

Original Research

Development and characterization of an affordable water-dispersible cellulose-based paper

Bruno Luís Ferreira^{1*} 

Gabriel Barros Baptistella¹ 

Natalia Cristina Silva¹ 

Maurício de Matos¹ 

Francielle Calegari¹ 

Daniel Gomes Constantino²

¹ SENAI Institute of Innovation in Electrochemistry, 80215-090, Curitiba-PR, Brazil.

² Recom - Labels and Packaging, 12944-110, Atibaia-SP, Brazil.

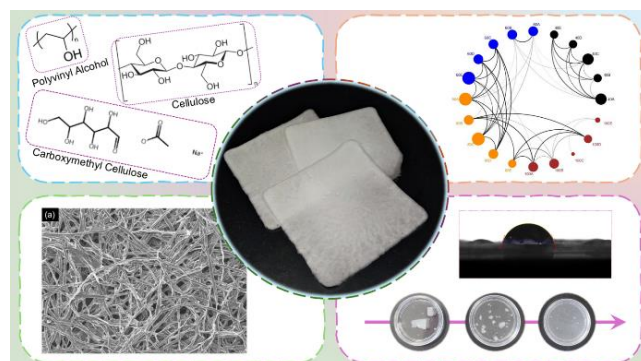
* Corresponding author: f.bruno@outlook.com

Received: May 1, 2026

Revised: October 6, 2026

Accepted: October 21, 2026

Published: October 28, 2026



Abstract: This study reports the development of a affordable, cellulose-based water-dispersible paper designed for sustainable material applications. By incorporating carboxymethyl cellulose (CMC), polyvinyl alcohol (PVA), and glycerol into a cellulose matrix, a balance of mechanical properties, thermal stability, and water dispersibility was achieved. The films were characterized by color measurements, tensile tests, scanning electron microscopy, thermogravimetric analysis, Fourier-transform infrared spectroscopy, contact angle, and disintegration measurements. The results demonstrated that increasing grammage (40 to 100 g/m²) improved breaking factor (551 to 1270 N/m) and elongation (9.0 to 14 %) while maintaining stable tensile strength (mean of 4.59 MPa), highlighting the role of structural organization. The developed paper exhibited excellent water dispersibility, with SEM and FTIR analyses confirming the uniform integration of additives within the cellulose matrix. These results demonstrate the potential of additive-modified cellulose straightforward systems to produce water-dispersible paper with tunable structural and functional properties, relevant for environmentally friendly material applications.

Keywords: Water-dispersible paper, cellulose-based materials, biodegradable materials, carboxymethyl cellulose, structure–property relationships.

Introduction

Since the 1950s, plastic production has surged, reaching over 330 million tons and potentially doubling in 20 years. Due to its long decomposition time, this non-biodegradable material poses risks to human health, wildlife, and ecosystems [1, 2].

Therefore, the production of films based on natural and/or biodegradable products is an alternative to reduce environmental pollution and damage to human health [1, 2].

The production of biopolymers has increased from 300,000 tons in 2009 to 2.11 million tons in 2019, with biodegradable plastics increasing from 36% in 2015 to 56% in 2019 [3]. Thus, several compounds from biodegradable sources have been investigated, as well as natural polymers such as proteins, polysaccharides, and lipids [2], or synthetic polymers such as polyvinyl alcohol and polyvinylpyrrolidone [4].

In recent decades, the production of films using natural polymers, such as cellulose and starch derivatives, has become

an emerging technology, particularly regarding biodegradability and non-toxicity [5, 6].

Cellulose (C₆H₁₀O₅)_n is a common natural polymer of glucose molecules linked by β-1-4-glycosidic bonds. It is the main structural component of plants and serves as a renewable and biodegradable resource, offering significant advantages in terms of sustainability [7, 8]. Due to its structural characteristics, cellulose has strong hydrogen bonds that are difficult to dissolve, making it naturally insoluble in water [7, 8].

Modifications to the structure can improve solubility and applications. Etherification transforms the hydroxy group (–OH) of cellulose into an ether (R–O–R), creating carboxymethyl cellulose (CMC). CMC is a natural anionic polysaccharide that is nontoxic and biodegradable. Its hydroxyl and carboxylic groups increase hydrophilicity, promoting water solubility [9]. CMC is a versatile compound used in various industries, including pharmaceuticals, cosmetics, and food [10].

Moreover, polyvinyl alcohol (PVA) is an important synthetic polymer used in biodegradable film production. It is nontoxic, cost-effective, flexible, thermostable, and soluble in water [11, 12]. PVA can create crosslinks, eliminating the need for crosslinking agents in the formulation [13].

© The author(s) 2026. This is an open access article published under the terms and conditions of the [Creative Commons Attribution International License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author(s) and source are credited. The author(s) granted the publication rights to [Scientia cum Industria](#).

Also, plasticizers, such as polyols (sorbitol, glycerol, ethylene glycol, and propylene glycol), are essential for film formation. These compounds alter the physical and mechanical properties of materials by reducing interactions in polymers, increasing the free volume between polymer chains, and improving the flexibility and extensibility of films [14, 15].

Furthermore, several areas address the production of polymeric films with water-soluble and/or water-dispersible properties. Most of these films comprise natural polymers, plasticizing agents, and crosslinks, such as Wilpiszewska *et al.*, (2020) [5] which developed films based on CMC, carboxymethyl starch (CMS), citric acid, and glycerol; Lawal *et al.* (2009) [16] reported a renewable and low-cost film based on CMS, suberic acid, glutaric acid, pimelic acid, and butane tetracarboxylic acid; Ghorpade *et al.*, (2019) [17] used CMC, PVA and citric acid to develop a polymeric film.

In recent years, there has been a growing interest in the development of water-soluble polymeric films as a sustainable alternative to conventional petroleum-based films, which have numerous environmental drawbacks, including pollution and non-biodegradability. These water-soluble films are not only designed to reduce the dependency on fossil fuels but also aim to alleviate the environmental impact associated with plastic waste.

Thus, this study aims to investigate the formulation and production of an affordable, cellulose-based water-dispersible polymeric film. This study investigated various methods of creating these films, including the selection of appropriate additives to enhance their functional properties and performance in multiple applications. Finally, the goal is to contribute to the development of eco-friendly film solutions that align with modern environmental standards.

Experimental Section

Materials

All experiments were carried out under standard pressure and temperature, with solutions prepared using deionized water. The reactants carboxymethylcellulose (CMC, Reactec), polyvinyl alcohol (PVA, Selvol), glycerol from vegetable source (Synth), and bleached *Eucalyptus grandis* cellulose (pressed and dried sheet donated by Klabin® company) were employed as acquired.

Preparation of the water-dispersible paper

In the first step, 10.0 g of cellulose (5.0 wt%) was cut into small pieces and then added to 500 mL of water, along with 0.5 g of CMC (0.1 wt%). The mixture was stirred at 1200 rpm for 120 min at 23 ± 2 °C using a mechanical stirrer (Fisatom – 713DS) equipped with a 50 mm sharp blade. Next, 356 g of this solution was combined with 40 g of a 5% PVA solution and 4.0 g of glycerol, then stirred for 5 min at 500 rpm, also at 23 ± 2 °C, using a mechanical stirrer. The final solution was stored at 4.0 ± 2 °C. To achieve different basis weights (ISO 536 for determination of grammage), this mixture was poured into a silicone mold (size 6.5 cm x 6.5 cm) and dried at 60 °C for 24 h at the desired grammage of 40, 60, 80, and 100 g/m².

Tensile test

The tensile test of the water-dispersible paper in the different grammages was conducted according to ASTM D882:2018 - *Standard Test Method for Tensile Properties of Thin Plastic Sheeting*, at the Center for Characterization and Development of Materials (CCDM) at UFSCar (Brazil), using an INSTRON universal testing machine, model 5969R, using a 50 N of trigger force, with a grip spacing of 30 mm, at an elongation speed of 5 mm min⁻¹. To perform the analysis, each sample of 40, 60, 80, and 100 g/m² was kept in a controlled environment (23 ± 2 °C and $50\% \pm 5\%$ RH) for 96 hours before the test and evaluated at least five times. For the analysis, samples weighing 40, 60, 80, and 100 g m⁻² were systematically prepared and placed in a controlled environmental chamber. The conditions within the chamber were maintained at a temperature of 23 ± 2 °C, and a relative humidity of $50 \pm 5\%$. Each sample was kept under these conditions for a duration of 96 hours to ensure stability and uniformity prior to testing. Following this acclimatization period, each sample underwent thorough evaluation, with a minimum of five separate assessments. The responses of Breaking Factor (N/m), Tensile Strength (MPa), and Elongation at break (%) were investigated.

Analytical methods and instruments

The color evaluation (L^* , a^* and b^* parameters of CIELAB scale) was performed using a BYK Spectro-guide Sphere Gloss S in three samples of the prepared water-dispersible paper. The morphology analysis was performed by scanning electron microscopy (SEM) using a JEOL JCM 7000 microscope at magnifications between 100x and 300x. Fourier infrared spectroscopy with attenuated total reflectance (FTIR-ATR) data were recorded on a Bruker Vertex 70 spectrometer with a resolution of 4 cm⁻¹ in the 400–4000 cm⁻¹ range. Thermogravimetric analyses (TGA) were run on a Netzsch STA 449F3 analyzer instrument under N₂ atmosphere from 30 to 400 °C with a temperature ramp of 10 °C min⁻¹.

Contact angle

The contact angle was measured using an SEO – Phoenix 300 Touch Automatic Contact Angle Analyzer, with the paper attached to an SAE 1020 carbon steel plate. A total of 300 frames were collected at 30 ms per frame, amounting to a 9-second analysis.

Disintegration evaluation

The disintegration evaluation was performed inspired on the method reported by Pfennich *et al.*, (2023) [18]. 1.5 x 1.5 cm of the prepared water-dispersible paper was placed into a 50 mL beaker with 10 mL of water at 23 ± 2 °C. Using a magnetic stirrer (IKA C-MAG HS 7), the paper disintegration was evaluated for 10, 20, and 30 s at approximately 500 to 750 RPM. After each period, the solution was placed in 50 mm disposable Petri dishes, and photos were taken.

Statistical analysis

All analyses were conducted in triplicate, and the results are presented as mean $\pm$ standard deviation. Mean comparisons were made using analysis of variance (ANOVA), followed by Tukey's test, with a 95% confidence interval to assess statistical differences among various factors, such as grammage.

Results and Discussion

Synthetic approach

To verify the successful synthesis of the water-dispersible paper, a small piece of the sample was carefully cut and placed into a beaker containing a small volume of distilled water. The beaker was gently swirled to ensure the sample was fully submerged. Throughout the observation, gentle manual agitation was carried out by manually stirring the water. The synthesis was successful when the sample began to break down rapidly into fine fibers, demonstrating its water-dispersible properties.

The film produced by the proposed methodology was consistent, with the final concentration (after drying) of the water-dispersible paper being approximately 61% cellulose, 3% CMC, 2% PVA, and 34% glycerol.

Tensile test

The tensile test was carried out in four different water-dispersible paper grammages: 40, 60, 80, and 100 g/m². The results are available in Table 1, and the properties evaluated were the breaking factor, which is the ratio of the force required to break the material to the area where the break occurred. This value shows us the specific resistance of the broken region. The second is the tensile strength, which indicates the pressure applied at the exact moment the material broke. Finally, the elongation property at break indicates how much the material stretches before breaking, which suggests its elasticity.

Table 1. Results obtained for the tensile test of the water-dispersible paper.

Grammage (g/m ²)	Breaking Factor (N/m)	Tensile Strength (MPa)	Elongation at break (%)
40	551 $\pm$ 54.81 ^c	4.86 $\pm$ 0.87 ^a	9.0 $\pm$ 1.15 ^c
60	858 $\pm$ 104.93 ^b	5.06 $\pm$ 0.77 ^a	11 $\pm$ 1.04 ^b
80	987 $\pm$ 127.24 ^b	3.86 $\pm$ 0.51 ^a	11 $\pm$ 0.68 ^b
100	1270 $\pm$ 176.13 ^a	4.57 $\pm$ 0.43 ^a	14 $\pm$ 1.20 ^a

Different letters in the same column indicate statistically significant differences according to Tukey's test (95% confidence).

The breaking factor showed an increasing trend with grammage, indicating that heavier-weight water-dispersible paper can withstand higher loads before failing. According to the results, only the samples with 60 g/m² (858 $\pm$ 104.93 N/m) and 80 g/m² (987 $\pm$ 127.24 N/m) can be statistically considered similar, suggesting that both support similar loads.

This was also evident in the elongation at break, where higher grammage levels were associated with a proportional increase in

the amount of plasticizing agents, such as glycerol, and the increase of polymer materials, such as PVA and CMC, these potentially enhanced the material's elasticity, plasticity, and ductibility of films by strengthening the interfiber bonding fields (by filling the spaces between the biopolymer chains) by chemical links within the areas of the water-dispersible paper [19, 20].

Considering that the final concentration of the plasticizer agent glycerol was 34%, the elongation at break ranged from 9 to 14%, Müller et al., (2009) [21] reported similar results when employing 30% glycerol as a plasticizer in films based on cassava starch and cellulose fibers (with addition of 0.10, 0.30, and 0.50 g of fiber/g dry starch), ranging from approximately 21 to 13%, respectively. Considering the films based on cellulose and using glycerol as a plasticizer, Paudel et al., (2023) [20] reported experiments with an elongation at break from 4.3 to 13.1 %, comparable to our data. Plasticizers enhance a film's elongation by reducing interactions between polymer chains and increasing molecular attraction [20].

However, the tensile strength ranged from 3.86 to 5.06 MPa. The analysis also revealed that this property does not directly depend on grammage, as no significant mean difference was observed according to the statistical evaluation.

This phenomenon is potentially affected by the distribution and composition of the fibers in the paper matrix, the addition of additives in the paper's composition and the manufacturing process, which significantly affects the material's response to applied mechanical forces. Paudel et al., (2023) [20] developed films based on cellulose and using glycerol as a plasticizer with a tensile strength from 0.8 to 22.4 MPa. In their experiments, the high tensile strength is associated with the addition of high concentrations of CaCl₂ (400mM), a source of Ca²⁺ ions responsible for crosslinking the cellulose chains in the presence of glycerol, enhancing the tensile strength [20]. As well as Müller et al., (2009) [21], reported tensile strength ranging from 8 to 22 MPa in the films based on cassava starch and cellulose fibers.

The findings suggest that tensile strength is not merely a function of the total number of fibers but of their load, being strongly affected by their organization and interconnection patterns [22]. Consequently, tensile strength values remained similar across the four grammage levels analyzed. This aligns with the findings of Chrispin Das et al., (2021) [23], which observed that the tensile strength of phenol formaldehyde composites reinforced with Areca and sisal fibers (based on natural cellulose fibers) is associated with the length and the content of these fibers.

This data suggests the internal fiber structure of the paper efficiently redistributes mechanical loads, independent of variations in paper thickness investigated in this paper. These observations highlight the critical role of fiber distribution and plasticizing agents in the mechanical performance of the paper, emphasizing structural organization and composition as key factors affecting tensile and breakage properties.

Finally, Figure 1 displays the network plot created based on the Euclidean distance with the breaking factor, tensile strength, and elongation at break data. The majority of 40 g/m² perform interconnections and also have a few and weak connections with

60 g/m². Few connections can be observed between 100 and 80 g/m². Moreover, Figure 1 reveals several interconnections among the different grammages, particularly between the 60 g/m² and 80 g/m² samples. These interconnections are characterized by the nodes' sizes and thick lines, which indicate their similarities.

Chemical characterization

Color evaluation

The color evaluation was carried out in triplicate in three samples of the prepared water-dispersible paper. The luminosity is indicated by the L* parameter, which represents the brightness varying from 0 (black) to 100 (white) [24]. The mean value was 94.93 ± 0.57 , near the total white sample. As a reference, a Whatman No.1 cellulosic paper reported by Matsuo et al., (2012) [25] has an L* value of 98.11 ± 0.01 , indicating the similarity of the water-dispersible paper.

The a* parameter indicates the color variation from green to red [24], with a value of 0.28 ± 0.10 . Also, the color variation from blue to yellow [24] is determined by the value of the b* parameter of 4.29 ± 0.59 . For comparison purposes, the cellulose

Whatman No.1 has the a* and b* parameters of -0.02 ± 0.01 and 2.31 ± 0.06 , respectively [25]. The data indicate that the developed water-dispersible paper color variation closely resembles that of white cellulosic paper, which is essential for customer acceptance.

Finally, the °HUE (color type), saturation (color variation according to lightness), and lightness (luminosity) calculated from the L*a*b* parameters were 37.01°, 37.84%, and 93.5%.

Thus, the additives in the formulation and the manufacturing processes of the water-dispersible paper do not affect the color changes in the paper production.

Scanning electron microscopy

The morphology of the water-dispersible paper was analyzed using Scanning Electron Microscopy (SEM). Figure 2 presents an SEM micrograph of the paper, with grammages ranging from 40 to 100 g/m², at 100x magnification. The image reveals a fibrillar structure with interconnected cellulose fibers. The cellulose fiber length distribution ranged predominantly between 10 and 22 µm, with an average fiber length of 16.44 µm and a

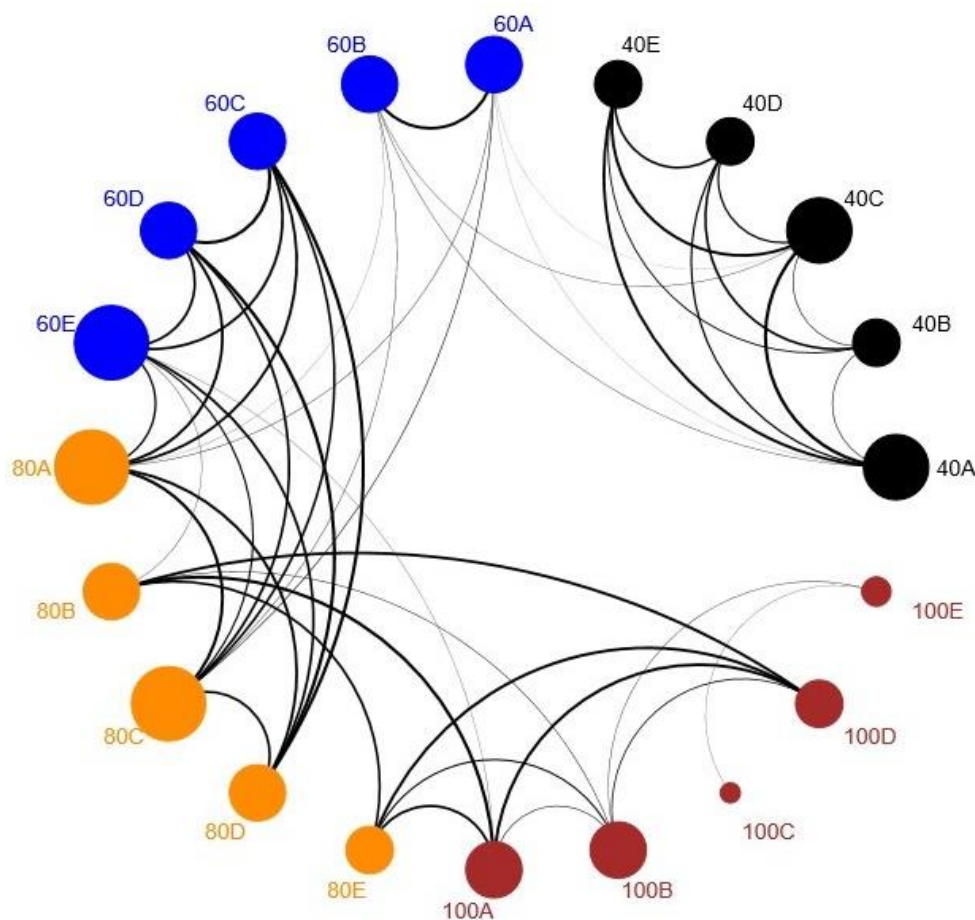


Figure 1. Network plot (Euclidean distance) with breaking factor, tensile strength, and elongation at break data responses.

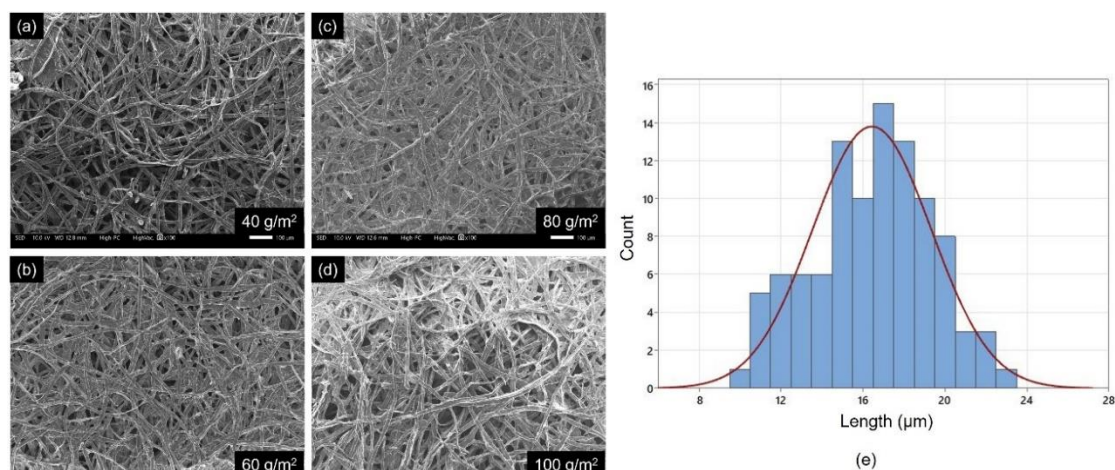


Figure 2. Scanning electron microscope (SEM) images at frontal section in four different grammages (40 (a), 60 (b), 80 (c) and 100 (d) g/m²) for the water dispersible paper at 100x magnification. The scale represents 100 μm.

standard deviation of 2.896 μm, regardless of its grammage, as shown in the histogram (Figure 2e). This narrow distribution highlights the uniformity in fiber size, which is crucial for ensuring consistent mechanical properties and structural integrity of the developed material. At 40 g/m², the fibers are less compact and display large void spaces. Increasing the grammage from 40 to 100 g/m² leads to a gradual increase in internal density, reducing the void spaces and improving the overall compactness of the paper.

Figure 3 shows the label section morphology. At 40 g/m², the fibers are loosely arranged, while higher grammages (60 to 100 g/m²) exhibit a more compact and well-distributed fiber network. This compaction correlates with increases in the breaking factor and elongation at break. However, tensile strength remains unaffected, indicating that inter-fiber interactions are stable across all grammages.

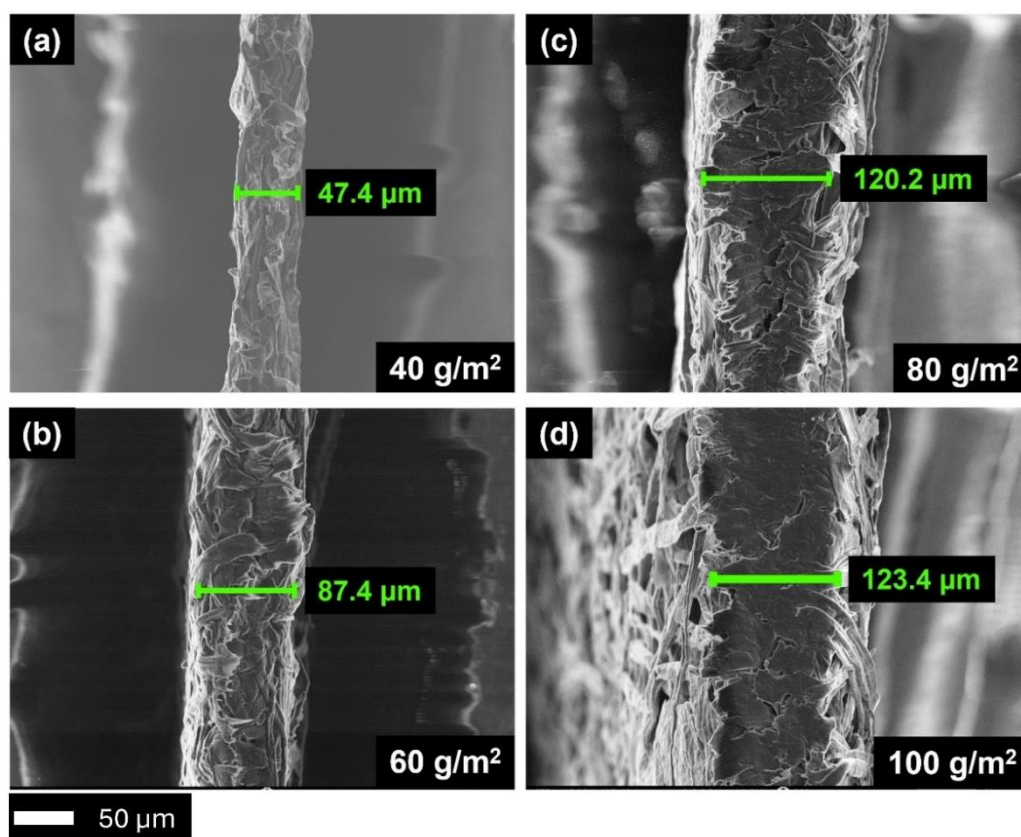


Figure 3. Scanning electron microscope (SEM) images at label section in four different grammages (40, 60, 80 and 100 g/m²) for the water dispersible paper at 300x magnification.

Fourier infrared spectroscopy

The FTIR spectrum of the prototype (Figure 4) is predominantly overlaid by the cellulose [26] spectrum, highlighting its major role in the composition (61% of the dry weight). Nevertheless, specific features reveal the presence and interaction of the other components CMC [27], PVA [28], and glycerol [29]. The O–H stretching band ($3500\text{--}3200\text{ cm}^{-1}$) appears slightly broadened, suggesting hydrogen bonding among the constituents. Subtle changes in the $1700\text{--}1600\text{ cm}^{-1}$ region point to the contribution of carboxylate groups from CMC. In the $1150\text{--}1000\text{ cm}^{-1}$ range, shifts and increased intensities indicate C–O–C and C–O functionalities from PVA and CMC. Additionally, variations below 1000 cm^{-1} suggest the influence of glycerol. These observations confirm that the additives are well incorporated and interact within the cellulose matrix rather than existing as isolated phases.

Thermogravimetric analysis

The thermogravimetric analysis was performed to evaluate the thermal stability of the water-dispersible paper. Figure 4b shows the degradation profile highlighting two different regions. The decreasing region A of Figure 4b is associated with a weight loss of approximately 10% ($T_{10\%}$), which indicates the loss of humidity with water evaporation at the temperature of $104.29\text{ }^{\circ}\text{C}$. Differently, Aragão Melo et al., (2018) [30] reported $T_{10\%}$ of neat cellulose ranging at $299\text{ }^{\circ}\text{C}$, which they associated with humidity and volatile evaporation. For pure glycerol, which is the second most prominent reagent in the water-dispersible paper formulation, the $T_{10\%}$ was $200\text{ }^{\circ}\text{C}$ according to the findings of Murillo and Ararat, (2022) [31].

According to our data, the $T_{20\%}$ associated with an approximately 20% weight loss was $217\text{ }^{\circ}\text{C}$, which is very similar to that reported by Murillo and Ararat, (2022) [31] for pure glycerol at $220\text{ }^{\circ}\text{C}$.

The region B of Figure 4b indicates the region temperature at which the most significant weight loss occurs, known as T_{max}

($^{\circ}\text{C}$), was observed to be $249\text{ }^{\circ}\text{C}$, indicating a mass loss of approximately 30% at that moment. In this region, dehydration, hydrolysis, oxidation, decarboxylation, and transglycosylation coincide in a single step [30]. This behavior is potentially associated with the amount of glycerol in the formulation, as demonstrated by Almazrouei et al., (2019) [32], who reported the mass single drop of pure glycerol at a temperature range of $139\text{--}259\text{ }^{\circ}\text{C}$.

Similarly, Andrade et al., (2025) [33] reported a T_{max} of $213.1\text{ }^{\circ}\text{C}$ for cellulose nanofibers. On the other hand, according to the findings reported by Aragão Melo et al., (2018) [30], the T_{max} for neat cellulose was recorded at $330\text{ }^{\circ}\text{C}$.

Finally, the residual mass after the heating process at $400\text{ }^{\circ}\text{C}$ was 16.87% (Figure 4b), indicating the presence of inorganic compounds, as demonstrated by the energy-dispersive spectroscopy analysis.

Contact angle

The contact angle measurements (Figure 5) were performed on papers with grammages of 40, 60, 80 and 100 g/m^2 , revealing a clear relationship between grammage and water absorption properties. Papers with higher grammages (60, 80 and 100 g/m^2) showed a faster reduction in contact angle, indicating enhanced water absorption and dispersion. This behavior is consistent with the more compact and uniformly distributed fiber network observed in the SEM analysis. The increased density at higher grammages facilitates water penetration by reducing void spaces within the structure, allowing for quicker interactions with the aqueous medium.

In contrast, the 40 g/m^2 paper exhibited a slower reduction in contact angle, corresponding to the loosely arranged fiber network and larger voids. These structural characteristics hinder immediate water absorption, leading to a less pronounced hydrodispersibility compared to higher grammages.

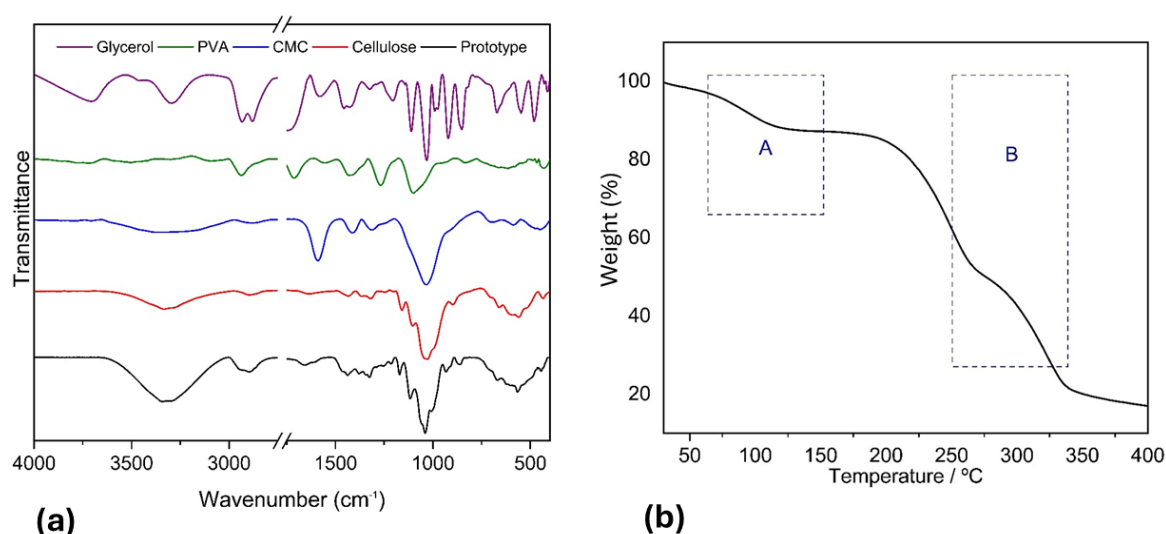


Figure 4. Infrared spectra (a) and thermogravimetric analysis (b) of the water-dispersible paper.

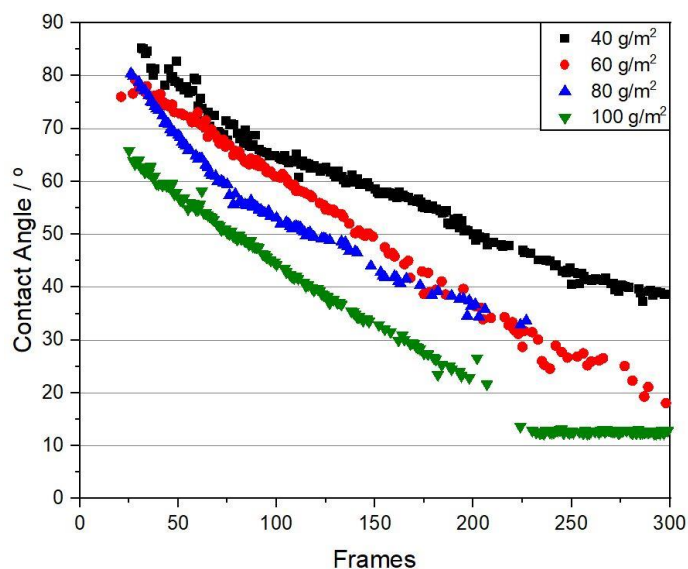


Figure 5. Contact angle measurements relative to captured frames (30 ms per frame) for prototype paper in four different grammages (40, 60, 80 and 100 g/m²).

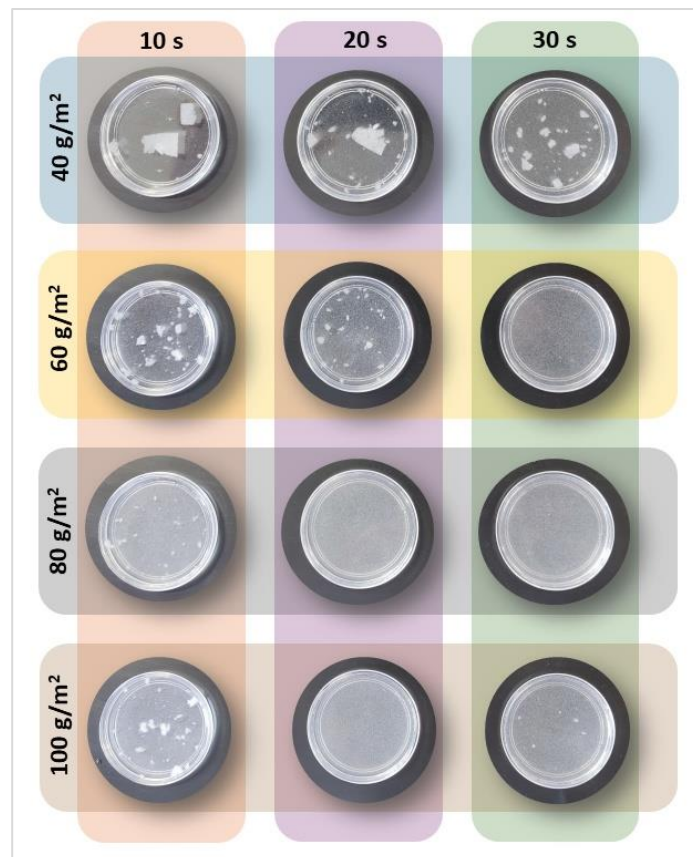


Figure 6. Disintegration test of the water-dispersible paper in different grammages at 10, 20 and 30s.

Disintegration evaluation of the water-dispersible paper

The disintegration test was performed at 10, 20, and 30 seconds using the grammages of 40, 60, 80, and 100 g/m². The photos in Figure 6 show the behavior of different grammages in terms of water disintegration properties. It is clear that higher grammages, such as 100 g/m², disintegrate faster than lower grammages. At 20 s, the 100 g/m² sample was disintegrated entirely. On the other hand, at 20 s and 30 s, the 40 g/m² sample had more paper particles in the water medium. At 60 g/m², total disintegration was observed at 30 s, while 80 g/m² was fully disintegrated at 20 s.

The findings presented in Figure 6 align with the conclusions of the contact angle analysis, indicating a clear relationship between grammage and contact angle. Specifically, lower grammages, exemplified by 40 g/m², demonstrated significantly higher contact angles than their higher grammage counterparts, such as 100 g/m². This observation strongly suggests that materials with lower grammage take longer to disintegrate fully.

Furthermore, these observations relate to the large contact area of water-dispersible paper with high grammages, leading to faster disintegration than those with lower grammages.

The proposed formulation of water-dispersible paper demonstrates remarkable efficiency, capable of disintegrating most of its surface area in water within just 30 seconds, irrespective of its grammage. This rapid dissolution highlights its effectiveness as a material in applications requiring quick biodegradability.

Conclusions

This study successfully demonstrated the synthesis and characterization of a cellulose-based water-dispersible paper with optimized mechanical and water-responsive properties. The findings indicate that grammage affects the breaking factor and elongation but not tensile strength, highlighting the significance of fiber distribution and plasticizing agents in improving material performance. The thermal and morphological analyses confirmed the integration and interaction of additives, which contribute to the material's hydrodispersibility and structural stability. The disintegration property of the water-dispersible paper is closely related to its contact angle response. In this context, it has been observed that materials with higher grammages exhibit a more rapid disintegration process. Additionally, these materials tend to have a lower contact angle in comparison to those with lower grammages. This relationship suggests that as the grammage increases, the disintegration efficiency improves, while also reflecting changes in their hydrophobic or hydrophilic characteristics as indicated by the contact angle. This innovative material serves as a sustainable solution to combat plastic waste, showcasing various applications across various sectors. In eco-friendly packaging, it can be utilized for food and dairy products, significantly reducing the reliance on traditional plastics. It acts as an effective drug carrier or wound dressing in the medical and

pharmaceutical fields, enhancing patient care. Furthermore, in agriculture, this material can be transformed into biodegradable seed carriers that dissolve when watered, promoting environmentally friendly farming practices. It can also be used in biodegradable shopping bags, which help minimize plastic bags, and it can play a role in hygiene products, such as toilet tissues and wipes. Future studies would explore the project's scalability and long-term environmental impacts to further validate its practical applications.

Acknowledgments

The authors are thankful to the EMBRAPPI (Brazilian Company for Industrial Research and Innovation) and FIEP-PR for support.

Authors' Contribution

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Bruno L. Ferreira, Gabriel B. Baptistella and Maurício de Matos. The first draft of the manuscript was written by Bruno L. Ferreira and Gabriel B. Baptistella, and all authors commented on previous versions of the manuscript. The supervision was carried out by Natalia C. Silva, Francielle Calegari and Daniel Gomes Constantino. All authors have approved the final version of the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] T. Sooksawat, M. Attapong, W. Saengsakun, S. Siripornadulsil, and W. Siripornadulsil, "Optimization of polyhydroxybutyrate (PHB) production by *Priestia megaterium* ASL11 and glycerol and thermoplastic properties of PHB-based films," *Biocatal. Agric. Biotechnol.*, vol. 54, p. 102951, Nov. 2023, doi: 10.1016/j.bcab.2023.102951.
- [2] C. V. Tonicioli Riguetto *et al.*, "Gelatin films from wastes: A review of production, characterization, and application trends in food preservation and agriculture," *Food Res. Int.*, vol. 162, p. 112114, Dec. 2022, doi: 10.1016/j.foodres.2022.112114.
- [3] S. Fatima, M. R. Khan, I. Ahmad, and M. B. Sadiq, "Recent advances in modified starch based biodegradable food packaging: A review," *Heliyon*, vol. 10, no. 6, p. e27453, Mar. 2024, doi: 10.1016/j.heliyon.2024.e27453.
- [4] K. Wilpiszewska and Z. Czech, "Water-Soluble Pressure-Sensitive Adhesives Containing Carboxymethyl Starch with Improved Adhesion to Paper," *J. Polym. Environ.*, vol. 26, no. 4, pp. 1453–1458, Apr. 2018, doi: 10.1007/s10924-017-1048-8.
- [5] K. Wilpiszewska, A. K. Antosik, B. Schmidt, J. Janik, and J. Rokicka, "Hydrophilic Films Based on Carboxymethylated Derivatives of Starch and Cellulose," *Polymers (Basel)*, vol. 12, no. 11, p. 2447, Oct. 2020, doi: 10.3390/polym12112447.
- [6] T. Spychaj, K. Wilpiszewska, and M. Zdanowicz, "Medium and high substituted carboxymethyl starch: Synthesis, characterization and application," *Starch - Stärke*, vol. 65, no. 1–2, pp. 22–33, Jan. 2013, doi: 10.1002/star.201200159.
- [7] B. M. Tselana, S. Muniyasamy, V. O. Ojijo, and W. Mhike, "Melt Processible Biodegradable Blends of Polyethylene Glycol Plasticized Cellulose Diacetate with Polylactic Acid and Polybutylene Adipate-Co-Terephthalate," *J. Polym. Environ.*, vol. 31, no. 11, pp. 4891–4908, Nov. 2023, doi: 10.1007/s10924-023-02925-8.
- [8] N. R. Saha *et al.*, "Nanocomposite films based on cellulose acetate/polyethylene glycol/modified montmorillonite as nontoxic active packaging material," *RSC Adv.*, vol. 6, no. 95, pp. 92569–92578, 2016, doi: 10.1039/C6RA17300D.
- [9] W. Tongdeesontorn, L. J. Mauer, S. Wongruong, P. Sriburi, and P. Rachtanapun, "Effect of carboxymethyl cellulose concentration on physical properties of biodegradable cassava starch-based films," *Chem. Cent. J.*, vol. 5, no. 1, p. 6, Dec. 2011, doi: 10.1186/1752-153X-5-6.
- [10] E. Pinto *et al.*, "Cellulose processing from biomass and its derivatization into carboxymethylcellulose: A review," *Sci. African.*, vol. 15, p. e01078, Mar. 2022, doi: 10.1016/j.sciaf.2021.e01078.
- [11] W. Zhang *et al.*, "Advances in sustainable food packaging applications of chitosan/polyvinyl alcohol blend films," *Food Chem.*, vol. 443, p. 138506, Jun. 2024, doi: 10.1016/j.foodchem.2024.138506.
- [12] A. Anbumani, S. Radhika, and C. M. Padma, "Synergistic effect of Polyvinyl alcohol and *Datura stramonium*: Approach towards active wound dressing," *J. Ind. Eng. Chem.*, vol. 134, pp. 289–300, Jun. 2024, doi: 10.1016/j.jiec.2023.12.059.
- [13] K. Zhang *et al.*, "Application of polyvinyl alcohol/chitosan copolymer hydrogels in biomedicine: A review," *Int. J. Biol. Macromol.*, vol. 242, p. 125192, Jul. 2023, doi: 10.1016/j.ijbiomac.2023.125192.
- [14] E. A. Arik Kibar and F. Us, "Thermal, mechanical and water adsorption properties of corn starch-carboxymethylcellulose/methylcellulose biodegradable films," *J. Food Eng.*, vol. 114, no. 1, pp. 123–131, Jan. 2013, doi: 10.1016/j.jfoodeng.2012.07.034.
- [15] M. F. Vargas-Torrico, M. A. Aguilar-Méndez, E. Ronquillo-de Jesús, M. R. Jaime-Fonseca, and E. von Borries-Medrano, "Preparation and characterization of gelatin-carboxymethylcellulose active film incorporated with pomegranate (*Punica granatum* L.) peel extract for the preservation of raspberry fruit," *Food Hydrocoll.*, vol. 150, pp. 1–10, 2023, doi: 10.1016/j.foodhyd.2023.107777.

- p. 109677, May 2024, doi: 10.1016/j.foodhyd.2023.109677.
- [16] O. S. Lawal, J. Storz, H. Storz, D. Lohmann, D. Lechner, and W.-M. Kulicke, "Hydrogels based on carboxymethyl cassava starch cross-linked with di- or polyfunctional carboxylic acids: Synthesis, water absorbent behavior and rheological characterizations," *Eur. Polym. J.*, vol. 45, no. 12, pp. 3399–3408, Dec. 2009, doi: 10.1016/j.eurpolymj.2009.09.019.
- [17] V. S. Ghorpade, R. J. Dias, K. K. Mali, and S. I. Mulla, "Citric acid crosslinked carboxymethylcellulose-polyvinyl alcohol hydrogel films for extended release of water soluble basic drugs," *J. Drug Deliv. Sci. Technol.*, vol. 52, pp. 421–430, Aug. 2019, doi: 10.1016/j.jddst.2019.05.013.
- [18] A. C. Pfennich, E. A. Schoeffmann, H. Lammer, and U. Hirn, "Water-dispersible paper for packaging applications – balancing material strength and dispersibility," *Nord. Pulp Pap. Res. J.*, vol. 38, no. 4, pp. 521–532, Dec. 2023, doi: 10.1515/npprj-2023-0048.
- [19] S. Kamel, M. El-Sakhawy, and A. M. A. Nada, "Mechanical properties of the paper sheets treated with different polymers," *Thermochim. Acta*, vol. 421, no. 1–2, pp. 81–85, Nov. 2004, doi: 10.1016/j.tca.2004.03.005.
- [20] S. Paudel, S. Regmi, and S. Janaswamy, "Effect of glycerol and sorbitol on cellulose-based biodegradable films," *Food Packag. Shelf Life*, vol. 37, p. 101090, Jun. 2023, doi: 10.1016/j.fpsl.2023.101090.
- [21] C. M. O. Müller, J. B. Laurindo, and F. Yamashita, "Effect of cellulose fibers addition on the mechanical properties and water vapor barrier of starch-based films," *Food Hydrocoll.*, vol. 23, no. 5, pp. 1328–1333, Jul. 2009, doi: 10.1016/j.foodhyd.2008.09.002.
- [22] H. Ku, H. Wang, N. Pattarachaiyakoo, and M. Trada, "A review on the tensile properties of natural fiber reinforced polymer composites," *Compos. Part B Eng.*, vol. 42, no. 4, pp. 856–873, Jun. 2011, doi: 10.1016/j.compositesb.2011.01.010.
- [23] M. Chrispin Das, A. Athijayamani, K. Arun Vasantha Geethan, D. Santhosh, and S. Prathap Singh, "Effects of length and content of natural cellulose fiber on the mechanical behaviors of phenol formaldehyde composites," *Mater. Today Proc.*, vol. 45, pp. 516–521, 2021, doi: 10.1016/j.matpr.2020.02.111.
- [24] B. L. Ferreira, "Effect of ultrasound treatment in fresh apple juices from different cultivars," *Iniciação Científica Cesumar*, vol. 25, no. 1, pp. 1–10, Dec. 2023, doi: 10.17765/2176-9192.2023v25n1e12028.
- [25] M. Matsuo, K. Umemura, and S. Kawai, "Kinetic analysis of color changes in cellulose during heat treatment," *J. Wood Sci.*, vol. 58, no. 2, pp. 113–119, Apr. 2012, doi: 10.1007/s10086-011-1235-5.
- [26] B. Abderrahim, E. Abderrahman, A. Mohamed, T. Fatima, T. Abdesselam, and O. Krim, "Kinetic Thermal Degradation of Cellulose, Polybutylene Succinate and a Green Composite: Comparative Study," *World J. Environ. Eng.*, vol. 3, no. 4, pp. 95–110, 2015, doi: 10.12691/wjee-3-4-1.
- [27] M. L. H. Rozali, N. H. Ahmad, and M. I. N. M. Isa, "Effect of Adipic Acid Composition on Structural and Conductivity Solid Biopolymer Electrolytes Based on Carboxy Methylcellulose Studies," *Am. J. Sustain. Agric.*, vol. 9, pp. 39–45, 2015.
- [28] H. S. Mansur, C. M. Sadahira, A. N. Souza, and A. A. P. Mansur, "FTIR spectroscopy characterization of poly (vinyl alcohol) hydrogel with different hydrolysis degree and chemically crosslinked with glutaraldehyde," *Mater. Sci. Eng. C*, vol. 28, no. 4, pp. 539–548, May 2008, doi: 10.1016/j.msec.2007.10.088.
- [29] E. L. Hanry, N. F. M. Redzwan, N. F. A. K. Badeges, and N. Surugau, "Characterization of biofilms developed from alginate extracted from *Padina* sp. incorporated with calcium chloride (CaCl₂)," *J. Phys. Conf. Ser.*, vol. 2314, no. 1, p. 012022, Aug. 2022, doi: 10.1088/1742-6596/2314/1/012022.
- [30] A. R. Aragão Melo, E. Oliveira da Silva, L. R. Menezes, and M. I. B. Tavares, "The effect of modified cellulose particles on morphology and properties ethylene vinyl acetate copolymer," *Polym. Test.*, vol. 68, pp. 333–339, Jul. 2018, doi: 10.1016/j.polymertesting.2018.04.012.
- [31] E. A. Murillo and C. A. Ararat, "An approach for the compatibility of thermoplastic starch/poly (lactic acid) blends using an ester obtained from glycerol and tall oil fatty acids," *J. Appl. Polym. Sci.*, vol. 139, no. 37, Oct. 2022, doi: 10.1002/app.52876.
- [32] M. Almazrouei, S. Elagroudy, and I. Janajreh, "Transesterification of waste cooking oil: Quality assessment via thermogravimetric analysis," *Energy Procedia*, vol. 158, pp. 2070–2076, Feb. 2019, doi: 10.1016/j.egypro.2019.01.478.
- [33] A. Andrade *et al.*, "Interaction of Nanofibrillated cellulose with lignin nanoparticles: Effects on CNF-LNP composite properties," *Carbohydr. Polym. Technol. Appl.*, vol. 9, p. 100651, Mar. 2025, doi: 10.1016/j.carpta.2024.100651.