VALORIZATION OF WOOD PULP TO MECHANICALLY STRONG, WATER RESISTANCE AND BIODEGRADABLE PACKAGING FOAMS BY WET FOAMING PROCESS

by

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B.S., University of Tehran, 2003

M.S., University of Tehran, 2005

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

Natural Resource and Environmental Studies- Environmental Science

UNIVERSITY OF NORTHERN BRITISH COLUMBIA August 2023

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Declaration of Originality and Data Authenticity:

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgment of collaborative research and discussions. The work was done under the direct supervision of Dr. Hossein Kazemian at the University of Northern British Columbia (UNBC). I affirm that the data reported herein are authentic, accurate, and represent my work conducted in the laboratory at UNBC. The raw data supporting my findings are preserved in their original form and are available for future reference and verification. This thesis has not been submitted to any other academic institution for the award of any degree or diploma.

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8 December 2023

Abstract

This research focuses on developing environmentally friendly, biodegradable foams as alternatives to traditional petroleum-based materials like polyurethane and expanded polystyrene (EPS). Utilizing pulp and lignin through a cost-effective method, the study optimized factors such as sodium dodecyl sulfate (SDS) concentration, lignin content, and foaming time to achieve desirable mechanical properties and porosity. The box-behnken design identified optimal samples with varied characteristics, including densities from 0.013 g/cm³ to 0.077 g/cm³ and porosities from 95.2% to 99.2%. The introduction of lignin improved foam strength, with compression pressures ranging from 37.5 to 379 kPa. Additionally, the impact of chitosan on porosity, strength, and water resistance was examined. Incorporating 20 wt.% of chitosan enhanced strength by 4% and reduced water absorption by 60%. Over three months, the biodegradable foams displayed significant degradation, introducing them as sustainable alternatives to EPS for diverse applications like packaging.

Keywords: Bio-based foam, pulp foam, lignin foam, porous material, biodegradable foam.

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Acknowledgement and Dedication

I extend my gratitude for the opportunity to work on this thesis, and I am truly thankful for the support and guidance I have received on this journey. I want to sincerely thank my thesis supervisor, Dr. Hossein Kazemian, whose expertise, encouragement, and support were instrumental in navigating the challenges of this research project. His guidance and mentorship have been invaluable. I extend my deepest gratitude to my esteemed committee members, Dr. Nasim Ghavidel, Dr. Jianbing Li, and Dr. Kerry Reimer, for their invaluable guidance, expertise, and unwavering support throughout this journey. I am also grateful to Dr. Hoorieh Jahanbani for her assistance in data analysis and revision. My heartfelt appreciation goes to my family for their unwavering support and love, serving as a constant source of motivation and inspiration. Lastly, I acknowledge the contributions of my professors, colleagues, and research participants. Without their support and insights, this thesis would not have been possible. Thank you all for being a part of this journey with me and for your invaluable contributions.

1 Introduction

1.1 Foam

Foams are a type of substance that contain gaseous voids. The word "foam" has its roots in the mediaeval German word "Veim," which means froth [1]. Foam is a multi-phase system consisting of dispersed gas bubbles, a continuous liquid phase, and surfactants [2]. Foams made from synthetic, non-renewable polymers such as polyurethane, polyethylene, and expanded polystyrene (EPS) currently dominate the market. However, there is a growing concern about their long-term sustainability and ecological impact. These petrochemical-based foams contribute to carbon footprint and plastic waste, and their decomposition can take hundreds to thousands of years.

1.2 Types of foams

Plastic materials are frequently selected as the preferred choice for packaging various consumer goods such as food, cosmetics, and pharmaceutical products. This preference is primarily attributed to the affordability, lightweight characteristics, and exceptional protective qualities exhibited by certain types of plastics. These plastics can include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), among others, which are commonly employed in the packaging industry due to their suitability for different product requirements and the advantageous properties they offer. However, the environmental concerns associated with traditional plastic packaging have led to the development and increased use of biomaterials for packaging applications.

In addition to the environmental concerns associated with petrochemical-based foams, the plastic and petrochemical industries also have negative impacts on sustainability. These industries consume a large amount of energy, release greenhouse gas emissions, generate wastewater and hazardous wastes, and store flammable and toxic materials. Therefore, there is a need to transition towards more sustainable practices in these industries [3]–[5]. Moreover, as prices continue to rise and petroleum feedstock becomes increasingly depleted, there is a growing emphasis on the identification and utilization of alternative, environmentally friendly raw materials [3]–[5]. In response to these concerns, extensive research has been dedicated to the advancement of biodegradable foams through the utilization of alternative eco-friendly raw materials. Biopolymer sources such as polysaccharides (starch and cellulose), proteins (wheat gluten and other proteins), and lipids have been extensively studied for the development of biodegradable food packaging foams. Among these sources, polysaccharides have received remarkable attention due to their abundance availability and good gas barrier properties [6].

The development of biodegradable foams from renewable resources, such as wood-based polymers, has gained significant interest. Biodegradable polymer-based solid foams have been studied for their material and structural properties, and their applications in the food industry have been explored. These foams offer the potential for sustainable alternatives to petrochemical-based foams, with the added advantage of being derived from renewable resources [7].

Bio-based foams are derived from renewable resources and offer a more sustainable alternative to traditional plastic foams. They can be categorized into different types based on the raw materials used and the manufacturing process employed. Some of the main bio-based foams used for packaging include Polylactic Acid (PLA)-based foams, Starch-based foams, Polyhydroxyalkanoates (PHA)-based foams, and cellulose-based foams.

The choice of bio-based foam depends on factors such as the specific packaging requirements, desired properties, and availability of raw materials. Continued research and development in the

field of bioplastics lead to the emergence of new and improved bioplastic foam materials for packaging applications. In this thesis, the production of cellulose-based foams has been studied due to its abundance and availability in British Columbia (BC) and Canada and the desired chemical and mechanical properties for food-packaging applications.

1.2.1 Cellulose-based foams

Cellulose, a natural polymer found in plant cell walls, is a main component of packaging foam due to its abundance, renewability, and desirable properties. Cellulose-based foams offer a sustainable alternative to traditional petrochemical-based foams and have gained significant attention in recent years. Several studies have explored the isolation and application of cellulose-based materials for the development of packaging foams [8], [9].

Cellulose is a linear homopolysaccharide consisting of β -anhydroglucose. Cellulose esters include cellulose acetate, cellulose triacetate, and cellulose acetate butyrate, whereas cellulose ethers include carboxymethylcellulose (CMC), methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), ethyl cellulose, hydroxyethyl cellulose, and hydroxyethyl methylcellulose [3].



Figure 1. Chemical structure of cellulose [3].

Typically, water does not dissolve cellulose or cellulose esters. The water-soluble derivatives of cellulose ethers are CMC, MC, and HPMC (Figure 2), which are primarily employed in the production of films.



Figure 2. Chemical structure of a) HPMC (where R is H, CH₃ or CH₃ or CH₃CH(OH)CH₂), b) MC (Where R is H or CH₃), and c) CMC [3].

CMC is a superior film-forming anionic linear polysaccharide that is non-toxic, renewable, biocompatible, and biodegradable. To provide texture and lessen the wetness of the products, it is frequently blended with other polymers. The moisture sorption characteristics of CMC are improved by the inclusion of hydroxyl and carboxylic groups. Because of its strong molecular structure and high molecular weight, CMC can be employed as a filler in bio composite films [3]. It was discovered that CMC might improve the barrier and mechanical qualities of food packaging films based on pea starch [3].

Although cellulose ether derivatives offer excellent film-forming and gas barrier qualities, their usage in the food packaging sector has been constrained by their high swelling properties, water

solubility, weak mechanical strength, and high-water absorption rate. As a result, the film becomes a possible contender for food packaging applications when cellulose ether derivatives are combined with other polymers, cross-linkers, and/or nanomaterials [3].

Cellulose-based materials, including micro-fibrillated cellulose, nanocellulose, and cellulose composites, have been extensively studied for their application in packaging foams. These materials offer advantages such as renewability, biodegradability, and desirable mechanical properties. Ongoing research aims to optimize production methods, enhance compatibility with other polymers, and address challenges related to moisture sensitivity and water resistance. The development of cellulose-based packaging foams contributes to the pursuit of sustainable and environmentally friendly packaging solutions.

One type of cellulose-based foam is micro-fibrillated cellulose (MFC) foam. MFC is produced by mechanically separating cellulose fibers into smaller elementary constituents, resulting in nano-scale cellulose fiber material. These materials have high strength, stiffness, and biodegradability, making them promising candidates for bio-nanocomposite production and packaging applications. The surface modification of cellulose fibers has been investigated to enhance their compatibility with hydrophobic polymers, addressing a challenge in using nanocellulose in composites [10].

Nanocellulose, including nanocrystalline cellulose and bacterial nanocellulose, has also been studied for its potential in packaging foams. Nanocrystalline cellulose can be used as a reinforcing agent in nanocomposites, improving their mechanical, thermal, and biodegradation properties [11]. Bacterial nanocellulose, produced by bacteria such as *Gluconacetobacter*, offers unique features and has been evaluated as a biomaterial for medical implants [12].

The combination of cellulose with other biopolymers has been explored to enhance the properties of packaging foams. For example, cellulose-chitosan foams have been developed through a simple and scalable method. These biodegradable foams exhibit low apparent density, high porosity, and good mechanical performance, making them suitable for various applications, including thermal insulation and packaging materials [13].

Recent research has also focused on the development of cellulose-mineral foams. The coordination interaction between cellulose and bentonite minerals has been utilized to produce biodegradable and recyclable foams with high mechanical strength and thermal stability [14]. These foams show potential for sustainable packaging applications, offering environmental benefits compared to petrochemical-based plastic foams [14].

The preference for plastic materials in packaging for various consumer goods such as food, cosmetics, and pharmaceutical products is often driven by factors such as affordability, lightweight characteristics, and protective properties. It is important to note that materials like MFC (Micro-fibrillated Cellulose) and CNC (Cellulose Nanocrystals) are typically avoided in this context due to their costly production processes and the use of chemicals inherent in their manufacturing.

1.2.2 Pulp-based foams

As a more environmentally friendly alternative, some packaging solutions opt to rely solely on pulp-based materials. Pulp-based packaging has gained prominence in sustainable packaging practices, owing to its advantages. For instance, it offers biodegradability, composability, and a reduced environmental footprint. Notable examples of products adopting pulp-based packaging include egg cartons, molded paper trays for fresh produce, and paperboard containers for dry goods, all of which utilize pulp as their primary material to align with eco-friendly and costeffective packaging objectives [15].

1.3 Wet-foaming process

Recent research has directed attention towards the innovative production of foam directly from pulp through a wet foaming process, termed as pulp foam (PF) [5], [16]. In these studies, the wet foaming process was employed, which entails the formation and stabilization of foams utilizing a liquid that wets the solid particles or surfaces involved. Wet foams are characterized by a high degree of liquid retention within the foam structure, resulting in a stable foam volume and fine cell structure [9].

The process is straightforward and cost-effective, comprising several sequential steps. Initially, pulp is pulverized, breaking it down into finer particles. Subsequently, the pulverized pulp undergoes soaking in water, facilitating the preparation of a workable consistency. The next step involves dispersion in a surfactant solution under constant stirring, ensuring the effective integration of the pulp particles. Finally, the treated mixture is subjected to drying, either in an oven or through exposure to air, completing the process. This uncomplicated procedure holds promise for various applications, offering a pragmatic and economical approach to harnessing the potential of pulp for diverse purposes. However, the final pulp foam has limitations in terms of practical application such as; inflammability [5], [17] insufficient mechanical strength [17], and bacterial growth, which could readily cause PF materials to spoil, especially in a hot and humid environment [18].

The enhancement of foam properties and mitigation of limitations such as inadequate mechanical strength and water solubility can be achieved through the incorporation of additives such as sodium tetraborate, lignin, and chitosan. By introducing carefully selected additives, packaging materials

can be tailored to meet specific performance and protection requirements while still maintaining their eco-friendly attributes. The selected materials and additives have been briefly introduced in the following sub-sections.

1.3.1 Sodium tetraborate

Borax, also known as sodium tetraborate (Na₂B₄O₇.10H₂O), is an intriguing option for a chemical cross-linker because of its favorable qualities such as non-toxicity, affordability, and water solubility. This makes it a promising choice for various applications [32], [33]. Borax acts as a crosslinking agent, improving structural integrity and flame retardancy. Crosslinking agents play a crucial role in the development of biodegradable packaging foams. These agents are polyfunctional compounds that are responsible for interconnecting polymer chains during the process, resulting in the formation of a three-dimensional network structure.

The addition of a crosslinking agent to the polymer matrix enhances the mechanical properties and stability of the foam. It improves the foam's resistance to deformation, increases its strength, and reduces its susceptibility to breakage or collapse. The crosslinking agent acts as a bridge between polymer chains, creating a network that provides structural integrity to the foam.

The choice of crosslinking agent in plastic foam production depends on the specific foam material and the desired properties of the foam. Different crosslinking agents can be used to achieve different foam structures and enhance mechanical, thermal, and chemical properties. In aqueous solutions, borax can dissociate into trigonal boric acid ($B(OH)_3$) and tetrahydroxy borate ions ($B(OH)^{4-}$), which interact with polymer functional groups, leading to the formation of didiol cross-links through covalent or hydrogen bonding. The cross-linking process, illustrated in Figure 3 is influenced by the pH of the solutions. Higher pH values result in increased tetra

hydroborate ions, enhancing cross-linking reactions. Consequently, poly vinyl acetate films crosslinked at pH 11 exhibit superior mechanical properties compared to those cross-linked at pH 4, underscoring the importance of pH control in optimizing cross-linking processes and improving material mechanical characteristics [21], [22].



Figure 3. Cross-linking mechanisms between hydroxyl groups of polymers and borax as a crosslinker [21].

In one study, borax, cross-linking agent, was employed to produce a lightweight and highly porous pulp foam with low density (13.3-16.4 mg.cm⁻³), high porosity (> 98%), high compressional strength (up to 74.1 kPa), low thermal conductivity (about 0.045 W/(m·K)) and improved flame-retardant properties [23].

1.3.2 Lignin

Lignin, a complex group of organic polymers, plays a vital structural role in the supporting tissues of most plants, found prominently in vascular tissues specialized for liquid transport and mechanical strength. Its chemical and morphological composition varies across plant species, consisting of hydrocarbon polymers with aliphatic and aromatic components. Lignin primarily comprise C6C3 units, such as p-hydroxyphenyl, guaiacyl, and syringyl units, interconnected by carbon–oxygen and carbon-carbon linkages in diverse bonding patterns[24], [25].



Figure 4. Main bonding patterns evidenced in native lignin (R1 = R2 = H in p-hydroxyphenyl units; R1 = OMe, R2 = H in guaiacyl units, R1 = R2 = OMe in syringyl units) [24].

Due to the enduring environmental repercussions associated with traditional composites, researchers globally are actively engaged in the exploration of lignin-based polymer composites as sustainable alternatives to petroleum-based counterparts. The incorporation of lignin into commercial polymers not only augments product biodegradability but also yields green or eco-friendly composites. Notably, the inclusion of lignin in polypropylene-reinforced kenaf core hybrid contributes to the heightened thermal stability and fire-retardant attributes of the resulting bionanocomposite. This signifies a pivotal step towards more environmentally conscious and sustainable material options [26]. Due to its distinctive chemical structure, lignin proves versatile in composite materials as a filler, stabilizer, compatibilizer, and reinforcement. Its suitability extends across various polymeric matrices, enhancing their wettability, mechanical strength, and fire-retardant properties, owing to the presence of aromatic and cross-linked functional groups.

This underscores lignin's multifaceted role in optimizing the performance of composite materials across diverse applications [27].

1.3.3 Chitosan

Another additive which can improve the pulp-foam properties is chitosan. Chitosan is a polymer of β -(1,4)-linked 2-acetamido-2-deoxy-d-glucopyranose and 2-amino-2-deoxy-D-glucopyranose. This polycationic biopolymer is generally obtained by alkaline deacetylation of chitin, which is the main component of the exoskeleton of crustaceans. It is soluble in acidic solutions because of the protonation of its $-NH_2$ group at the C–2 position of the glucosamine unit. Owing to its biodegradability and unique physicochemical properties, it is widely used in the preparation of hydrogels, films, fibers, foams and biomedicine[28]. Chitosan improves mechanical strength and provides antimicrobial benefits.





This natural high molecular polymer with excellent biocompatibility and biodegradability can be completely degraded without causing harm to the environment [15].

To incorporate chitosan into pulp foam, several methods can be employed based on the desired application and properties of the foam. The following approaches have been demonstrated:

Coating Method: Lustriane et al. [28] and Lujan et al. [13] have shown that chitosan coatings can improve the water resistance and mechanical strength of various materials, including paper and foam. In this method, chitosan is dissolved in a suitable solvent and applied as a coating onto the surface of the pulp foam using techniques such as dip coating, spray coating, or brush coating. The chitosan coating forms a protective layer on the foam, enhancing its water resistance.

Incorporation during Foam Formation: Lujan et al. [13] prepared bio-based foams from cellulose pulp and chitosan through a simple method. In this approach, chitosan is mixed with cellulose pulp before foaming. The mixture is then processed using techniques such as freeze-drying or foaming agents to obtain the foam with chitosan uniformly distributed throughout the structure. This method allows for the direct integration of chitosan into the foam matrix, improving its water resistance and mechanical properties. In another report, cationic chitosan and/or polyvinylamine were added during the foam-forming process to give the foams water stability and antimicrobial properties [30].

Chemical Modification: Sawant et al. [31] investigated the use of modified bleached hardwood pulp-chitosan composite foam as a super absorbent material. In this method, chitosan is chemically bonded to the pulp fibers, enhancing their water resistance and absorption properties. The modified pulp fibers can then be used to produce foam with improved water resistance.

1.3.4 Surfactant

In the foam production, surfactants can be used to stabilize the air bubble by adsorbing at the gasliquid interface and control its structure. For example, in the study by Shen et. al., surfactants were added as foaming agent components in the production of polyurethane box foam. The surfactants help to reduce the surface tension of the liquid mixture, allowing for the formation of stable foam bubbles and uniform cell structures. In foaming process, surfactant is used to control cell size and to protect against collision and collapse [32].

When there is a water solution containing specialized foaming surfactants, air can be used as a blowing agent in foam production. When air is introduced into, it can generate many bubbles, leading to the formation of foam. The surfactants reduce the surface tension of the water solution, allowing for the stabilization and expansion of the foam [33].

Sodium dodecyl sulfate (SDS), an anionic surfactant widely employed in applications such as plastic foam production, stands out for its notable environmental characteristics. SDS is easily biodegradable, minimizing environmental impact, and does not accumulate in biological systems. Its high-water solubility prevents adsorption to soil or sediment, contributing to environmental safety. Ran et al. investigated the foam forming process and the impact of SDS on foam properties for cellulose-based materials derived from pulp. The researchers created ultra-lightweight cellulose foams by introducing SDS into an aqueous NaOH/urea solution through intensive mixing. This addition of SDS resulted in the formation of a foam structure containing micro and nanopores, with bubbles measuring approximately $20-100 \mu$ in the solutions [34].

Liao et al. combined refined pulp fibers, polyamide (PAE), and sodium dodecyl sulfate to synthesize foam with good mechanical strength; this foam formed a porous structure through internal hydrogen and chemical bonding between cellulose fibers [35].

1.3.5 Drying methods

The drying step in the wet foam process to produce pulp foam is an important stage in achieving the desired properties of the foam material, maintaining the structural integrity and pore structure of the foam. The drying process plays a role in preventing crack formation in the foam material. Additionally, the properties of the foam material, such as cell structure, mechanical properties, and liquid absorption capacity, can be characterized to assess the quality of the foam.

Cervin et al. [36] highlighted the use of surface-modified cellulose nanofibrils (CNFs) for producing stable wet foams, emphasizing the preservation of a homogeneous pore structure during drying. The drying process involves an oven and a porous ceramic frit to maintain the cellular structure. Optimal drying temperature and time are essential parameters for achieving desired foam properties. The research underscores the significance of controlled drying conditions in obtaining consistent and desirable foam characteristics.

Gonzenbach et al. [37] stated that the low strength of wet foams and the high stresses during water evaporation make the drying step challenging. Therefore, careful control of the drying conditions is necessary to avoid cracks in the foam material.

1.4 Food packaging

Promoting the utilization of bio-based materials in food packaging is a strategic initiative aimed at enhancing the adoption of sustainable resources and mitigating environmental pollution [5]. The global demand for food packaging is driven by the increasing urbanization and changes in foodconsumption patterns [9]. With the world's population expected to reach 9.7 billion by 2050, and two-thirds of it residing in urban areas, there is a growing need for efficient food packaging solutions to address the challenges of transport, storage, and consumption. Urban dwellers, often leading hectic lifestyles, show a preference for processed foods over fresh ones, leading to a reliance on supermarkets and convenience stores. This shift has resulted in larger supply chains heavily dependent on packaged food [38].

The food packaging industry is now exploring more sustainable alternatives, with a focus on biobased and biodegradable materials, including bioplastics, paper, and cardboard. The goal is to minimize environmental impact and reduce dependence on fossil-based plastics. Despite these advancements, the complexity of the food packaging system requires consideration of various factors such as product type, water resistance, biodegradability, and rigidity [39].

1.5 Biodegradability

The term "biodegradability" is not well defined in the literature [40]. There is no agreed-upon standard for biodegradability, and many plastics that are deemed biodegradable take years to break down completely or even turn into microplastic pollution. Biodegradability describes a procedure rather than a set of circumstances or a time limit [35]. There have been standards for biodegradation tests, however they are somewhat broad and include things like minimum and maximum incubation times. If a chemical breaks down by at least 70% in 14 days, it might be referred to as "inherently degradable." If a bioplastic breaks down by at least 90% in 6 months in aquatic conditions or 24 months in soil, it can be referred to as "ultimately degradable" [36]. The biodegradability of polymers depends on; (a) the chain length or molecular weight of the polymer, (b) the complexity of the chemical formula and (c) the crystallinity of the polymer. The

highest degradation rate generally occurs for low molecular weight amorphous polymers with low levels of complexity [42].

Harrison et al. critically evaluated the biodegradability requirements for plastic bags in aquatic habitats, emphasizing the need for new regulations to address toxicity and microplastic development [43].

1.6 Prior research

The pursuit of innovative technologies and technical solutions for the development of bio-based and sustainable packaging is a pressing and continual endeavor. This urgency stems from the need to reduce reliance on petroleum-based foams and address specific packaging requirements, making it a high-interest area for researchers and producers alike. In Table 1, an overview of various reviewed sources provides insights into the materials, densities, and compressive strengths associated with different formulations. Lujan et al. explored the use of cellulose and chitosan, showcasing a density range of 0.060-0.123 g/cm³ and compressive strengths between 0.017-0.111 MPa at 10% strain. Other studies, such as those by Liao et al., Wu et al., He et al., Zheng et al., and Liu et al., investigated diverse combinations involving pulp, surfactants, fire retardants, and more, each presenting unique density and compressive strength characteristics tailored to specific applications and performance criteria. These findings underscore the multifaceted nature of biobased packaging research and its potential to offer tailored solutions for sustainable and effective alternatives to conventional foams.

T-LL 1	<u> </u>	- f 11		
I able 1.	Overview	of the	reviewed	sources.

Material	Density (g/cm ³)	Compressive strength (MPa)	Ref.
Cellulose, Chitosan	0.060-0.123	0.017-0.111 (@10% strain)	[13]

Pulp, PAE, and SDS	0.126-0.168	0.0139-0.221 (@80% strain)	[35]
Pulp, CPAM, chitosan, SDS	0.3965-0.7628	0.4839-0.433 (@50% strain)	[18]
Pulp, SDS, borate	0.133-0.166	0.0026-0.071 (@50% strain)	[23]
Pulp, SDS, fire retardant	0.047-0.06	NA	[44]
Wood fiber, surfactant, CPAM	0.01-0.44	NA	[45]

As part of our current studies in order to introduce bio-based materials [46], in the present study, we have adopted a straightforward methodology to synthesize bio-based foams utilizing cellulose pulp, sodium dodecyl sulfate (SDS), and lignin. The primary objective is to develop lightweight, water-resistant, and biodegradable porous materials specifically tailored for food packaging applications. Employing a Box-Behnken design, we systematically examined the influence of three critical factors lignin content, SDS concentration, and foaming time on both the apparent density and mechanical properties of the resulting foams. The Box-Behnken design is favored over other fractional factorial designs due to its efficiency in estimating main effects and interactions with fewer experimental runs, ensuring a balanced and rotatable design. Its flexibility and ability to accommodate factors with different levels make it suitable for a wide range of experimental settings, making it a popular choice in various fields of research and industrial applications. Notably, our research represents a pioneering effort in the field, as there is a noticeable gap in the existing literature regarding the investigation of experimental conditions and their impact on the mechanical properties of pulp-lignin foams produced through the foam-forming method. Furthermore, we conducted a comprehensive evaluation of other essential properties, including foam morphology, water sensitivity, and soil biodegradability, providing a holistic understanding of the material's performance characteristics. Through this study, we aim to contribute valuable insights and advancements to the realm of sustainable packaging materials.

2 Materials and methods

2.1 Materials

A commercial bleached wood pulp and lignin powder (AmallinTM LPH with molecular weight 5,000-8,000 Da¹) were supplied by Canfor pulp mill located in Prince George, and West Fraser mill in Quesnel, British Columbia, Canada, respectively. Sodium dodecyl sulfate (SDS, \geq 98.0%), sodium tetraborate decahydrate (Na₂B₄O₇·10H₂O, \geq 99%, analytical grade), sodium hydroxide, acetone, and acetic acid were purchased from Sigma-Aldrich Co. Ltd. Chitosan powder (85%, deacetylated) was obtained from Thermo Scientific Chemicals (China). All chemicals were used directly without any purification.

2.2 Preparation of colloidal lignin particle dispersions

The formation of colloidal lignin particles followed the previous research with minor adjustments [47]. Briefly, the process was started with the dissolution of 10.00 g of lignin (dry basis) in 500 mL of acetone/water (3:1, v/v). The resulting solution was stirred for 3 hours at room temperature, followed by filtration using a glass microfiber filter (Whatman GF/F, pore size 0.8μ m) to eliminate undissolved solids. The resulting solution was promptly poured into 1000 g of vigorously stirred deionized water. Subsequently, acetone was eliminated through evaporation under reduced pressure at 40 °C and the colloidal lignin particle dispersions was obtained with a mass yield of 80% wt.

¹ 1 Dalton (Da) = 1 g/mol



Figure 6. Colloidal lignin particle dispersion

2.3 Pulp foam preparation

The pulp foams were synthesized following the procedure reported in S. He *et al* [23] with some modifications. 10 grams of wood pulps were initially pulverized and subsequently immersed in distilled water. 8 wt.% of borate was introduced into the pulp suspension, and the pH of the suspension was adjusted to 10 using NaOH (0.25 M). This suspension was then placed in an 80 °C oven for one hour to complete the cross-linking reaction Followed by cooling down the suspension. The chosen ranges for the factors in the study, including SDS concentration (2-6% wt.), lignin concentration (0-30% wt.), and mixing time (10-40 min.), were selected to comprehensively explore their effects on the properties of wood pulp-based packaging foam. This range was determined based on prior literature, preliminary experiments, and practical considerations to encompass a broad spectrum of conditions relevant to the manufacturing process. Then, varying amounts of surfactant (SDS) in the range of 2-6 wt.% based on oven-dried pulp, were added into the solution under mechanical stirring condition at 2300 rpm. Additionally, a determined quantity of lignin suspension, ranging from 0-30 wt.% based on oven-dried pulp, was

added to the pulp suspension. The resulting mixture underwent vigorous mechanical stirring for different durations, varying between 10-40 minutes. Subsequently, the mixture was filtered through a sieve with 50 mesh size (6 inches diameter) to eliminate excess water, and the foams obtained were transferred to an oven set at 60 °C for 18 hours.

2.4 Preparation of water-resistant foam

10 grams of pulverized wood pulps were immersed in 700 ml distilled water. Then 0.8 g of borate was subsequently added into the pulp suspension and the pH of the suspension was adjusted to 10 by using NaOH and then the suspension was heated to 80°C for 1 hour (called suspension A). 2 g of chitosan powder was dissolved in 200 ml of 2 wt.% acetic acid solution and stirred for 24 h. The pH of chitosan solution (5.5) was controlled by NaOH (called suspension B) [18]. Once the suspension A cooled down to room temperature, 0.47 g SDS was added into suspension with mechanical stirring. After 5 minutes, suspension B was poured to the previous suspension. Furthermore, a determined volume of a lignin suspension (containing 3 g lignin 30 wt.%) was introduced into the pulp suspension. The resulting mixture underwent vigorous mechanical stirring for 40 minutes. Following this, the mixture was subjected to filtration through a sieve to eliminate excess water, then the filtrate was heated at 60 °C for 18 hours. This sample was named OF2.

2.5 Apparent density and porosity

The apparent volumetric mass density (ρ_{app}) of pulp foams was calculated using the provided equation (Eq. 1) [48]:

 $\rho_{app} = m/V_{dried} Eq. (1)$

In this equation:

 ρ_{app} represents the apparent volumetric mass density of the pulp foam. "m" denotes the mass of the dried pulp foam in grams (g). "V_{dried}" signifies the volume of the dried pulp foam in cubic centimeters (cm³).



Figure 7. Measuring Dimensions of Foams with Digital Caliper.

To determine the porosity (P) of pulp foams Eq. (2) was used [48],

 $P = (1 - \rho/\rho_0) * 100\%$. Eq. (2)

where ρ represents the density of the pulp foams, and ρ_0 is the density of wood pulps, set at $\rho_0 = 1.6 \text{ g/cm}^3$.

2.6 Mechanical test

Uniaxial compression tests were performed according to ASTM D1641 using an INSTRON 5565 Universal Testing Instrument from INSTRON Co., Ltd, USA. This instrument was equipped with two compression plates and a 250 N load cell. The tests were performed at a controlled temperature of 23°C and a relative humidity of 50%.

To prepare the foam samples for testing, they were cut into smaller dimensions with a height of 30 mm. These prepared samples were then subjected to compression between two plates at a controlled loading rate of 10 mm/min. The final strain was set to reach 75% of the original sample height. Throughout this process, the stress-strain curve of the samples was generated. The data was recorded and averaged from 3 measurements.

To accurately measure the mechanical strength, it was essential to determine the surface area of the foam samples. This was achieved by cutting each sample into small square pieces with dimensions of 2 cm x 2 cm, resulting in a surface area of 4 cm² (0.0004 m^2), as calculated using the formula:

Surface area (A) = $d^2 = 4 \text{ cm}^2 = 0.0004 \text{ m}^2$.

2.7 Water resistance and water absorption test

The water resistance of the foams was assessed using a methodology described by Zheng et. al. [16]. Foam samples with dimensions of $25 \times 25 \times 30 \text{ mm}^3$, were subjected to prolonged immersion in distilled water over 24 hours and extending to 14 consecutive days. Further images were captured and compared.

To evaluate the water absorption capacity of the foams, cubic samples were immersed in 200 mL of distilled water at room temperature for 40 min. The wet foams were removed from the water, gently dried with a tissue paper, and immediately weighed at different intervals, and water absorption was calculated using equation 3:

water absorption =
$$(m_w - m_d)/m_d$$
 Eq. (3)

where m_d is the mass of the dry foam and m_w is the mass of the wet foam at a certain time. The tests were performed in triplicate and the average reading is reported.

2.8 Biodegradability test of the pulp foam

The biodegradability of the pulp foams was assessed through a soil landfill experiment (Figure 8) following the previous literature [35]. A dried sample measuring $2 \times 2 \times 3 \text{ cm}^3$ was placed in the soil, and its morphology was examined at intervals of 7 days over a 90-day period. Concurrently, the quality of the samples was documented both before and after burial.



Figure 8. The photo of landfill area prepared for biodegradation test.

2.9 Experimental design

Box-behnken design is a type of response surface design used in experimental design and optimization. Box-behnken design was performed using Minitab® Release 20 to evaluate the effects of the experimental factors including concentration of lignin, concentration of SDS, mixing (foaming) time and their interactions on the response variables. For this purpose, a total of fifteen experimental runs were selected for the foam production process (Table 2).

Table 2. Box-behnken design of experiments for 15 trial runs including three variables.

Sample	SDS (%)	Lignin (%)	Time (min)
PF1	2	0	25
PF2	4	15	25
PF3	2	15	10
PF4	2	15	40
PF5	4	15	25
PF6	6	15	40
PF7	6	15	10
PF8	4	0	10
PF9	2	30	25
PF10	4	15	25
PF11	6	0	25
PF12	6	30	25
PF13	4	0	40
PF14	4	30	40
PF15	4	30	10

This design was used to find the optimal conditions of multiple independent variables that influence the performance of a system. The aim is to determine the ideal combination of these factors that leads to the desired outcome, maximizing porosity and strength. Based on the established optimal conditions of SDS concentration (4.7 wt.%), lignin concentration (30 wt.%), and mixing time (40 minutes) OF1 was synthesized. In this study, each sample was synthesized three times independently to ensure the reliability and reproducibility of the results. The average value from these replicates is reported to account for any variations and to provide a more accurate representation of the data.

2.10 Characterization

ATR-FTIR spectrum was measured on an FTIR spectrometer (VERTEX 70, Bruker, Germany) with wavenumber ranging from 4000 cm⁻¹ to 400 cm⁻¹ by cutting dry foams with a sharp scalpel into slices. Thermogravimetric analysis (TGA) was performed using a Discovery TGA (TA Instruments) under a nitrogen flow of 25 mL/min. The samples were placed in platinum pans and heated at 10 °C/min from 30 to 800 °C. High-resolution scanning electron microscopy (FE-SEM) images were acquired utilizing an FEI Helios Nanolab 650. The samples were cut into small fragments using a sharp scalpel and sputtered with gold/palladium to study their morphology.

3 Results and discussion

3.1 Apparent density and porosity

The density and the porosity of synthesized pulp foams are presented in Table 3 as the two comparable responses from the experimental design. The lowest density and the highest porosity are one of the two main factors that will contribute to identifying the optimum foam products properties. These findings suggest that the composition and preparation parameters significantly influence the apparent densities and porosities of the pulp foams, which have implications for their applications in various industries. The apparent density of the pulp foams varies, with values ranging from 0.013 g/cm³ to 0.077 g/cm³. These values are comparable to those reported for

cellulose-based foams and aerogels $(0.001-0.2 \text{ g/cm}^3)$ [46]. The obtained results, however, are slightly higher than the typical densities of commercial foams, such as polyurethane foams $(0.035-0.040 \text{ g/cm}^3)$ [49] or expanded polystyrene $(0.015-0.075 \text{ g/cm}^3)$ [50]. The highest density (0.077 g/cm^3) corresponds to the conditions of 2% SDS, 30% lignin, and the mixing time of 25 minutes. This suggests a more compact and heavier foam under these specific circumstances. The lowest density (0.013 g/cm^3) was obtained with 6% SDS, 0% lignin, and at 25 minutes.

Sample	Porosity (%)	Density $(g/cm^3 \pm 0.01)$
PF1	98.8	0.020
PF2	98.5	0.024
PF3	98.0	0.032
PF4	98.1	0.030
PF5	98.4	0.026
PF6	98.6	0.023
PF7	98.6	0.023
PF8	99.0	0.016
PF9	95.2	0.077
PF10	98.3	0.028
PF11	99.2	0.013
PF12	97.0	0.048
PF13	99.1	0.015
PF14	96.9	0.049

Table 3. The density and porosity of pulp foam samples at different concentrations of SDS, lignin, and mixing time.

Sample	Porosity (%)	Density $(g/cm^3 \pm 0.01)$
PF15	96.9	0.050

The results suggest a correlation between the rise in lignin content and the reduction in SDS concentration, leading to a simultaneous increase in foam density.



Figure 9.Effect of SDS concentration on foam density.



Figure 10.Effect of lignin concentration on foam density.

This may be attributed to an augmentation in hydrogen interactions between pulp and lignin in the absence of a surfactant. Moreover, it can be asserted that lignin particles permeate the voids in the pulp fiber's structure, thereby decreasing the porosity of the structure as more lignin is introduced to the foam suspension. The time did not seem to have a meaningful effect on the density and porosity of the samples.

Table 4. Comparison of density of pulp foam samples with commercial samples.

Samples	Density Range (g/cm ³)		
EPS Foams [2]	0.015-0.075		
Polyurethane Foams [3]	0.035-0.040		
Synthesized Samples	0.013-0.077		

3.2 Mechanical strength

The mechanical strength of pulp foams was a critical parameter in finding the optimum foam product with a strong reliance with the addition of lignin. The compression curves are shown in Figure 11. The primary objective of conducting compressive stress measurements was to determine the load required to compress the foam samples to 75% of their initial heights as the results are summarized in Table 5. As can be seen, the compressive stress of pulp foams significantly increased with the increasing of lignin from 0 to 30% and decreasing SDS from 6 to 2%. This result indicated the stronger electrostatic interaction or hydrogen bonds between pulp and lignin functional groups with elevated lignin content. Furthermore, the compressive stress of pulp foam samples exhibited the same trends with the density [51].

The stress values range from 37.5 kPa -379 kPa. The highest compressive stress corresponds to 4% SDS, 30% lignin, and 40 minutes mixing time (PF14). The stress of PF14 at a strain of 75% was 379 kPa, and that was over 10 times higher than PF-11 (with 6% SDS but without lignin). SDS concentration had a negative effect on mechanical properties due to the mechanical properties with density dependency. Lower concentrations of SDS lead to denser structures, which is correlated to higher mechanical properties [52].

Liao et al. [35] obtained stress values for 80% strain of pulp foams (13.9-221 kPa) for cellulose pulp foams that were comparable to those obtained in the present work. Compressive strength values were comparable to those reported for commercial foams such as expanded polystyrene (EPS) (53–138 kPa) [50] or polyurethane foams (164–174 kPa).



Figure 11. Stress-strain curve of pulp foam with different SDS and lignin concentration.

Table 5.	The load	l and	stress need	ed to	compress	sample	foams to	75%	o of	their	initial	heigh	ıt
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Sample	Load (kN) @ 75%	Stress (kPa) @ 75%
PF1	0.0199	49.8
PF2	0.0748	187.0
PF3	0.0929	232.3
PF4	0.0826	206.5
PF5	0.0792	198.0
PF6	0.058	145.0
PF7	0.0464	116.0
PF8	0.0248	62.0

Sample	Load (kN) @ 75%	Stress (kPa) @ 75%
PF9	0.1159	289.8
PF10	0.0751	187.8
PF11	0.015	37.5
PF12	0.1048	262.0
PF13	0.0219	54.8
PF14	0.1516	379.0
PF15	0.1334	333.5

3.3 FTIR analysis of PF13 and OF1

To identify the functional groups, the FTIR-ATR spectrum was studied. Sample PF13 and optimized sample (OF1) were selected for further characterization to investigate the lignin integration and the results are depicted in Figure 12. A wide peak with the maximum at 3285 cm⁻¹ was assigned to the stretching vibrations of O–H bonds present in the PF13, OF1 and lignin. In turn, two bands with the maximum at 2881 cm⁻¹ can be related to the stretching vibrations of C–H present in the pulp and lignin structures [53].

An absorption band within the wavenumber range of 1590–1509 cm⁻¹ can be attributed to the vibrations of aromatic rings present in the lignin structure. This band exhibits a strong bond in pristine lignin, is somewhat visible in OF1, and is absent in PF13, which lacks lignin. The signals corresponding to the deformation vibrations of the C–H bonds in the lignin structure were observed at 1465–1455 cm⁻¹ [54]. The high-intensity band at 1027 cm⁻¹ is related to the characteristic C–O bonds vibrations of secondary alcohols and ethers present in the main chain of the cellulose macromolecules [55].



Figure 12. The FTIR spectra of PF13 (4 wt.% SDS without lignin), OF1 (optimized pulp foam containing 4.7 wt.% SDS and 30 wt.% lignin), and pristine lignin.

3.4 Chitosan integration

Incorporating chitosan into the pulp foam enhanced its water resistance, a crucial attribute for packaging purposes [56]. To assess this improvement, we generated a sample designated as OF2 and conducted a comprehensive analysis of its performance. The density and porosity of optimum sample (OF1) and water-resistant optimum foam (OF2) were also measured (Table 6). Moreover, the load and stress of optimum sample (OF1) and water-resistant optimum foam (OF2) were also measured (Table 6).

Table 6. The density, porosity, load, and stress of samples (OF1) and (OF2).

Sample	Porosity (%)	Density (g/cm ³)	Load (kN) @ 75%	Stress (kPa) @75%
OF1	96.9	0.049	0.149	372.5

Sample	Porosity (%)	Density (g/cm ³)	Load (kN) @ 75%	Stress (kPa) @75%
OF2	95.12	0.078	0.155	387.5

As the results shown, addition of chitosan increased the density and decreased the porosity of foam [57]. This finding is in good agreement with SEM images (





Figure 15-c) that show less porous structure for OF2. The compressive strength of OF2 increased with the addition of chitosan [18]. Chitosan with the increase of molecular weight can improve the tensile strength of OF2 compared to OF1 [58].

Figure 13 presented the FTIR-ATR spectra of OF1, OF2, and pure chitosan. The pattern of peaks is similar to those reported in the literature. A strong band in the region 3332–3270 cm⁻¹ for chitosan and OF2 corresponds to N-H and O-H stretching, as well as the intramolecular hydrogen bonds in chitosan structure. The absorption bands at around 2970 and 2823 cm⁻¹ can be attributed to C-H symmetric and asymmetric stretching, respectively. These bands are characteristics typical of polysaccharide and are found in other polysaccharide spectra, such as xylem [22], glucans [23]

and carrageenans [24]. The presence of residual N-acetyl groups was confirmed by the bands at around 1662 cm⁻¹ (C=O stretching of amide I) and 1313 cm⁻¹ (C-N stretching of amide III), respectively that appears in chitosan and OF2 spectrums. We did not find the small band at 1575 cm⁻¹ that corresponds to N-H bending of amide II. This is the third band characteristic of typical N-acetyl groups, and it was probably overlapped by other bands. A band at 1588 cm⁻¹ corresponds to the N-H bending of the primary amine [25]. The CH₂ bending and CH₃ symmetrical deformations were confirmed by the presence of bands at around 1424 and 1375 cm⁻¹, respectively. The absorption band at 1153 cm⁻¹ can be attributed to asymmetric stretching of the C-O-C bridge that is visible in all three samples. The bands at 1066 and 1026 cm⁻¹ correspond to C-O stretching of ether bonds that are presented in the OF1 and OF2 samples suggesting the intermolecular bonding among the samples. All bands are found in the spectra of samples of chitosan reported in the literatures and confirmed the integration of chitosan in OF2 structure [59].



Figure 13. The FT-IR spectra of OF1 (optimized pulp foam containing 4.7 wt.% SDS and 30 wt.% lignin), OF2 (optimized pulp foam containing 4.7 wt.% SDS, 30 wt.% lignin, and 20 wt.% chitosan), and pure chitosan.

3.5 Thermal stability

To investigate the thermal stability behavior of the three chosen foams (OF1, OF2, and PF13),

thermogravimetric analysis (TGA) was conducted.



Figure 14. TG curves of the studied foams (OF1, OF2, and PF13).

Figure 14 displays the TG curves for the synthesized foams (OF1 and OF2 and the pure sample (PF13) to observe the effect of chitosan and lignin incorporation, respectively. A slight initial weight loss, occurring in the 25–125 °C range, is attributed to the evaporation of both physically absorbed and hydrogen-bonded water [60]. The main decomposition step for the studied foams took place in the 235–370 °C interval, in which weight loss is caused by two phenomena: (I) cellulose degradation by rupture of glycosidic bonds in the cellulose foam (PF13 and OF1) [52] and (II) chitosan degradation (OF2) through deacetylation and breaking of glycosidic bonds occurs. Weight loss above 370 °C is thought to be caused by the production of volatile low-molecular-weight compounds [60]. Compared to PF13, OF1 had a slightly higher initial decomposition rate, indicating that the lignin's presence had lowered the initial decomposition temperature.

It was found that the chitosan-containing foam (OF2) had reduced T_{onset} and T_{max} , suggesting that the chitosan addition promoted the early start of decomposition. This is related to the fact that chitosan decomposes at a lower temperature than pure cellulose [60]. Compared to pure pulp foam (PF13), OF2 displayed a larger residual weight due to its chitosan content. This residual weight refers to the amount of material that remains after the decomposition process. The increase in residual weight in OF2 suggests that the chitosan component contributes to the formation of charred residue during decomposition. This charred residue has a protective effect, reducing the extent of material decomposition [52]. [61]. As a result, the analyzed foams degrade at high temperatures and the presence of chitosan slowed down the rate of decomposition.

3.6 Morphology analysis

The morphology of pure pulp and three selected foams (PF13, OF1, and OF2) were examined.





Figure 15. Macrostructure and SEM micrographs of the studied foams. General overviews at 100× magnification of (A) pulp, (B) PF13, (C) OF1 and (D) OF2 and morphology of the fibers at 3000× from (a) pulp, (b) PF13, (c) OF1, and (d) OF2.

3.7 Water resistant and water absorption evaluation

One challenge with cellulose-based biomaterials is that they really like water because they have a lot of hydroxyl groups. This makes them easily damaged by water and allows germs to grow on them [62].

To assess the water sensitivity of synthesized foam, two optimized samples, OF1 and OF2 after chitosan integration were tested. Visual immersion in water was observed following immediate immersion, after 5 days and after 14 days in distillated water as presented in Figure 14-a-c, respectively. Upon immediate immersion of the samples (Figure 14-a), OF1 was completely submerged, whereas OF2 exhibited a distinctive behavior [9] remaining afloat with approximately 50% of its height above the waterline.

Subsequent observations after 5 days revealed a consistent trend. OF2 maintained impressive water repellent, with about 5% of its height above the water surface, and the foam's integrity remained intact (Figure 14-b). In contrast, OF1 remained submerged, exhibiting higher swelling, while cellulose fiber accumulated at the bottom of the beaker, with a slight distortion of its cubic form (Figure 16-b). Remarkably, over a 14-day period, OF2 continued to resist submersion, with still 3% of its height above the water surface, while OF1 gradually misstructured in the water (see Figure 16-c).

These findings underscore the pivotal role of chitosan in enhancing the water-resistant of the foam samples and hold substantial implications for potential applications in water-sensitive environments [15].

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Figure 16. Final position of the OF2 and OF1 foams in the water-resistance test upon a) immediate immersion, b) after 5 days in water, and c) after14 days in distillated water.
To ascertain water absorption, the foam samples (OF1 and OF2) were immersed in distilled water for a duration of 40 minutes, with periodic weighing intervals. It was observed that the OF1 and OF2 absorbed water approximately 4 to 9 times their original weight, respectively.



Figure 17. Water absorption capacity of the OF1 and OF2 foams.

OF1 immediately reached its maximum water absorption capacity (10 g of water/ weight of dry foam), while OF2 exhibited a more gradual absorption trend. Significantly, OF2 demonstrated lower water absorption capacities compared to OF1, a result attributed to the enhanced water-resistant and rigid properties imparted by chitosan in the foam. This rigidity mitigates fiber

swelling and disentanglement upon water exposure. As showed in Figure 17, the cellulose fiber separation and swelling were notably higher than those observed in OF2, leading to the loss of cubic shape and an increased water uptake. This highlights the superior performance of OF2 in water-resistance testing, as this property is inherently tied to water absorption in cellulose-based materials.

These findings emphasize a substantial reduction in water absorption achieved by incorporating chitosan into the foams. This reduction is crucial for mitigating the risk of structural compromise due to swelling and serves as a preventive measure against microbial proliferation. OF2 emerges as a promising candidate for applications where water stability is paramount, such as water-oil separation, water filtration systems, and packaging designed for contact with moisture-laden products [15].

3.8 Biodegradation test

To investigate the biodegradability of the foam samples, a series of experiments were conducted. The foam samples were cut to uniform sizes and buried underground, and photographs were taken at various time intervals, specifically at 20 days, 40 days, and after 90 days of burial, to assess their degradation progress as depicted in Figure 16-b,c, and d, respectively [35]. The experiment commenced on the 20th of July 2023. The average temperature, average pH, and humidity in the burial area, during the investigation, were recorded at 14.5 °C, 7, and 61%, respectively. After 20-day, the initial photographs revealed an approximately 20% reduction in the height of the foam samples (Figure 18-b). After 40 days, significant changes were observed, with a notable 28% reduction in the sample height (Figure 18-c). The photos taken after three months of burial showed that the foam samples had undergone substantial biodegradation to the extent that they were

challenging to recover from the soil due to adhesion of dirt particles (Figure 18-d) and made it difficult to obtain accurate measurements [51].

For further investigation, FTIR-ATR analysis was conducted on the pulp foam (PF13) (Figure 18) shows FTIR spectra of the different foams before and after 90 days of burial tests. This technique allows to follow the evolution of the functional groups involved in the process by variations of the corresponding absorptions. The spectrum corresponding to PF13 after 90 days of biodegradation presented a noticeable increase in the absorbance intensity at 1624 cm⁻¹ and range 2920-2840 cm⁻¹. These changes suggest increase in the carboxyl groups content and aliphatic components of the residua samples from cellulose structure [63]. However, for the other functional groups noticeable changes were not observed. Additional analysis, especially under conditions such as acidic or alkaline media in a longer period, is recommended to clarify the specific molecular transformations and degradation mechanisms taking place in pulp foam.



Figure 18. To the right: the FTIR spectra of PF13 before and after 90 days of burial test, and to the left: images of the samples after a) day 0, b) 20 days, c) 40 days, and d) 90 days of the burial.

4 Conclusion

This thesis has investigated the synthesis of lightweight, water-resistant, and biodegradable pulp foams using cellulose pulp. Utilizing a box-behnken experimental design, we methodically explored the influence of three primary factors including, lignin content, SDS concentration, and foaming time on both the apparent density and mechanical characteristics of the foams. The measured apparent densities and porosities of synthesized pulp foams exhibit diverse characteristics with densities ranging from 0.013 g/cm³ to 0.077 g/cm³ and porosities from 95.2% to 99.22%. The obtained results are comparable to the typical densities of commercial foams, such as polyurethane foams (0.035–0.040 g/cm³) [49] or expanded polystyrene (0.015–0.075 g/cm³) [50]. Compressive stress measurements reveal varying compression loads among samples, ranging from 0.0150 kN to 0.1516 kN. By employing statistical model, optimal parameters including surfactant (SDS) concentration, lignin content, and foaming time (4.7 wt.%, 30 wt.%, and 40 minutes, respectively) were determined (OF1). Result showed that lignin addition led to low porosity and high strength foam. To enhance water resistance, chitosan was incorporated into the optimal foam (OF2), and FTIR spectroscopy and SEM confirmed the chemical composition of chitosan in the modified foam sample. Water resistance tests demonstrated exceptional floatability and stability with chitosan addition, suggesting potential applications in water-sensitive environments. Furthermore, the burial tests revealed that foams started breaking down over a period of three months. This comprehensive investigation provides a systematic understanding of factors influencing pulp foam properties, paving the way for tailored applications in packaging. The results contribute to the development of sustainable and versatile materials with improved mechanical performance and water resistance. The simplicity and cost-effectiveness of the proposed synthesis process distinguish these foams from commercial alternatives, although it still needs further market and feasibility assessment. For our upcoming plans, we aim to apply various concentrations of chitosan to systematically investigate its impact on porosity and density. Additionally, we seek to explore novel applications, such as building insulation materials, broadening the scope of our research and potential contributions to innovative solutions.

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