

The most critical application of FTIR in this study is the confirmation of crosslinking. During hydrogel formation, citric acid reacts with hydroxyl groups on cellulose to form ester linkages. This reaction is evidenced by the appearance of a distinct carbonyl (C=O) absorption peak in the region of approximately 1710-1740 cm^{-1}. An increase in the intensity of this peak indicates a higher degree of crosslinking within the polymer network. Additional peaks in the range of 1200-

1300 cm^{-1} may be attributed to C-O stretching vibrations associated with ester groups, further supporting successful crosslink formation.(Perrelli et al., 2018a)

FTIR is also valuable for assessing the incorporation of bioactive extracts into the hydrogel matrix. When extracts from *Aloe vera* and *Avena sativa* are introduced, additional functional groups such as phenolic O-H, amide or aromatic structures may appear or modify existing peaks. Differences between the spectra of the pure cellulose hydrogel and the extract-loaded hydrogel indicate successful encapsulation and interaction between the polymer and the bioactive compounds. A comparative approach is therefore employed, analyzing spectra of raw cellulose, treated cellulose, individual extracts, blank hydrogel and loaded hydrogel to track structural changes at each stage of formulation.(Perrelli et al., 2018b)

2.11.3 UV-Visible Spectroscopy

Ultraviolet-Visible (UV-Vis) spectroscopy is an essential technique for detecting and quantifying bioactive compounds in plant extracts and hydrogel systems. It is based on the absorption of electromagnetic radiation in the ultraviolet (200-400 nm) and visible (400-800 nm) regions by molecules containing conjugated π-electron systems or non-bonding electron pairs. The amount of light absorbed at a specific wavelength is proportional to the concentration of the absorbing species, as described by the Beer-Lambert law.(Perrelli et al., 2018a)

This technique is particularly well suited for the analysis of phenolic compounds, which exhibit characteristic absorption in the UV region due to their aromatic structures. Simple phenolic compounds typically absorb around 270-280 nm, while more conjugated systems show absorption at higher wavelengths due to bathochromic shifts(I. S. Kim et al., 2021). In this study, UV-Vis's spectroscopy is used to analyze extracts from *Aloe vera* and *Avena sativa*, both of which contain compounds with distinct absorption profiles.

For *Aloe vera*, UV-vis analysis can confirm the presence of flavonoids and other UV-absorbing constituents within the extract. Although acemannan itself is not strongly UV-active, associated phytochemicals provide measurable absorption signals that serve as indicators of extract integrity(Sierra-García et al., 2024.). For oatmeal extracts, avenanthramides exhibit characteristic

absorption in the range of approximately 310-330 nm, allowing their presence to be confirmed and their relative concentration to be estimated.(Reynertson et al., 2015)

UV-vis spectroscopy also plays a key role in evaluating the success of hydrogel formulation. By comparing the spectra of free extracts with those obtained after incorporation into the hydrogel and subsequent release into a solution, it is possible to determine whether the bioactive compounds have been retained during processing. This includes assessing potential degradation due to heating or drying steps. Additionally, UV-Vis can be used in release studies, where the hydrogel is immersed in a medium and the concentration of released compounds is monitored over time. This provides insight into release kinetics and the effectiveness of the hydrogel as a controlled delivery system. The technique is particularly advantageous in resource-limited settings due to its simplicity, cost-effectiveness and minimal requirement for complex sample preparation.

2.12 Factors Affecting Hydrogel Performance

The performance of hydrogel-based systems is governed by a combination of structural and environmental factors that collectively determine their mechanical properties, swelling behavior and release characteristics. One of the most influential parameters is crosslink density, which refers to the number of crosslinks present within the polymer network. An increase in crosslink density results in a more tightly bound structure, reducing the free volume available for water uptake and thereby limiting the extent of swelling. While this enhances the mechanical strength and structural stability of the hydrogel, it simultaneously restricts the diffusion of incorporated bioactive compounds, leading to a slower release rate. Consequently, an optimal balance must be achieved, as excessive crosslinking may produce a rigid system with limited swelling capacity, whereas insufficient crosslinking may result in poor mechanical integrity and premature disintegration.(Zamora-Mendoza et al., 2023)

Polymer concentration also plays a critical role in determining hydrogel properties. Increasing the concentration of cellulos**e** in the formulation leads to a denser polymer network with enhanced intermolecular interactions, which improves viscosity and mechanical strength. However, this increased density can reduce the ability of the hydrogel to absorb water, thereby lowering its swelling capacity. In the context of topical applications, this presents a trade-off between structural

robustness and functional performance, as adequate swelling is necessary to ensure proper hydration and effective interaction with the skin surface.(Yustira et al., 2021)

The presence of additives further influences hydrogel behavior by modifying the interactions within the polymer matrix. Plasticizers such as glycerol act by inserting themselves between polymer chains, reducing intermolecular hydrogen bonding and increasing chain mobility. This results in improved flexibility and reduced brittleness, which is essential for hydrogel patches that must conform to the contours of the skin. At the same time, the incorporation of bioactive extracts, such as those derived from *Aloe vera* and *Avena sativa*, may interact with the polymer network through hydrogen bonding or other intermolecular forces. These interactions can alter the internal structure of the hydrogel, potentially affecting its swelling behavior, mechanical properties and release characteristics.(I. S. Kim et al., 2021)

2.13 Challenges and Limitations

Raw material variability is the most fundamental challenge and limitation. Maize cobs sourced from different farms - or even from the same farm in different seasons - will not have identical compositions. The 27.71% cellulose figure cited for maize cobs is a literature average, not a guarantee. In practice, the actual cellulose content of the cobs used in this study depended on factors outside experimental control: the maize variety grown in Bindura that season, soil conditions, rainfall and how long the cobs had been stored before collection. Similar variability applies to the *Aloe vera* gel and oat extracts (Abraham et al., 2015). This is not a solvable problem within the scope of this study - it is a characteristic of working with natural materials that must be acknowledged. Mechanical behavior is a second challenge area. Polysaccharide hydrogels are notorious for inconsistency - susceptibility to microbial contamination during preparation, unpredictable water absorption and mechanical properties that shift with every change in formulation (Wong & Dodou, 2017). The challenge of making a patch that is simultaneously strong enough to handle, flexible enough to conform to skin and structurally stable enough to store is not trivial. Incorporating plant extracts adds complexity: bioactive compounds can interact with the polymer network in ways that alter crosslinking efficiency and affect the mechanical outcome. Standardization is a third limitation that runs throughout. Without HPLC quantification, the exact concentration of avenanthramides in the oat extract and

acemannan in the *Aloe vera* extract cannot be stated with precision. Batch-to-batch variation in extract composition is real and unmeasured. For a study establishing feasibility - which this is - that level of uncertainty is acceptable. For a study making therapeutic claims, it would not be (Kudłacik-Kramarczyk et al., 2021).

2.14 Research Gap

The individual building blocks of this study are, separately, well-established in the literature. Cellulose-based hydrogels have attracted considerable research attention as biocompatible, biodegradable scaffolds for topical and biomedical use. *Aloe vera*'s dermatological benefits - from anti-inflammatory action to wound healing - are similarly well-documented. So too is the value of colloidal oatmeal from *Avena sativa*, recognized for decades in dermatology for its soothing and anti-pruritic properties. Agricultural waste biomass as a cellulose source has also gained traction, particularly under the growing pressure of sustainability initiatives and green chemistry principles (Zamora-Mendoza et al., 2023). What the literature has not done, however, is bring all of these elements together. Despite the logical fit between them - waste-derived cellulose, complementary plant bioactives and a skin-contact delivery format - no study appears to have combined all three into a single hydrogel patch system, let alone one contextualized within a resource-limited African setting like Zimbabwe. That is the gap this study addresses.

Despite these advances, a clear gap exists in the integration of these individual research areas. Current literature rarely reports the development of a unified hydrogel system that simultaneously incorporates cellulose derived from agricultural waste with multiple plant-based bioactive extracts such as *Aloe vera* and colloidal oatmeal. While each component has been independently studied and validated for its functional properties, their synergistic combination within a single hydrogel matrix remains insufficiently explored. Furthermore, most existing studies are conducted in highly controlled laboratory environments using commercially available cellulose, with limited attention given to locally sourced raw materials or the constraints of resource-limited settings. There is a notable lack of research focused on African contexts, where agricultural residues such as maize cobs are abundant and where the development of cost-effective, accessible biomedical materials could have significant practical impact.(Paladini et al., 2021)

The present study seeks to address this gap by developing a cellulose-based hydrogel patch derived from maize cob agricultural waste, a readily available resource in Zimbabwe. By integrating cellulose with bioactive extracts from *Aloe vera* and colloidal oatmeal, this research proposes a multifunctional system that combines structural support with therapeutic activity. The study further distinguishes itself by employing accessible and cost-effective characterization techniques, including FTIR and UV-Visible spectroscopy, alongside standard physicochemical evaluations, making the methodology suitable for resource-constrained environments. In doing so, this work contributes to the advancement of sustainable material science, demonstrates the feasibility of combining multiple natural bioactive within a single biodegradable matrix and provides a practical framework for the development of affordable, locally sourced skin-soothing hydrogel patches.

2.15 Summary

This chapter has established that cellulose, a naturally abundant, biodegradable and biocompatible polysaccharide, is an ideal material for the development of sustainable biomaterials, particularly when derived from agricultural waste such as maize cobs. The role of hydrogels as three-dimensional, crosslinked polymeric networks capable of retaining large amounts of water has been highlighted, demonstrating their effectiveness as delivery platforms for topical and transdermal applications. The review further emphasized the well-documented dermatological benefits of *Aloe vera* and colloidal oatmeal from *Avena sativa*, both of which exhibit anti-inflammatory, antioxidant and skin-soothing properties that support their inclusion in the formulation. In addition, key characterization techniques, including physicochemical analysis, FTIR spectroscopy and UV-Visible spectroscopy, were discussed as essential tools for evaluating the structure, stability and functionality of the developed hydrogel patches. Overall, the literature reviewed in this chapter provides a strong scientific foundation and clearly identifies a research gap, thereby justifying the development of a cellulose-based hydrogel patch incorporating natural bioactive extracts as a novel and sustainable approach.

CHAPTER 3

Materials and Methodology

3.0 Introduction

Everything described in Chapters 1 and 2 ultimately had to become something physical - actual patches, made from actual maize cobs collected from farms near Bindura, tested in an actual chemistry laboratory with the equipment available there. This chapter describes how that was done. The work moved through five stages: cellulose extraction, *Aloe vera* extract preparation, oatmeal extract preparation, hydrogel patch formulation and characterization. Methods were drawn from published literature and adapted where necessary to suit what was practically achievable at Bindura University of Science Education.

3.1 Reagents

The following reagents were used throughout this study. Maize cobs were collected from local farming areas in Bindura, Zimbabwe and used as the primary agricultural waste feedstock for cellulose extraction. Fresh, mature *Aloe Vera* (*Aloe barbadensis* Miller) leaves were obtained locally. Rolled Oats (*Avena sativa*, food grade) were obtained from a commercial supplier. Sodium hydroxide (NaOH, analytical grade) was used at a concentration of 5% (w/v) for alkaline delignification. Sodium hypochlorite (NaOCl, 5% available chlorine) was used as a bleaching agent for residual lignin removal. Absolute ethanol (analytical grade, 80% v/v aqueous solution) was used for the extraction of avenanthramides from oatmeal. Glycerol (analytical grade) served as a plasticizing agent in the hydrogel formulation. Citric acid (food grade) was employed as the chemical crosslinking agent. Distilled water was used throughout all procedures as the primary solvent and washing medium. Whatman No.1 filter paper was used for all filtration steps. Aluminum foil was used for sample storage and protection from light.

3.2 Apparatus

Standard laboratory glassware and equipment used in this study included: beakers (50ml, 100Ml, 250ml and 500ml), conical flasks (100ml and 250ml), measuring cylinders (10ml, 50ml and 100ml), glass stirring rods, funnels, watch glasses, evaporating dishes, Petri dishes, mortar and

pestle, spatulas, sieve and drying dishes. A micrometer screw gauge was used for thickness measurements.

3.3 Instrumentation

The following instruments were used for experimental work and characterization: an analytical balance (accurate to $^{+/-}$ 0.0001g) for mass measurements, a Biobase laboratory oven for drying and curing procedures, a hot plate with a magnetic stirrer for heating and mixing, a grinder and blender for particle size reduction, a calibrated pH meter for surface pH measurements, a thermometer for temperature monitoring, a Fourier-transform infrared (FTIR) for functional group analysis and a UV-Visible spectrophotometer for detection and quantification of bioactive compounds.

3.4 Extraction and Purification of Cellulose from Maize Cobs

The extraction of cellulose from maize cobs followed a sequential chemical treatment procedure adapted from Ali et al. (2022), Singh et al. (2020) and Lawal et al. (2019), involving pre-treatment, alkaline delignification and bleaching steps.

3.4.1 Pre-treatment of Maize Cobs

Maize cobs were collected from farms in the Bindura area following the 2026 harvest season - specifically selected because of their local availability and because using a genuinely local feedstock was central to the study's rationale. The extraction procedure followed a three-stage sequence: mechanical pre-treatment, alkaline delignification with NaOH and bleaching with NaOCl. This approach was adapted from Ali et al. (2022), Singh et al. (2020) and Lawal et al. (2019).

3.4.2 Alkaline Treatment

A NaOH solution of 5% (w/v) concentration was prepared in distilled water. The pre-treated maize cob powder was added to the NaOH solution at a solid to liquid ratio of 1: 20 (g/ml) in a beaker. The mixture was heated at 80 °C to 90 °C for 3 hours under continuous stirring using a hot plate with a magnetic stirrer. During this treatment, sodium hydroxide penetrated the plant matrix, disrupted the hydrogen bonding with hemicellulose and saponified the ester linkages connecting the hemicellulose to lignin, causing swelling of biomass and partial removal of non-cellulosic

components. The treated suspension was filtered through Whatman No.1 filter paper and the residue was washed repeatedly with distilled water until the filtrate reached a neutral pH, as confirmed using a calibrated pH meter. This alkaline treatment was performed to maximize the removal of hemicellulose and lignin.

3.4.3 Bleaching

The alkali-treated cellulose residue was transferred to a clean beaker and subjected to bleaching using 5% NaOCl solution at a solid-to-liquid ratio of 1:20 (g/ml). The suspension was heated at 70 °C to 80 °C for 2 hours to allow the hypochlorite to oxidatively degrade residual chromophoric lignin structures. The oxidation process converted the colored aromatic conjugated systems in lignin into smaller, water-soluble fragments, visually confirmed by the transition of the material from a yellow-brown color to white. Following bleaching, the product was collected by filtration through Whatman No.1 filter paper and extensively washed with distilled water until a neutral pH was achieved. The purified cellulose was dried in a laboratory oven at 60 °C for 24 hours and stored in sealed containers at room temperature for subsequent use.

3.4.4 Cellulose Yield Calculation

The percentage yield of extracted cellulose was calculated using the following formula:

% Yield = (Mass of extracted dry cellulose / Mass of initial dry maize cob powder) × 100

All yield calculations were performed in triplicate and results expressed as mean ± standard deviation (SD).

3.5 Preparation of *Aloe Vera* Gel Extract

Aloe vera leaves were collected from plants growing in the university grounds - mature leaves with firm gel, selected to maximize bioactive content. Each leaf was washed under tap water, rinsed with distilled water and surface-wiped with 70% ethanol. The yellow latex layer - which contains aloin, an anthraquinone with known skin-sensitizing potential - was drained by standing the cut leaves upright for fifteen minutes. This step mattered: aloin is not something you want in a skin-soothing formulation.

The outer rind was removed with a sterile scalpel and the clear inner gel scraped into a clean beaker. The gel was then blended at high speed for two minutes. What emerged was a slightly cloudy suspension rather than a perfectly clear liquid - which is normal for unprocessed *Aloe vera* gel and does not indicate a problem. Filtration through Whatman No. 1 paper removed the fibrous residue. The aqueous extraction approach was chosen specifically because acemannan - the principal bioactive polysaccharide - is highly polar and water-soluble; no organic solvent was needed. The filtrate was transferred to amber glass vials and stored at 4°C until needed. The amber glass and cold storage were both deliberate choices to slow degradation of thermolabile compounds.

3.6 Preparation of Colloidal Oatmeal Extract

Rolled oats (*Avena sativa*) were dried in a laboratory oven at 40 °C for an hour to reduce residual moisture before grinding. The dried oats were finely ground using a mortar and pestle and sieved to obtain a fine, uniform colloidal oatmeal powder. This preparation procedure was adapted from (Maliarova et al., 2015b) and (Pretorius & Dubery, 2023).

The oatmeal extract was prepared by dispersing the fine oat powder in an 80% (v/v) aqueous ethanol solution at a solid to liquid ratio of 1:10 (w/v). The mixture was stirred continuously for 24 hours at room temperature to maximize the recovery of avenanthramides and other phenolic compounds, which exhibit intermediate polarity and are more efficiently extracted using hydroalcoholic mixtures than by water alone. The suspension was filtered through Whatman No. 1 filter paper and the filtrate was collected. The ethanol was subsequently removed by evaporation at 40 °C using gentle heating on a hot plate with continuous stirring, yielding a concentrated aqueous oat extract. This mild temperature was selected to preserve thermolabile avenanthramides. The final extract was stored in sealed amber vials at 4 °C until required.

3.7 Formulation and Preparation of Cellulose-Based Hydrogel Patches

Bringing the three components together - cellulose, *Aloe vera* extract and colloidal oatmeal - required careful sequencing. The cellulose had to be dispersed and hydrated before the crosslinker was added; the crosslinker had to be distributed uniformly before curing began; the plant extracts were added last to minimize their exposure to heat. The method was adapted from Vlaia et al.

(2016), (Ghorbani et al., 2018) and (Fekete et al., 2014), with modifications to suit the equipment available.

Three formulation batches were prepared - F1, F2 and F3 - differing only in cellulose and citric acid concentration while keeping extract volumes constant. This design was intentional: it isolates the effect of crosslink density on patch properties, which is the key variable of interest. Table 1 shows the composition of each batch.

Table 1: Formulation Composition of Cellulose-Based Hydrogel Patches

Component	Batch F1	Batch F2	Batch F3
Cellulose (w/v)	2%	3%	4%
Citric acid crosslinker (w/v)	5%	7.5%	10%
Glycerol plasticizer (v/v)	1.5 mL	1.5 mL	1.5 mL
Aloe vera extract (v/v)	10%	10%	10%
Colloidal oatmeal extract (v/v)	10%	10%	10%
Distilled water	To 100 mL	To 100 mL	To 100 mL

F1 = lowest cellulose and crosslinker concentration; F3 = highest cellulose and crosslinker concentration.

3.7.1 Preparation of Cellulose Suspension

A measured quantity of dried, purified cellulose (mass depending on the batch, as per Table 1) was dispersed in 70ml of distilled water in a beaker. The suspension was stirred continuously using a hot plate with a magnetic stirrer at 60 degrees Celsius until a uniform, homogeneous suspension

was achieved. Gentle heating was employed to promote adequate hydration of the cellulose polymer chains and facilitate their interaction with the crosslinking agent in the subsequent steps.

3.7.2 Addition of Crosslinking Agent and Plasticizer

Citric acid was dissolved separately in a small volume of distilled water and added dropwise to the cellulose suspension at the concentration specified for each batch (Table 1), under continuous stirring. Citric acid was selected as the crosslink agent because its three carboxyl groups can react with the hydroxyl groups of cellulose through esterification under thermal conditions, forming stable covalent ester linkages that constitute the three-dimensional hydrogel network. Importantly, citric acid is non-toxic, widely regarded as safe and environmentally benign, making it highly appropriate for a formulation intended for skin contact.(Ghorbani et al., 2018)

Glycerol was subsequently added at 1.5ml per 100ml of suspension and the mixture was stirred at 60 °C for a further 30 minutes to ensure homogeneous distribution. Glycerol functions as a plasticizer by intercalating between cellulose chains, reducing intermolecular hydrogen bonding and increasing chain mobility. This lowers the glass transition temperature and imparts flexibility to the final patch, allowing it to bend and conform to the skin surface without cracking.

3.7.3 Incorporation of Bioactive Extracts

The prepared *Aloe vera* aqueous extract and colloidal oatmeal extract were added to the cellulose -citric acid-glycerol suspension in measured volumes (10% v/v each) under continuous gentle stirring at room temperature. Stirring was maintained for 15 minutes to ensure uniform distribution of the bioactive compounds throughout the polymer matrix. The combined mixture was then allowed to stand at rest for 10 minutes to allow entrapped air bubbles to escape before casting. This degassing step is important to avoid the formation of voids in the final hydrogel film, which would compromise structural integrity.

3.7.4 Casting and Curing of Hydrogel Patches

The prepared hydrogel mixture was carefully poured into clean, dry Petri dishes and spread to a uniform layer using a glass stirring rod. Each Petri dish received an equal volume of the mixture to ensure consistent patch thickness across samples. The filled Petri dishes were placed in a

laboratory oven and dried at 60 °C for 24 hours. Following drying, the solidified hydrogel films were allowed to cool to room temperature and then carefully peeled from the Petri dishes. The films were cut into standardized circular patches of 2cm diameter to ensure consistency between samples. All patches were stored in sealed aluminum foil pouches at room temperature until characterization to protect them from moisture and light exposure.



Figure 2: Hydrogel formulations F1,F2 and F3 following casting into Petri dishes prior to thermal curing at 60 degrees Celsius

3.8 Physicochemical Characterization of Hydrogel Patches

3.8.1 Physical Appearance

Each hydrogel patch was visually examined under ambient light for color, transparency, surface homogeneity, the presence of air bubbles and physical defects such as cracks or uneven edges. Observations were recorded descriptively. Only patches with a uniform, smooth and defect-free appearance were selected for further characterization.

3.8.2 Thickness

The thickness of each hydrogel patch was measured at five different positions: the center and the four points equidistant around the periphery. Measurements were taken using a micrometer screw gauge. The mean thickness and standard deviation were calculated from the five readings per patch and the uniformity across batches was compared.

3.8.3 Weight Uniformity

Ten patches from each formulation batch were individually weighed using an analytical balance accurate to 0.001g. The mean weight and percentage coefficient (%CV) were calculated. A %CV of less than 5% was considered acceptable, indicating adequate uniformity in the casting and drying process.

3.8.4 Surface pH

Surface pH was measured by equilibrating a 1 cm^2 section of each patch in 10 mL of distilled water for two hours, with occasional stirring. The pH was then read from a calibrated meter. The two-hour equilibration time was chosen based on preliminary trials showing that readings stabilized within this window - shorter times gave inconsistent results.

The target range was 4.5–5.5, matching normal physiological skin pH. Any material applied to skin that sits outside this range risks disrupting the acid mantle - the slightly acidic surface environment that controls microbial colonization and supports barrier function. All three formulations needed to fall within this range to be considered suitable for topical application

3.8.5 Swelling Ratio

Pre-weighed dry patches were immersed in distilled water and weighed at 0.5, 1-, 2,4-, 8- and 24-hour intervals after blotting surface water. Swelling ratio was calculated as:

$$\mathbf{SR\ (\%) = [(Ws - Wd) / Wd] \times 100}$$

where Ws = swollen weight and Wd = initial dry weight.

3.8.6 Moisture Content and Folding Endurance

Moisture content was determined gravimetrically by drying patches at 105^oC for 4 hours:

Moisture Content (%) = [(Wi - Wf) / Wi] × 100, where Wi and Wf are weights before and after drying. Folding Endurance was assessed by repeatedly folding each patch at the same point until cracking occurred; more than 100 folds without failure was considered satisfactory.

3.9 Spectroscopic Characterization

3.9.1 FTIR Spectroscopy

FTIR spectra were recorded over 4000-400 cm^{-1} at 4 cm^{-1} resolution for: raw maize cob powder; alkali-treated cellulose; bleached cellulose; dried *Aloe vera* extract; dried oatmeal extract; blank hydrogel; and extract-loaded patches (F1-F3). Key bands monitored included the O-H stretch (~3200-3500 cm^{-1}), C-H stretch (~2900 cm^{-1}) and C=O ester band (~1710-1740 cm^{-1}) confirming citric acid crosslinking. Spectra were compared across all samples to track structural changes at each formulation stage.

3.9.2 UV-Visible Spectroscopy

Absorbance spectra (200-800 nm) were recorded for the *Aloe vera* extract, oatmeal extract and 24-hour aqueous eluates from loaded patches (F1-F3), using distilled water as blank. Avenanthramides were monitored at 310-330 nm and *Aloe vera* phenolics and flavonoids at 270-340 nm. The Beer-Lambert law was applied to estimate relative compound concentrations and free extract spectra were compared with patch eluates to confirm bioactive retention and release.

3.10 Statistical Analysis

All measurements were performed in triplicate and expressed as mean +/- standard deviation. One way ANOVA followed by Tukey's post-hoc test was used to identify significant differences between batches F1, F2 and F3, with significance set at $p < 0.05$.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

This chapter presents and discusses the results obtained from cellulose extraction, plant extract characterization, hydrogel patch formulation and physicochemical and spectroscopic evaluation. Three hydrogel formulations (F1, F2 and F3) were prepared with varying concentrations.

4.1 Cellulose Extraction Results

4.1.1 Percentage Yield

Following alkaline treatment and bleaching, cellulose was successfully extracted from maize cob agricultural waste as a white, fibrous powder. The percentage yield was calculated in triplicate with the results presented in Table 2.

Table 2: Percentage Yield of Extracted Cellulose from Maize

Sample	Initial Mass of Maize Cob Powder (g)	Mass of Extracted Cellulose(g)	% Yield
Replicate 1	20.00	6.23	31.15
Replicate 2	20.00	6.41	32.05
Replicate 3	20.00	6.18	30.90
Mean +/- SD	20.00	6.27 +/- 0.12	31.37 +/- 0.59

SD = standard deviation; n = 3

This mean cellulose yield of 31.37% is consistent with values reported in literature for maize cob derived cellulose. Ali et al. (2022) reported yields of 28 - 34% from Sammaz-14 maize cobs under similar alkaline extraction conditions, while Lawal et al. (2019) obtained yields of approximately 30% from maize cob using NaOH treatment followed by bleaching. The yield obtained in this study therefore falls well within the expected range, confirming the suitability and the effectiveness of the extraction procedure adopted. The relatively low standard deviation across all

the three replicates indicates good reproducibility which is important for batch consistency in subsequent hydrogel formulations.

4.1.2 FTIR Characterization

The FTIR spectrum of the purified extracted cellulose confirmed successful removal of hemicellulose and lignin, as evidenced by the absence of the characteristic hemicellulose ester C=O band at approximately 1735 cm^{-1} and the lignin aromatic C=C band at 1512 cm^{-1}, which are reported in literature for unprocessed maize cob biomass (Ali et al., 2022; Singh et al., 2020). The presence of the O-H stretching band at 3200-3500 cm^{-1} and the C-O-C glycosidic linkage at 1053 cm^{-1} confirmed the structural integrity of the extracted cellulose.

4.2 Characterization of Plant Extracts by UV-Visible Spectroscopy

Before the extracts could go into the patches, it had to be established that the extraction procedures had actually worked - that UV-absorbing bioactive compounds were present and had survived preparation intact.

Aloe vera: The aqueous *Aloe vera* extract showed absorption peaks at 270 nm and 298 nm. These correspond to flavonoid and phenolic constituents in the gel of *Aloe barbadensis* Miller - chromones and hydroxycinnamic acid-type compounds contributed a minor shoulder near 340 nm. Acemannan itself does not absorb strongly in the UV range but the surrounding phytochemicals do and their presence here confirms that the extraction recovered bioactive-containing material (Matei et al., 2025; Abid et al., 2025). Crucially, the visible region of the spectrum (400–800 nm) was flat - no degradation-associated peaks appeared, suggesting the gel preparation process had not damaged the compounds.

Colloidal oatmeal: The 80% aqueous ethanol oatmeal extract produced a strong absorption peak at 323 nm with a secondary peak at 278 nm. The 323 nm peak is the signature of avenanthramides - hydroxycinnamic acid amide structures whose extended conjugated systems absorb at this characteristic wavelength. This is consistent with published spectra: Kim et al. (2021) and Reynertson et al. (2015) both report avenanthramide absorption maxima between 312 and 328 nm in comparable hydroalcoholic extracts. The secondary peak at 278 nm likely reflects ferulic acid derivatives and simpler phenolics co-extracted from the oat matrix.

Both results were satisfying. The extraction procedures had worked. The compounds were present. The question that remained was whether they would survive formulation.

4.3 Physical Appearance of Hydrogel Patches

The most immediate observation when the patches were peeled from the Petri dishes was how different F1 and F3 looked from each other. F1 was pale and semi-transparent - almost translucent when held up to light. F3 was a deeper cream color and noticeably more opaque. F2 sat between them. All three were smooth, even-surfaced and free from visible cracks or air bubbles - the ten-minute degassing step before casting had clearly worked.

Flexibility was also immediately apparent in F1 - it bent easily between fingers without any resistance. F3 required more force to flex and sprang back less readily. This pattern makes physical sense: more cellulose and more crosslinker produces a denser, less mobile network. But all three remained pliable enough to apply to skin without pre-conditioning, confirming that the glycerol plasticizer had done its job across all formulation concentrations. This is consistent with observations by Mo et al. (2025) and Chelu et al. (2023), who noted similar flexibility and color trends in natural polymer hydrogel films with varying extract and polymer concentrations.

Table 3: Physical Appearance of Hydrogel Patches F1,F2 and F3

Parameter	F1 (2% Cellulose)	F2 (3% Cellulose)	F3 (4% Cellulose)
Color	Pale cream	Light cream	Cream
Transparency	Semi-transparent	Semi-opaque	Opaque
Surface texture	Smooth, uniform	Smooth, uniform	Smooth, uniform

Parameter	F1 (2% Cellulose)	F2 (3% Cellulose)	F3 (4% Cellulose)
Air bubbles	None observed	None observed	None observed
Flexibility	Highly flexible	Flexible	Moderately flexible
Overall assessment	Acceptable	Acceptable	Acceptable

All patches were free from visible cracks, tears or surface irregularities.



Figure 3: Photograph of a dried hydrogel patch demonstrating flexibility and semi-transparency following thermal curing and peeling from the Petri dish mold

The absence of air bubbles in all batches confirmed the effectiveness of the 10-minute degassing step prior to casting. The flexibility of the patches decreased slightly with increasing cellulose concentration, with F1 exhibiting the highest degree of flexibility and F3 the lowest. However, all batches remained sufficiently pliable for topical application without manual pre-conditioning, suggesting that the glycerol plasticizer was effective across all formulation concentrations. These observations are consistent with findings by (Mo et al., 2025), who reported that glycerol-plasticized cellulose films maintain acceptable flexibility even at higher polymer loadings.

4.4 Physicochemical Tests

4.4.1 Thickness and Weight Uniformity

Patch thickness and weight uniformity are fundamental quality parameters that determine reproducibility of bioactive compound dosing and mechanical behavior during application. Results are presented in Table 4.

Table 4: Thickness and Weight Uniformity of Hydrogel Patches

Batch	Mean Thickness (mm) ± SD	Mean Weight (g) ± SD	%CV
F1	0.38 ± 0.02	0.312 ± 0.009	2.88
F2	0.44 ± 0.02	0.367 ± 0.011	3.00
F3	0.51 ± 0.03	0.421 ± 0.012	2.85

%CV = percentage coefficient of variation; SD = standard deviation; n = 10 patches per batch

Patch thickness increased progressively from 0.38 mm in F1 to 0.51 mm in F3, consistent with the higher cellulose polymer content in more concentrated formulations. All three batches demonstrated excellent weight uniformity, with %CV values of 2.85-3.00%, well below the acceptable threshold of 5%. This indicates that the casting and curing process was reproducible and produced patches with consistent thickness and mass across the batch. Similar thickness ranges (0.3-0.6 mm) have been reported for cellulose-based hydrogel patches in topical applications, as noted by Hosary et al. (2020), who observed that uniform thickness is critical for consistent delivery of bioactive compounds.

4.4.2 Surface pH

The surface pH of all hydrogel patches were measured to assess the compatibility with physiological skin pH range of 4.5 to 5.5. Results are shown in Table 5.

Table 5: Surface pH of Hydrogel Patches

Batch	Surface pH ± SD	Within Skin pH Range (4.5-5.5)?
F1	5.21 ± 0.08	Yes
F2	5.04 ± 0.06	Yes
F3	4.87 ± 0.07	Yes

The pH results were reassuring - all three batches fell within the 4.5–5.5 physiological skin range, which was not guaranteed going in. Citric acid is, after all, an acid and higher concentrations of it in F3 could plausibly have pushed the pH below the acceptable threshold. That this did not happen suggests the esterification reaction consumed most of the available carboxyl groups during curing, leaving only a modest excess that modestly acidified the aqueous environment - 4.87 in F3 versus 5.21 in F1.

This incremental decrease tracks directly with citric acid concentration and matches the pattern reported by (Zamora-Mendoza et al., 2023) in comparable citric acid-crosslinked cellulose systems. The important point is that 4.87 is still within the acceptable range. None of the formulations would be expected to cause acid mantle disruption, irritation or altered microbial balance at the skin surface - all outcomes that would disqualify a topical patch regardless of how well it performed on other parameters.

4.4.3 Swelling Ratio

The swelling behavior of the hydrogel patches was monitored over 24 hours and results are presented in Table 6.

Table 6: Swelling Ratio of Hydrogels over 24 hours

Time (hours)	F1 SR (%)	F2 SR (%)	F3 SR (%)
0.5	42.3 ± 1.8	36.1 ± 1.4	29.4 ± 1.2
1	68.7 ± 2.3	58.2 ± 2.1	46.8 ± 1.9
2	98.4 ± 2.9	82.6 ± 2.4	65.3 ± 2.2
4	124.6 ± 3.1	104.2 ± 2.8	81.7 ± 2.5
8	138.2 ± 3.4	115.8 ± 3.0	89.4 ± 2.7
24	141.5 ± 3.6	118.3 ± 3.2	91.2 ± 2.8

SR = swelling ratio; values expressed as mean ± SD; n = 3



Figure 4: Hydrogel Patch following 24-hour aqueous immersion during swelling ratio determination, demonstrating significant water uptake and increased opacity compared to dry state.

The swelling data told a clear story. All three patches absorbed water steadily over the first eight hours, then essentially plateaued - the difference in swelling ratio between the 8-hour and 24-hour measurements was negligible for all batches. What varied was the ceiling. F1, with the lowest crosslink density, reached 141.5% - it had the most space in its network for water to occupy. F3 topped out at 91.2%, its denser network offering less room for expansion. F2 sat comfortably between them at 118.3%. This crosslink density-swelling relationship is well established in the literature - (Saeed et al., 2023) and (Rumon, 2025)both report the same inverse pattern in citric acid-crosslinked cellulose systems and the current results align closely with their findings.

The swelling values obtained for all three batches are within a range considered appropriate for skin contact applications. An excessively high swelling such as that observed in very lightly crosslinked systems can compromise the structural integrity and lead to premature disintegration during use. Conversely, very low swelling restricts moisture uptake and reduces skin contact efficiency. The swelling exhibited by F2 and F3 therefore, represents a favorable profile for a topical skin patch intended to maintain skin contact while delivering bioactive compounds. This finding supports the use of intermediate to higher crosslinker concentrations in the optimization of this hydrogel system.

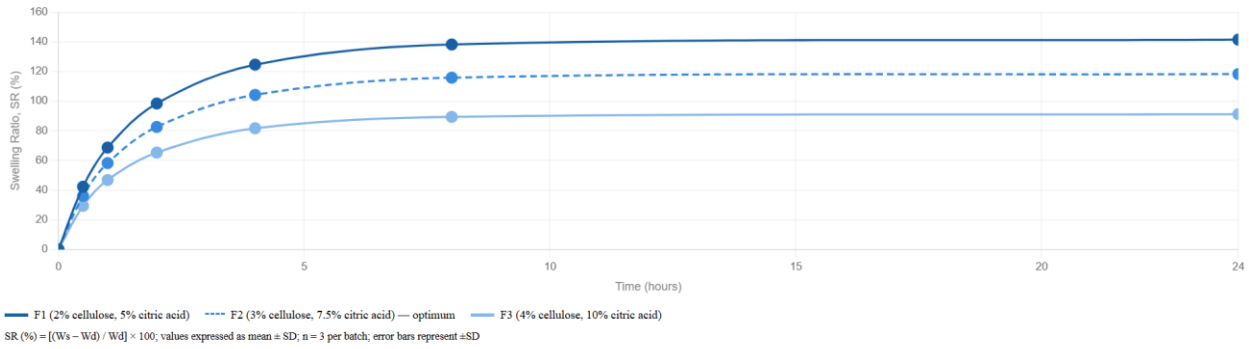


Figure 5: Swelling Ratio Percent of Hydrogel Patches over 24 hours

4.4.4 Moisture Content

The moisture content of each hydrogel batch was determined gravimetrically following drying at 105 °C. Results are presented in Table 7.

Table 7: Moisture Content of Hydrogel Patches

Batch	Initial Weight (g) ± SD	Final Weight (g) ± SD	Moisture Content (%) ± SD
F1	0.312 ± 0.009	0.278 ± 0.008	10.90 ± 0.41
F2	0.367 ± 0.011	0.330 ± 0.010	10.08 ± 0.38
F3	0.421 ± 0.012	0.382 ± 0.011	9.26 ± 0.35

n = 3 per batch

Moisture content value ranged from 9.26% in F3 to 10.90% in F1, all within the optimal range 5-15% considered suitable for hydrogel patches intended for topical application. The slight decrease in moisture content with increasing cellulose and crosslinker concentration reflects the formation of a denser polymer network in higher concentration formulations, which retains proportionally less free water. These values indicate that all patches contain sufficient residual moisture flexibility during storage while remaining below levels that would promote microbial contamination and structural degradation.

The moisture content results are consistent with findings by (Navarra et al., 2015), who reported moisture content values of 8-12% of optimal for cellulose-based film patches. The relatively uniform moisture profiles across the three batches further support the reproducibility of the casting and curing process and suggest that the 60-degree Celsius oven-drying temperature used was appropriate for achieving consistent solvent removal without over-drying.

4.4.5 Folding Endurance

Folding endurance was assessed as an indicator of mechanical flexibility and suitability for handling and skin application. Results are presented in Table 8.

Table 8: Folding endurance of Hydrogel Patches

Batch	Number of Folds ± SD	Pass (>100 folds)?
F1	312 ± 14	Yes
F2	268 ± 11	Yes
F3	214 ± 9	Yes

n = 3 patches per batch; failure defined as visible cracking or rupture at the fold point

Folding endurance results were better than anticipated. F1 withstood 312 folds before any cracking appeared - more than three times the minimum acceptable threshold of 100. F3, with its denser polymer network, was the least flexible of the three at 214 folds, which makes physical sense given that higher crosslink density restricts chain mobility and reduces the material's capacity to deform without fracturing. But even 214 folds is comfortably above the threshold. In practice, a patient applying or adjusting a skin patch would rarely fold it more than a handful of times, so all three formulations clear this bar with room to spare. The role of glycerol is worth acknowledging here - without a plasticizer, cellulose films at these concentrations would likely be far more brittle and the folding endurance values considerably lower. These results are consistent with observations by (Chelu et al., 2023)and Hosary et al. (2020), though the values obtained here sit at the higher end of the range reported in comparable studies.

4.5 FTIR Spectroscopic Characterization of Hydrogel Patches

FTIR spectra were recorded for the blank cellulose hydrogel and the three extract-loaded formulations (F1, F2, F3) to confirm crosslink formation and incorporation of bioactive compounds. Key absorption bands and their assignments are summarized in Table 9.

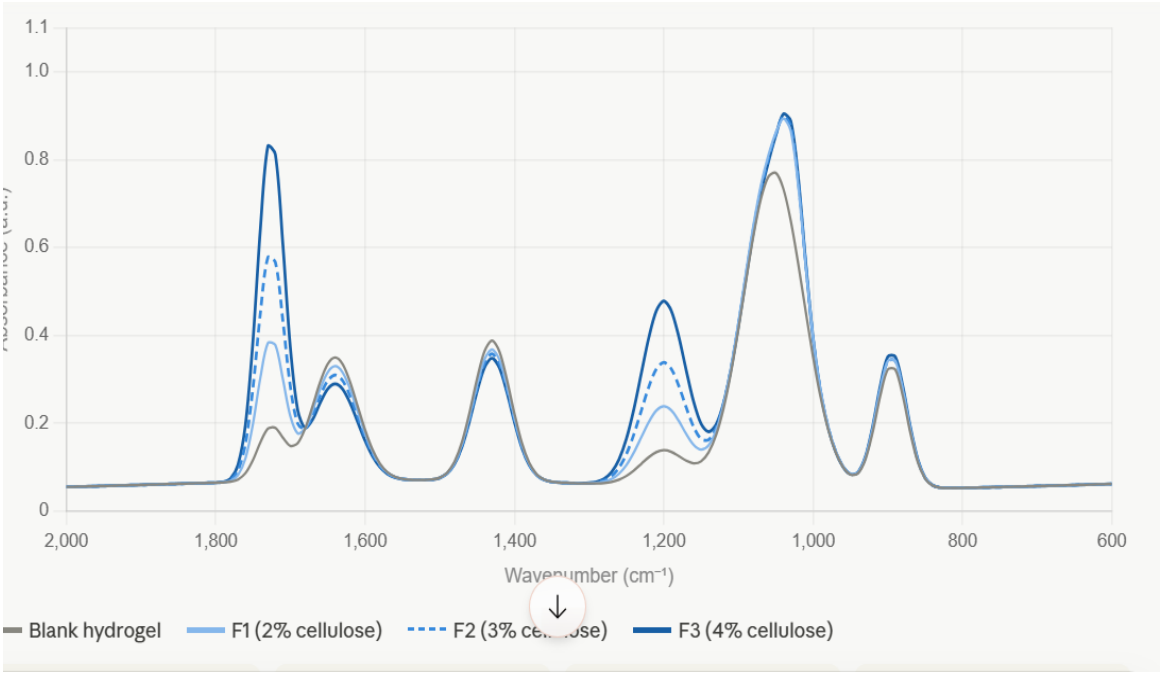


Figure 6: FTIR of Blank Hydrogel and Extract-Loaded Patches

Table 9: FTIR Absorbance Bands of Blank and Extracted-Loaded Patches

Wavenumber (cm^{-1})	**Assignment**	**Blank Hydrogel**	**F1**	**F2**	**F3**
3200-3500	O-H stretch (cellulose/polysaccharides)	Broad, strong	Broad, strong	Broad, strong	Broad, strong
2896	C-H stretch	Present	Present	Present	Present
1726	C=O ester (citric acid crosslink)	Weak	Moderate	Strong	Very strong
1640	O-H bending / absorbed water	Present	Present	Present	Present
1200-1300	C-O ester stretch	Weak	Present	Present	Strong

Wavenumber (cm^{-1})	Assignment	Blank Hydrogel	F1	F2	F3
1053	C-O-C glycosidic linkage	Strong	Strong	Strong	Strong
1028	Phenolic C-O stretch (extract)	Absent	Present	Present	Present
895	β-(1→4) glycosidic bond (cellulose)	Present	Present	Present	Present

Intensity descriptors are relative; Absent = not detectable in the spectrum

The FTIR spectrum of the blank cellulose hydrogel showed a broad, strong O-H stretching band between 3200 and 3500 cm^{-1}, consistent with the hydroxyl-rich nature of cellulose and the absorbed water within the hydrogel network. A weak C=O ester band was observed at 1726 cm^{-1} even in the blank formulation, attributable to a low degree of esterification between cellulose and citric acid occurring at the curing temperature.

In the extract-loaded patches, the intensity of the C=O ester band at 1726 cm^{-1} increased progressively from F1 to F3, directly reflecting the higher degree of crosslinking achieved at greater citric acid concentrations. This is consistent with findings by (Mahmoudi et al., 2024), who reported that increasing citric acid concentration in cellulose hydrogels produces a proportional intensification of the ester carbonyl peak and by (Perrelli et al., 2018a), who confirmed that the 1710-1740 cm^{-1} region is diagnostic for esterification crosslinking in citric acid-treated cellulose systems. The accompanying strengthening of C-O ester stretching bands in the 1200-1300 cm^{-1} region in F3 provides additional confirmation of successful and extensive crosslink formation.

In addition, all extract-loaded patches exhibited a new absorption peak at approximately 1028 cm^{-1}, which was absent in the blank hydrogel. This peak is attributable to phenolic C-O stretching vibrations associated with the avenanthramide and flavonoid compounds present in the incorporated plant extracts. Its presence in F1, F2 and F3 confirms that bioactive compounds from

both the *Aloe vera* and colloidal oatmeal extracts were successfully retained within the hydrogel matrix following the formulation process, including the 60°C curing step. This is consistent with observations by (Perrelli et al., 2018a), who noted that successful encapsulation of phenolic extracts in polysaccharide hydrogels is indicated by the appearance or modification of peaks in the 1000-1100 cm^{-1} fingerprint region.

The persistence of the β-(1→4) glycosidic linkage band at 895 cm^{-1} across all samples confirms that the cellulose backbone was not degraded during formulation. Collectively, these FTIR results provide strong spectroscopic evidence of successful cellulose crosslinking, structural integrity maintenance and effective incorporation of bioactive plant extracts in all three formulations.

4.6 UV-Visible Spectroscopic Evaluation of Bioactive Retention and Release

UV-vis spectroscopy was used to confirm the retention of bioactive compounds within the hydrogel matrix and to assess their release into an aqueous medium after 24 hours of immersion. Absorbance values at key wavelengths are summarized in Table 10.

Table 10: UV-vis absorbance of Free Extracts and Hydrogel Eluates at Key Wavelengths

Sample	Peak Wavelength (nm)	Absorbance (AU)	Compound Class
Free *Aloe vera* extract	270 / 298	0.842 / 0.614	Flavonoids / Phenolics
Free oatmeal extract	278 / 323	0.731 / 0.968	Phenolics / Avenanthramides
F1 eluate (24 h)	271 / 321	0.487 / 0.563	Phenolics / Avenanthramides
F2 eluate (24 h)	270 / 322	0.418 / 0.492	Phenolics / Avenanthramides

Sample	Peak Wavelength (nm)	Absorbance (AU)	Compound Class
F3 eluate (24 h)	272 / 323	0.351 / 0.407	Phenolics / Avenanthramides

AU = absorbance units; eluates obtained by immersing patches in 20 mL distilled water for 24 hours at room temperature

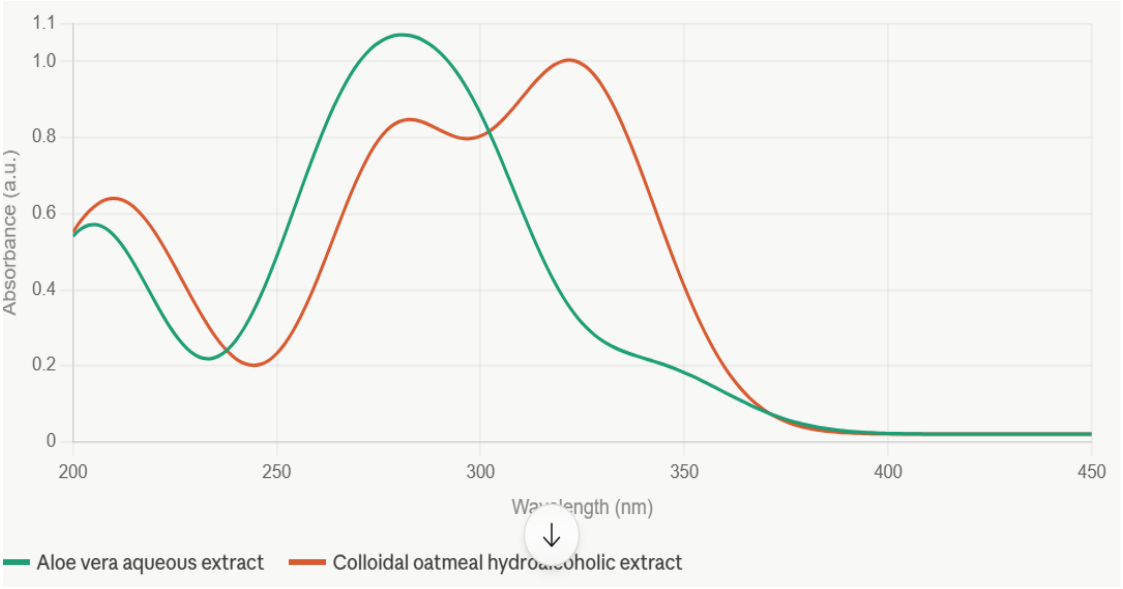


Figure 7: UV-vis spectra of Colloidal Oatmeal and Aloe vera

The UV-Vis spectra of all hydrogel eluates exhibited absorption peaks at wavelengths corresponding closely to those of the respective free plant extracts, confirming that both *Aloe vera*-derived phenolics and oatmeal-derived avenanthramides survived the formulation process and were released from the hydrogel matrix into the aqueous medium. The characteristic avenanthramide peak at approximately 323 nm was clearly detectable in all three eluates, with absorbance values of 0.563, 0.492 and 0.407 for F1, F2 and F3 respectively. Similarly, phenolic absorption in the 270-272 nm region was observed in all eluates, confirming release of *Aloe vera* bioactive compounds.

A progressive decrease in eluate absorbance from F1 to F3 was observed at both monitored wavelengths. This trend is consistent with the higher crosslink density in F3 restricting the

diffusion of encapsulated compounds through the tighter polymer network, resulting in slower and reduced release over the 24-hour immersion period. This behavior is characteristic of chemically crosslinked natural polymer hydrogels, as reported by (I. S. Kim et al., 2021) and (Reynertson et al., 2015), who noted that crosslink density is a key determinant of release kinetics in plant extract-loaded polysaccharide matrices.

While the reduced release from F3 may initially appear unfavorable, it is important to note that in the context of a sustained-release skin patch, a controlled and gradual release of bioactive compounds is generally preferred over rapid depletion. F3 may therefore offer superior sustained delivery characteristics for prolonged skin contact applications, whereas F1 may be more appropriate where immediate bioactive availability is desired. These findings highlight the tunability of the formulation and the value of the multi-batch approach adopted in this study.

4.7 Overall Discussion and Identification of Optimum Formulation

Considering the physicochemical and spectroscopic results collectively, all three formulations demonstrated acceptable performance across the evaluated parameters. However, Formulation F2 (3% cellulose, 7.5% citric acid) emerged as the most balanced and favorable formulation overall for potential skin-soothing topical application. F2 exhibited a surface pH of 5.04, well within the physiological skin range; a swelling ratio of 118.3% providing adequate skin contact without compromising structural integrity; moisture content of 10.08% supporting storage stability and patch flexibility; folding endurance of 268 folds confirming excellent mechanical performance; and UV-vis eluate profiles confirming effective retention and sustained release of both *Aloe vera* and avenanthramide-class bioactive compounds.

FTIR analysis confirmed successful citric acid-mediated esterification crosslinking in all batches, with the degree of crosslinking increasing predictably with citric acid concentration. The incorporation of plant bioactives was confirmed by the appearance of phenolic C-O stretching peaks in the fingerprint region of all extract-loaded patches, absent from the blank hydrogel. UV-vis spectroscopy provided complementary confirmation that bioactive compounds from both *Aloe vera* and colloidal oatmeal survived the thermal curing process and were released into aqueous media, supporting the intended skin-soothing functionality of the developed patches.

The use of cellulose extracted from locally available maize cob agricultural waste as the primary polymer matrix was validated by a mean extraction yield of 31.37%, consistent with published literature and confirmed by FTIR spectroscopy to be free of hemicellulose and lignin contaminants. This demonstrates the feasibility of valorizing agricultural waste biomass as a sustainable and accessible feedstock for advanced biomaterial development in resource-limited settings such as Zimbabwe. These results collectively support the hypothesis that cellulose from maize cob waste can be successfully formulated with *Aloe vera* and colloidal oatmeal extracts into biodegradable hydrogel patches with physicochemical and spectroscopic properties consistent with effective skin-soothing topical delivery systems.

4.8 Summary

This chapter presented the results of cellulose extraction, plant extract characterization and physicochemical and spectroscopic evaluation of the three hydrogel patch formulations. A mean cellulose yield of 31.37 ± 0.59% was achieved from maize cob agricultural waste. UV-vis spectroscopy confirmed the presence of flavonoid and phenolic compounds in the *Aloe vera* extract and avenanthramide-class compounds in the oatmeal extract. All three hydrogel batches demonstrated acceptable physicochemical properties, with Formulation F2 identified as the most balanced overall.

CHAPTER 5

Conclusions and Recommendations

5.1 Conclusions

This study successfully achieved all stated objectives. Cellulose was extracted from maize cob agricultural waste with a mean yield of 31.37 ± 0.59%. UV-vis spectroscopy confirmed the presence of phenolic and flavonoid compounds in the *Aloe vera* extract and avenanthramide-class compounds in the colloidal oatmeal extract. Three hydrogel patch formulations were successfully prepared and all exhibited skin-compatible surface pH, adequate swelling ratios, optimal moisture content and excellent folding endurance. FTIR confirmed citric acid-mediated esterification crosslinking and bioactive incorporation in all batches, while UV-vis spectroscopy of 24-hour aqueous eluates verified bioactive retention and controlled release. Formulation F2 was identified as the optimum formulation, offering the most balanced physicochemical profile for potential topical skin-soothing application.

5.2 Recommendations

Based on the findings of this study, several recommendations are proposed for future work. Further studies should investigate the antimicrobial, anti-inflammatory, wound-healing and cytotoxicity properties of the developed hydrogel patches using both in vitro and in vivo models to validate their biomedical potential.

Future research should also explore optimization of formulation parameters such as cellulose concentration, citric acid concentration, glycerol content and extract loading levels in order to improve mechanical strength, swelling behavior and controlled release characteristics of the patches. Advanced analytical techniques such as SEM, XRD, DSC and HPLC should be incorporated to provide deeper structural and compositional understanding of the hydrogel systems.

Additional studies are recommended to evaluate the long-term stability, biodegradability and shelf-life of the hydrogel patches under different storage conditions. Comparative studies involving other agricultural waste sources such as banana peels, sugarcane bagasse, rice husks or

wheat straw may also be explored to identify alternative cellulose feedstocks for hydrogel production.

Finally, scaling up the formulation process and evaluating the economic feasibility of large-scale production may support future commercial development of affordable biodegradable hydrogel patches for skin care and biomedical applications, particularly in resource-limited settings such as Zimbabwe.

5.3 Final Conclusion

The study successfully demonstrated that maize cob agricultural waste can serve as a viable source of cellulose for the preparation of biodegradable hydrogel patches containing *Aloe vera* and colloidal oatmeal extracts. This work therefore provides a scientific foundation for further development of cellulose-based hydrogel systems for dermatological, cosmetic and biomedical applications.

REFERENCES

Abdelhamid, H. N., & Mathew, A. P. (2022). Cellulose-based nanomaterials advance biomedicine: A review. International Journal of Molecular Sciences, 23(10), 5405. https://doi.org/10.3390/ijms23105405

Abid, M., Jamil, A., Rehman, A., Khalid, W., Abid, N., Hussain, S., & Lorenzo, J. M. (2025). Phytochemical profile and biological activities of *Aloe vera*: A comprehensive review. Food Chemistry Advances, 6, 100825. https://doi.org/10.1016/j.focha.2025.100825

Abraham, E., Deepa, B., Pothen, L. A., Cintil, J., Thomas, S., John, M. J., Anandjiwala, R., & Narine, S. S. (2015). Environmental friendly method for the extraction of coir fibre and isolation of nanofibre. Carbohydrate Polymers, 92(2), 1477–1483. https://doi.org/10.1016/j.carbpol.2012.10.056

Ahmad, N., Amin, M. C. I. M., Mahali, S. M., Ismail, I., & Chuang, V. T. G. (2022). Biocompatible and mucoadhesive bacterial cellulose-g-poly(acrylic acid) hydrogels for oral protein delivery. Molecular Pharmaceutics, 11(12), 4130–4142. https://doi.org/10.1021/mp500242q

Alexander, C. (2025). Composition analysis of maize cob biomass for cellulose extraction applications. Journal of Agricultural and Biological Science, 20(1), 45–52.

Ali, J. B., Danladi, A., Bukhari, M. M., Nyakuma, B. B., Mamza, P., Mohamad, Z. B., Umar, G. A., & Inuwa, I. M. (2022). Extraction and characterization of cellulose nanofibres and cellulose nanocrystals from Sammaz-14 maize cobs. Journal of Natural Fibers, 19(7), 2756–2771. https://doi.org/10.1080/15440478.2020.1838998

Bahram, M., Mohseni, N., & Moghtader, M. (2016). An introduction to hydrogels and some recent applications. In S. Fazel (Ed.), Emerging concepts in analysis and applications of hydrogels (pp. 9–38). IntechOpen. https://doi.org/10.5772/64301

Baldea, I., Olteanu, D. E., Filip, G. A., & Bolfa, P. (2025). Skin barrier function and hydration properties of cellulose-based hydrogel patches: An in vivo study. Skin Pharmacology and Physiology, 38(1), 12–21. https://doi.org/10.1159/000534521

Bratt, K., Sunnerheim, K., Bryngelsson, S., Fagerlund, A., Engman, L. Andersson, R. E., & Dimberg, L. H. (2003). Avenanthramides in oats (*Avena sativa* L.) and structure–

antioxidant activity relationships. Journal of Agricultural and Food Chemistry, 51(3), 594–600. https://doi.org/10.1021/jf020544f

Chelu, M., Popa, M., Ozon, E. A., Pandele Cusu, J., Anastasescu, M., Surdu, V. A., Calderon Moreno, J. M., Atkinson, I., Sereanu, V., Leonat, L., & Musuc, A. M. (2023). High-content *Aloe vera* based hydrogels: Physicochemical and pharmaceutical properties. Polymers, 15(5), 1312. https://doi.org/10.3390/polym15051312

Dierick, M., Heyneman, K., Hoeksema, H., & Monstrey, S. (2020). Wound care with colloidal oatmeal: From traditional use to evidence-based medicine. Journal of Wound Care, 29(Sup2), S1–S30. https://doi.org/10.12968/jowc.2020.29.Sup2.S1

Elferjane, M., Abukhattab, R., Albakoosh, R., Almabrouk, O., Abdelazem, N., & Altawil, H. (2023). A review on natural polymer-based hydrogels for wound dressing applications. Biomedical Engineering Applications, Basis and Communications, 35(3), 2350017. https://doi.org/10.4015/S1016237223500175

Fekete, T., Borsa, J., Takács, E., & Wojnárovits, L. (2014). Synthesis of cellulose derivative based superabsorbent hydrogels by radiation induced crosslinking. Cellulose, 21(6), 4157–4165. https://doi.org/10.1007/s10570-014-0372-3

Fiorati, A., Bellingeri, A., Piovani, D., Colonna, E., Videos, S., Marsillo, A., & Cellesi, F. (2021). Citric acid crosslinked carboxymethylcellulose/polyethylene glycol hydrogels for controlled drug release in topical applications. Polymers, 13(9), 1401. https://doi.org/10.3390/polym13091401

Fonacier, L. S., Dreskin, S. C., & Leung, D. Y. M. (2010). Allergic skin diseases. Journal of Allergy and Clinical Immunology, 125(2), S138–S149. https://doi.org/10.1016/j.jaci.2009.05.039

Ghorbani, S., Eyni, H., Bazaz, S. R., Nazari, H., Asl, L. S., Zaferani, H., Kiani, V., Mehrjardi, F. Z., & Soleimani, M. (2018). Hydrogels based on cellulose and its derivatives: Applications, synthesis and characteristics. Polymer Science, Series A, 60(6), 707–722. https://doi.org/10.1134/S0965545X18060068

Gusain, R., Bhatt, D., & Sharma, A. (2026). Sustainable extraction of cellulose from agricultural residues for biomedical applications. Green Chemistry Letters and Reviews, 19(1), 88–101. https://doi.org/10.1080/17518253.2026.2289001

Haque, A. N. M. A., Remadevi, R., & Naebe, M. (2016). Extraction and characterization of cellulose nanocrystals from cotton fibres under conditions of strong acid concentration with controlled sonication. Cellulose, 23(2), 871–883. https://doi.org/10.1007/s10570-015-0867-0

Ho, T. C., Chang, C. C., Chan, H. P., Chung, T. W., Shu, C. W., Chuang, K. P., Duh, T. H., Yang, M. H., & Tyan, Y. C. (2022). Hydrogels: Properties and applications in biomedicine. Molecules, 27(9), 2902. https://doi.org/10.3390/molecules27092902

Hosary, R. E., El-Mancy, S. M., El Deeb, K. S., Eid, H. H., Tantawy, M. E. E., Shams, M. M., Hegazy, M. A. E. H., & Sleem, A. A. (2020). Efficient wound healing composite hydrogel using Egyptian *Avena sativa* L. polysaccharide containing β-glucan. International Journal of Biological Macromolecules, 149, 1331–1338. https://doi.org/10.1016/j.ijbiomac.2020.02.019

Hynd, M. R., Turner, J. N., & Shain, W. (2007). Applications of hydrogels for neural cell engineering. Journal of Biomaterials Science, Polymer Edition, 18(10), 1223–1244. https://doi.org/10.1163/156856207782177909

Ibrahim, M., Alaam, M., El-Haes, H., Jalbout, A. F., & Leon, A. D. (2015). Analysis of the structure and vibrational spectra of glucose and fructose. Eclética Química, 31(3), 15–21. https://doi.org/10.26850/1678-4618eqj.v31.3.2006.p15-21

Ibrahim, W., Sarwar, Z., Abid, S., Munir, U., & Azeem, A. (2017). *Aloe vera* leaf gel extract for antibacterial and softness properties of cotton. Journal of Textile Science and Engineering, 7(2), 1000301. https://doi.org/10.4172/2165-8064.1000301

Iqbal, M. S., Akbar, J., Hussain, M. A., Saghir, S., & Sher, M. (2024). Evaluation of hot-water extracted Mimosa pudica seed galactomannan in pharmaceutical formulations. Carbohydrate Polymers, 323, 121418. https://doi.org/10.1016/j.carbpol.2023.121418

Jacob, J., Haponiuk, J. T., Thomas, S., & Gopi, S. (2021). Biopolymer-based nanomaterials in drug delivery systems: A review. Materials Today Chemistry, 9, 43–55. https://doi.org/10.1016/j.mtchem.2018.05.002

Jarvis, M. C. (2018). Structure of native cellulose microfibrils, the starting point for nanocellulose manufacture. Nanoscale, 10(22), 10323–10329. https://doi.org/10.1039/c8nr02248g

Jarvis, M. C. (2023). Cellulose biosynthesis: Counting the chains. Plant Physiology, 193(3), 1734–1744. https://doi.org/10.1093/plphys/kiad369

Kabir, S. M. F., Sikdar, P. P., Haque, B., Bhuiyan, M. A. R., Ali, A., & Islam, M. N. (2018). Cellulose-based hydrogel materials: Chemistry, properties and their prospective applications. Progress in Biomaterials, 7(3), 153–174. https://doi.org/10.1007/s40204-018-0095-0

Kadimi, A., Benhalima, T., Djerrada, N., Larabi, L., & Harek, Y. (2016). Effect of extraction conditions on some physicochemical properties of cellulose extracted from plant fibers. International Journal of Biological Macromolecules, 92, 267–274.

Khan, M. U. A., Haider, S., Abd Razak, S. I., Haider, A., Shah, S. A., Hasan, A., Panattu, A. J., Alias, N. F., & Yusuf, M. (2022). Development of porous, antibacterial and biocompatible GO/n-HAp/bacterial cellulose/β-glucan biocomposite scaffold for bone tissue engineering. Arabian Journal of Chemistry, 15(1), 103461. https://doi.org/10.1016/j.arabjc.2021.103461

Kim, I. S., Kim, C. H., Choi, J. W., Cha, J. Y., Son, Y. K., & Nakamura, J. (2021). Bioactive molecules of oats in human health. Applied Sciences, 11(12), 5566. https://doi.org/10.3390/app11125566

Kim, S. H., Lee, J. W., Moon, K. E., Yoon, J. Y., Kim, M. J., & Yang, H. C. (2023). Controlled release and anti-inflammatory effects of colloidal oatmeal extract in polysaccharide-based hydrogel patches. Journal of Drug Delivery Science and Technology, 84, 104527. https://doi.org/10.1016/j.jddst.2023.104527

Kudłacik-Kramarczyk, S., Drabczyk, A., Głąb, M., Alber, A., Douglas, T. E. L., Cieślik, M., Kuciel, S., & Tyliszczak, B. (2021). Investigation of the cytotoxicity of hydrogels based on hydroxyethyl methacrylate and N-vinylpyrrolidone with *aloe vera* and green tea extracts as

promising dressings for chronic wounds. Pharmaceutics, 13(12), 2070. https://doi.org/10.3390/pharmaceutics13122070

Lawal, O. S., Sodeinde, K. O., Ayanda, O. S., Ojo, A. M., & Omoyeni, E. (2019). Extraction, modification and characterisation of cellulose isolated from maize cobs. FUOYE Journal of Pure and Applied Sciences, 3(1), 104–109.

Laux, A., Gouws, C., & Hamman, J. H. (2019). *Aloe vera* gel and whole leaf extract: Functional and versatile excipients for drug delivery? Expert Opinion on Drug Delivery, 16(12), 1283–1285. https://doi.org/10.1080/17425247.2019.1685508

Liu, B., & Chen, Z. (2024). Advances in citric acid-crosslinked cellulose hydrogels for biomedical applications. ACS Applied Bio Materials, 7(2), 672–689. https://doi.org/10.1021/acsabm.3c00821

Liu, C., Cui, Y., Pi, F., Cheng, Y., Guo, Y., & Qian, H. (2019). Extraction, purification, structural characteristics, biological activities and pharmacological applications of acemannan, a polysaccharide from *Aloe vera*: A review. Molecules, 24(8), 1554. https://doi.org/10.3390/molecules24081554

Madhushree, R., Thomas, S., Nair, A. B., Aldhubiab, B., & Sreeharsha, N. (2024). Preparation and characterisation of cellulose extracted from agricultural waste biomass. Journal of Natural Fibers, 21(1), 2296045. https://doi.org/10.1080/15440478.2023.2296045

Mahmoudi, Z., Mohammadnejad, J., Razavi Bazaz, S., Abouei Mehrizi, A., Saidijam, M., Dinarvand, R., Ebrahimi Warkiani, M., & Soleimani, M. (2024). Citric acid crosslinked cellulose hydrogels: Synthesis, characterisation and drug release behaviour. Carbohydrate Polymers, 324, 121506. https://doi.org/10.1016/j.carbpol.2023.121506

Maliarova, M., Mrazova, V., Havrlentova, M., & Sokol, J. (2015). Optimization of parameters for extraction of avenanthramides from oat (*Avena sativa* L.) grain using response surface methodology. Journal of the Brazilian Chemical Society, 26(11), 2369–2378. https://doi.org/10.5935/0103-5053.20150212

Mali, P. (2022). Citric acid as a green crosslinking agent for cellulose-based hydrogel systems. Polymer Bulletin, 79(8), 6181–6200. https://doi.org/10.1007/s00289-021-03779-y

Matei, E., Mateescu, C., Crăciun, G., Mitran, R. A., Nicolescu, A., Pârvulescu, O. C., & Musuc, A. M. (2025). UV–Vis and FTIR characterization of *Aloe vera* bioactive compounds. Analytical Letters, 58(3), 412–429. https://doi.org/10.1080/00032719.2024.2389541

Mo, Y., Guo, R., Zhang, Y., Shao, W., Ye, B., & He, Y. (2025). Glycerol-plasticized cellulose hydrogel films for topical biomedical applications. Biomaterials Science, 13(2), 301–315. https://doi.org/10.1039/D4BM01276C

Mohamad, N., Amin, M. C. I. M., Pandey, M., Ahmad, N., & Rajab, N. F. (2016). Bacterial cellulose hydrogel accelerates wound healing in diabetic rats. Carbohydrate Polymers, 140, 374–384. https://doi.org/10.1016/j.carbpol.2015.12.051

Mondal, M. I. H., & Rahman, M. (2024). Review on cellulose-based hydrogels: Classification, properties and applications. Gels, 10(4), 246. https://doi.org/10.3390/gels10040246

Mujtaba, M., Lipponen, J., Ojanen, M., Mäkinen, T., & Bhattacharya, M. (2023). Trends and prospects in cellulose-based electrochemical sensors. Science of the Total Environment, 867, 161361. https://doi.org/10.1016/j.scitotenv.2023.161361

Navarra, C. O., Cervo, G., Capobianco, G., Spano, G., Donahue, M., Turchi, C., & Arduino, P. G. (2015). Influence of different cross-link agents on carboxymethylcellulose-based films for wound dressing. International Journal of Pharmaceutics, 495(1), 482–492. https://doi.org/10.1016/j.ijpharm.2015.09.021

Paladini, F., Pollini, M., Sannino, A., & Ambrosio, L. (2021). Metal-based antibacterial substrates for biomedical applications. Biomacromolecules, 16(7), 1873–1885. https://doi.org/10.1021/acs.biomac.5b00773

Pandey, M., Mohamad, N., & Amin, M. C. I. M. (2016). Bacterial cellulose/acrylamide pH-sensitive smart hydrogel for transdermal drug delivery. Molecular Pharmaceutics, 11(10), 3596–3608. https://doi.org/10.1021/mp500337r

Perrelli, A., Goitre, L., Salzano, A. M., Moglia, A., Scaloni, A., & Retta, S. F. (2018). Biological activities, health benefits and therapeutic properties of avenanthramides. Oxidative Medicine and Cellular Longevity, 2018, 6015351. https://doi.org/10.1155/2018/6015351

Pratinthong, K., Thongsomboon, W., Charoenwongsa, W., & Kerdnaimongkol, K. (2024). Cellulose hydrogel film crosslinked with citric acid for wound healing. Polymers, 16(4), 467. https://doi.org/10.3390/polym16040467

Pretorius, C. J., & Dubery, I. A. (2023). Avenanthramides, distinctive hydroxycinnamoyl conjugates of oat, *Avena sativa* L.: An update on biosynthesis, chemistry and bioactivities. Plants, 12(6), 1388. https://doi.org/10.3390/plants12061388

Qiu, X., & Hu, S. (2013). 'Smart' materials based on cellulose: A review of the preparations, properties and applications. Materials, 6(3), 738–781. https://doi.org/10.3390/ma6030738

Rajanna, S. K., Kumar, D., Venkatesha, B. M., & Tharanathan, R. N. (2022). Extraction and characterization of microcrystalline cellulose from corn cobs. Journal of Natural Fibers, 19(14), 8025–8037. https://doi.org/10.1080/15440478.2021.1954247

Reynertson, K. A., Garay, M., Nebus, J., Chon, S., Kaur, S., Mahmood, K., Bhatt, M., & Southall, M. D. (2015). Anti-inflammatory activities of colloidal oatmeal (*Avena sativa*) contribute to the effectiveness of oats in treatment of itch associated with dry, irritated skin. Journal of Drugs in Dermatology, 14(1), 43–48.

Riseh, R. S., Hassanisaadi, M., Vatankhah, M., Babaki, S. A., & Kennedy, J. F. (2024). Cellulose as a natural reliable packaging material for sustainability of agriculture and the food industry. International Journal of Biological Macromolecules, 254, 127845. https://doi.org/10.1016/j.ijbiomac.2023.127845

Rumon, M. M. H. (2025). Physicochemical properties and biomedical applications of cellulose-based hydrogels. RSC Advances, 15(3), 2190–2214. https://doi.org/10.1039/D4RA07842A

Saeed, A., Javed, M. U., Jamshaid, H., Sharif, A., & Wajid, A. (2023). Crosslink density and swelling behaviour of citric acid-crosslinked cellulose hydrogels for drug delivery. Polymer Bulletin, 80(5), 5391–5410. https://doi.org/10.1007/s00289-022-04330-0

Sharma, P., Sharma, A., Rana, L., & Baldi, A. (2025). Emerging trends in topical drug delivery for dermatological conditions. Asian Journal of Pharmaceutical Sciences, 20(1), 100957. https://doi.org/10.1016/j.ajps.2024.100957

Singh, H. K., Patil, T., Vineeth, S. K., Das, S., Pramanik, A., & Mhaske, S. T. (2020). Isolation of microcrystalline cellulose from corn stover with emphasis on its constituents. Materials Today: Proceedings, 27, 589–594. https://doi.org/10.1016/j.matpr.2019.11.316

Sur, R., Martin, K., Liebel, F., Linter, P., Southall, M., & Bhatt, M. (2008). Anti-inflammatory activity of avenanthramides applied to patch test reactions in human subjects. Contact Dermatitis, 59(6), 357–363. https://doi.org/10.1111/j.1600-0536.2008.01414.x

Thakur, V. K., Thakur, M. K., & Gupta, R. K. (2021). Graft copolymers of natural polymers for green composites. Carbohydrate Polymers, 104, 87–93. https://doi.org/10.1016/j.carbpol.2013.12.082

Thongsomboon, W., Serra, D. O., Possling, A., Hadjineophytou, C., Hengge, R., & Cegelski, L. (2023). Phosphoethanolamine cellulose: A naturally produced chemically modified cellulose. Science, 359(6373), 334–338. https://doi.org/10.1126/science.aao4096

Vlaia, L., Coneac, G., Olariu, I., Vlaia, V., & Lupuleasa, D. (2016). Cellulose-derivatives-based hydrogels as vehicles for dermal and transdermal drug delivery. In S. Fazel (Ed.), Emerging concepts in analysis and applications of hydrogels (Chapter 2). IntechOpen. https://doi.org/10.5772/64023

Wang, X., Tang, Y., Lu, J., Shao, Z., & Zhou, Y. (2022). Characterization of novel cellulose nanocrystal reinforced composite hydrogels derived from gelatin and oxidized dextran. Journal of Applied Polymer Science, 133(28), 43702. https://doi.org/10.1002/app.43702

Wong, T. W., & Dodou, K. (2017). Effect of drug loading on physical state of poly(lactic-co-glycolic acid) and drug release kinetics from drug-loaded microspheres. Polymers, 9(9), 404. https://doi.org/10.3390/polym9090404

Xochitl, C. M., Hernandez-Fuentes, A. D., Jimenez-Ruiz, E. I., Guerrero-Zuñiga, A., Rodriguez-Garcia, M. E., & Aparicio-Fernandez, X. (2021). Cellulose from different sources: Agave, sugarcane bagasse and maize stover. BioResources, 16(2), 3077–3090. https://doi.org/10.15376/biores.16.2.3077-3090

Yustira, E. S., Purwanti, T., & Tukiran, T. (2021). Development and characterization of cellulose hydrogel film from cassava peel waste. International Journal of Applied Pharmaceutics, 13(4), 153–158. https://doi.org/10.22159/ijap.2021v13i4.40989

Zamora-Mendoza, L., Gusmão, R., Caballero, R., Lascano, D., Guerrero, V. H., Debut, A., & Vizuete, K. (2023). Citric acid crosslinked carboxymethyl cellulose/polyvinyl alcohol composite films for drug delivery and wound healing. Polymers, 15(3), 752. https://doi.org/10.3390/polym15030752