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Sustainable Extraction and Valorization of Sunflower Stem Pith as an Absorbent Core for Hygiene Applications

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ABSTRACT

This study aimed at the extraction of a natural biodegradable absorbent material from sunflower stem pith (SSP) as an eco-friendly option for hygiene products like baby diapers and sanitary pads. Researchers used sodium hypochlorite (NaOCl) treatment under mild conditions to effectively isolate the absorbent core. The process was optimized using response surface methodology (RSM) based on a central composite design (CCD), adjusting the solid-liquid ratio, extraction time, and temperature. The data proved that the best conditions, which were a 10 g/mL solid-liquid ratio, 15 minutes, and 95°C, led to an extraction efficiency of 68.85%. Statistical analysis (ANOVA) confirmed that the model was significant ($p < 0.0001$). FT-IR and TGA analysis showed that the extracted absorbent core had structural and thermal properties similar to commercially available products. The moisture retention tests revealed that NaOCl-treated samples absorbed more moisture due to optimal particle size and enhanced porosity. Water absorption and free swell tests further showed the superior absorbent performance of EAC. Overall, NaOCl treatment proved to be a viable, economical method for extracting high-yield absorbent core material from sunflower stem pith.

KEYWORDS

Absorption capacity, fibre morphology, hypochlorite treatment, medical textiles, process optimization, waste utilization

CITATION

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1. Introduction

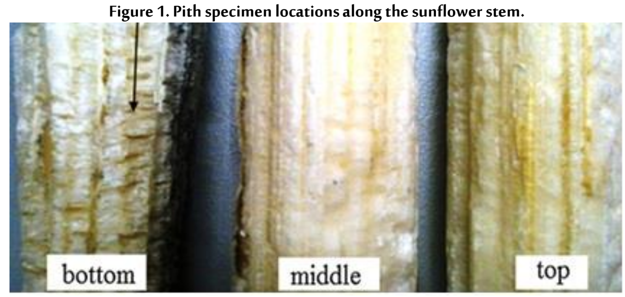
The global demand for hygiene products, such as sanitary pads and baby diapers, is growing, which highlights the urgent need for sustainable alternatives to traditional petroleum-based superabsorbent polymers (SAPs) (Capizzi and Ferguson 2005). While synthetic SAPs are highly effective at retaining liquid, they pose significant environmental and health risks, including potential skin irritation and toxic shock syndrome (El Nemr, 2012; Mirzaie, *et al.*, 2025). As a result, research is increasingly focusing on creating biodegradable, eco-friendly materials from agricultural and industrial waste (Taj, *et al.,* 2007). This shift aligns with zero-waste and circular economy principles. Bio-based SAPs, made from renewable sources, are promising candidates for hygiene applications because of their natural biodegradability and strong fluid absorption (Dhiman *et al.,* 2023; Liu, *et al.,* 2025; Sareen, 2021).

1.1. Sunflower Stem Pith as a Sustainable Alternative:

Sunflower stem pith (SSP), a lignocellulosic byproduct of sunflower oil production, represents a vast and underutilized biomass source with natural absorbent properties (Xu, 2016). Converting SSP into a bio-based absorbent core offers a solution to waste management issues, as this material is often disposed of in landfills or by burning. This process supports sustainable material cycles (Xu, *et al.,* 2020). With a cellulose content of 35-45%, SSP is well-suited for creating absorbent materials due to its lightweight, fibrous, and highly porous structure (Jain, *et al.,* 2019; Sun, *et al.,* 2013). Compared to synthetic absorbents, SSP offers key advantages such as biodegradable, low-density, and inexpensive, which can lead to lighter products and reduced manufacturing costs (Casquilho, *et al.,* 2013).

The absorbent capacity of sunflower stems varies along their length due to changes in anatomical composition. For instance, the basal (lower) portions are more porous, with porosity up to 63% and larger cavities. In contrast, the apical (upper) parts are denser and have lower water diffusivity (Sun, *et al.,* 2013; Kamal 2011) (Figure 1). The middle regions may have lignified cell walls and structural irregularities that restrict fluid movement. Because of this natural variability, carefully selecting and processing the SSP is crucial to maximizing its absorbent performance.

Figure 1. Pith specimen locations along the sunflower stem.



In addition to its physical structure, SSP contained a variety of phytochemicals, including phenolics, flavonoids, and alkaloids, which have been shown to have antimicrobial properties against bacteria like *Staphylococcus aureus* (Kamal 2011; Verma *et al.,* 2016).

1.2. Material Properties and Characteristics:

Based on an analysis of both the upper and lower pith regions (Table 1), key properties are consistent such as a density of 29 kg/m³, a cellulose content of 31.5%, and a lignin content of 2.5%. However, the hemicellulose content shows a slight axial variation, estimated to be around 27.5% in the lower region and 25.0% in the upper region. This difference is related to the increased need for mechanical support in the lower part of the plant. A significant difference was observed in porosity. The lower pith had a porosity of 63%. However, the upper pith had 56% of porosity. This difference correlates with a higher diffusion coefficient in the lower pith (200×10^3 mm²/s) compared to the upper pith (110×10^3 mm²/s).

The table also revealed that the specific heat capacity (1300 J/kg·K) and thermal conductivity (0.039 W/m·K) remained consistent across both regions. These combined phytochemical and physicochemical traits made SSP highly suitable for hygiene and biomedical applications that

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require both absorbency and antimicrobial properties.

Table 1. Physical and chemical characteristics of SSP at different stem locations (Jain *et al.,* 2019; Sun et.al 2013).

Property	Top location	Bottom location
	Pith	Pith
Density (kg.m^3)	29	29
Cellulose (%)	31.5	31.5
Lignin (%)	2.5	2.5
Porosity (%)	56	63
Hemicellulose	25	27.5
Diffusion coefficient (10^{3}mm^{2}s^{-1})	110	200
Heat capacity (J.kg$^{-1.}$ k^{-1})	1300	1300
Thermal conductivity (w.m$^{-1.}$ k^{-1})	0.039	0.039

1.3. Eco-Friendly Extraction of Cellulose:

Traditional methods for extracting cellulose from natural fibers often rely on harsh chemicals like sulfuric or hydrochloric acids, or on expensive, energy-intensive enzymatic processes that can harm the environment (Wyman, *et al.,* 2005; Weise, *et al.,* 1996). An alternative approach, using alkaline sodium hypochlorite (NaOCl) hydrolysis, shows promise for extracting porous cellulose from sunflower pith fibers (Xu, 2016; Costa, *et al.,* 2018). Despite its potential for eco-friendly modification of cellulose in absorbent materials, this method has not been extensively studied for sunflower pith.

Sodium hypochlorite (NaOCl) is effective at selectively removing lignin and hemicellulose under mild conditions, which helps to improve the final cellulose content (Afridi, *et al.,* 2021). A systematic study of extraction parameters such as the solid-liquid ratio, temperature, and extraction time is essential for optimizing the yield and functional properties of the final product. Studies confirmed that statistically based methods like Response Surface Methodology (RSM) and Central Composite Design (CCD) are powerful tools for this optimization (Demirel and Kalyan, 2012; Ahmed, *et al.*, 2025).

Hence, the goal of this research was to develop and optimize a NaOCl-based extraction method to produce a high-performance absorbent core from sunflower stem pith. The extracted material was characterized using techniques like FT-IR spectroscopy and thermal analysis (TGA), and its functional properties (including water retention, free swell, and moisture absorption) were evaluated and compared to commercial absorbents. The ultimate objective was to support the transition from synthetic SAPs to sustainable, biodegradable, and non-toxic materials for use in hygiene products.

2. Materials and Methods

2.1. Materials:

Sunflower stem pith (SSP) was collected from agricultural fields around Bahir Dar, Ethiopia -including Merawi, Durbetie, and Burie regions. Sodium hydroxide (NaOH) was sourced from the Ethiopian Institute of Textile and Fashion Technology (EiTEX) laboratory, while 2% NaOCl solution was procured from a certified local chemical supplier.

2.2. Pith Specimen Location:

Sunflower stems (Helianthus annuus L.) were identified and characterized according to the taxonomic guidelines described by Arenas-Salazar,*et al.,* 2025; Arenas-Salazar, *et al.,* 2025). The stems were mechanically separated into bark and pith to differentiate their respective functional roles. For this study, pith samples were collected from three longitudinal regions - the bottom, middle, and top of stems approximately 765 mm in length. Longitudinal and radial sections were carefully extracted from various regions along the stem height to evaluate the anatomical structure and density variations of sunflower stem pith (SSP).

2.3. Pith Specimen Preparation:

Following the manual harvesting methods from Sun, *et al.,* (2013), the outer bark of the sunflower stems was carefully removed to reveal the inner pith. From different heights of the stems, cylindrical cross sections of the pith with diameters between 15 to 25 mm were collected. The middle pith region had a diameter 1.20 times larger than the base, and 1.02 times larger than the top. The samples without bark were kept in ambient conditions until they were processed further. To cut the soft, spongy core, the outer bark was scraped away. The cleaned pith was kept in dry conditions to avoid microbial degradation until further processing.

2.4. Preparation of Extracted Absorbent Core (EAC):

2.4.1. Alkali Pre-treatment with NaOH

The extracted pith was initially subjected to alkali treatment for scouring and removal of surface impurities. A material-to-liquor ratio (MLR) of 1:20 was employed, using NaOH at concentrations of 2% and 4%. The treatment was conducted at 100 °C for 60 minutes with constant agitation. The recipe for the alkali pre-treatment is shown in Table 2. After treatment, samples were thoroughly rinsed with distilled water until a neutral pH (~7.0) was achieved.

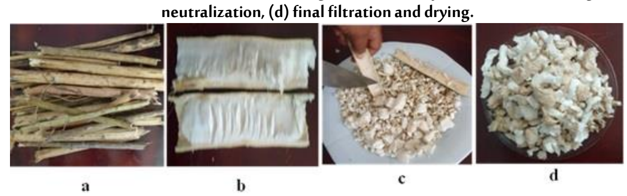
Table 2. Conditions for NaOH-based scouring treatment of SSP.

Test	NaOH Concentration (%)	MLR	Temperature (°C)	Time (min)
1	2	1:20	100	60
2	4	1:20	100	60

2.4.2. NaOCl Treatment

Following alkali pre-treatment, the dried and neutralized pith was subjected to oxidative hydrolysis using 2% NaOCl. The treatment was conducted in a glass beaker with a solid-to-liquid ratio varying between 5 - 15 g/mL. The reaction temperature ranged from 90 - 100 °C, with extraction times between 10 - 20 minutes. The slurry was continuously stirred to ensure uniform exposure. After the treatment, the extracted absorbent core (EAC) was rinsed multiple times with distilled water until no chlorine was detected using potassium iodide-starch paper (<0.1 ppm Cl_2). Samples were neutralized to pH 7.0 with sodium thiosulfate to ensure complete chlorine removal and material safety and dried under natural sunlight at ambient temperature (~30 °C) until a constant weight was reached (Figure 2).

Figure 2. Stepwise NaOCl-based extraction process of sunflower stem pith (Ahmed, *et al.*, 2025) (a) Initial water and NaOCl soaking, (b) NaOCl-only treatment, (c) rinsing and neutralization, (d) final filtration and drying.



2.4.3. Extraction Yield Calculation

Extraction yield was computed based on the initial dry weight of the raw pith and the final weight of the EAC obtained. The percentage yield (Y) was calculated using the equation:

$$\text{Extracted Yield \%} = \frac{\text{Final Dry Weight of extracted Pith}}{\text{Initial Weight of Raw Pith Powder}} * 100 \quad (5)$$

2.5. Experimental Design and Optimization:

To optimize NaOCl treatment conditions, a Response Surface Methodology (RSM) approach was adopted using Central Composite Design (CCD). The independent variables were (Table 3):

- Solid–liquid ratio (A: 5-15 g/mL)
- Extraction time (B: 10-20 min)
- Extraction temperature (C: 90-100 °C)

A total of 20 randomized experimental runs were designed and analyzed using *Statistica 13* software. The second-order polynomial model used to predict extraction yield was:

$$Y = \beta_0 + \beta_i X_i + \beta_{ij} X_i X_j + \beta_{ii} X^2{}_i \quad (1)$$

Where Y is the predicted response (extraction yield), β_0 is the intercept, βi represents the linear coefficients, βij denotes the interaction coefficients, βii are the quadratic coefficients, and Xi, Xj are the coded independent variables, with i, j = 1, 2, 3.

Table 3. Independent variables and their coded levels used in CCD.

Factor	Variable	Low Level (−1)	High Level (+1)
A	Solid–liquid ratio (g/mL)	5	15
B	Extraction time (min)	10	20
C	Temperature (°C)	90	100

2.6. Characterization Techniques:

2.6.1. FT-IR Spectroscopy

FT-IR analysis was conducted using a VERTEX-70 spectrophotometer (Bruker, Germany). Samples were blended with potassium bromide (KBr) and pressed into translucent pellets. Spectra were recorded in the range of 4000 - 400 cm^{-1} with a resolution of 2 cm^{-1} over 20 scans.

2.6.2. Thermogravimetric Analysis (TGA)

TGA was performed on an STA449 F3 thermal analyser (Netzsch, Germany) under a nitrogen flow of 40 mL/min. Approximately 10 mg of dry EAC powder was heated from 30 °C to 600 °C at a rate of 10 °C/min to assess thermal degradation behavior.

2.7. Functional Performance Testing:

2.7.1. Water Absorption Test

Water absorption kinetics were studied by immersing pre-dried EAC samples in distilled water and recording weight gain at 10, 30, 60, 90, and 120 minutes. The absorption capacity was calculated using:

$$\text{Weight Gain} = \frac{w2 - w1}{w1} \quad (2)$$

Where: w_1 = initial (dry) weight, w_2 = weight after water absorption

2.7.2. Free Swell Test

Following the method of Muthu and Li (2014), 0.1–0.3 g of EAC powder was enclosed in a polypropylene bag and immersed in a saline solution (9 g NaCl per liter of water). After 30 minutes of soaking, excess liquid was drained, and samples were weighed to determine swell capacity:

$$\text{Free swell absorption} = \frac{W1 - W0}{W0} \quad (3)$$

Where: W0 = initial (dry) weight of the sample, W1 = weight of the swollen sample

2.7.3. Moisture Content Determination

Samples were oven-dried at 105 °C and weighed periodically until constant mass was achieved. Moisture content (%) was calculated by:

$$\text{Moisture Content (Mc\%)} = \frac{\text{Initial weight (W1)} - \text{Oven dry weight (W2)}}{\text{Initial weight (W1)}} \quad (4)$$

2.7.4. Sieve Analysis

A 5 g sample of ground EAC was subjected to manual sieve analysis using a 425-micron mesh. Coarse and fine fractions were separated and classified. The milled SSP was passed through a series of mesh sieves, and the majority of particles were retained in the 250-500 μm range, considered optimal for absorbent performance. This test assesses particle size distribution, which influences absorbency and processability (Jamshaid, *et al.,* 2022).

3. Results and Discussion

3.1. Optimization of Extraction Parameters Using RSM:

The optimization of extraction parameters for sunflower stem pith powder (SSPP) was conducted using Response Surface Methodology (RSM) under a Central Composite Design (CCD) framework. Response Surface Methodology (RSM), particularly Central Composite Design (CCD), has been widely applied in optimizing extraction from agro-wastes (Boateng, 2023). The aim was to maximize extraction yield by evaluating the effects and interactions of three critical variables: solid–liquid ratio (A), extraction time (B), and temperature (C).

The experimental design comprised 20 randomized runs (Table 4) and revealed yields ranging from 63% to 74%, with the optimal combination yielding 68.85%, as confirmed by the desirability function (Figure 3). This level of efficiency indicated effective removal of lignin and hemicellulose, with minimal cellulose degradation.

$$\text{Extracted yield\%} = \frac{137.7\ (g)}{200\ (g)} * 100 = 68.85\%$$

Figure 3. Predicted vs actual response for extraction yield

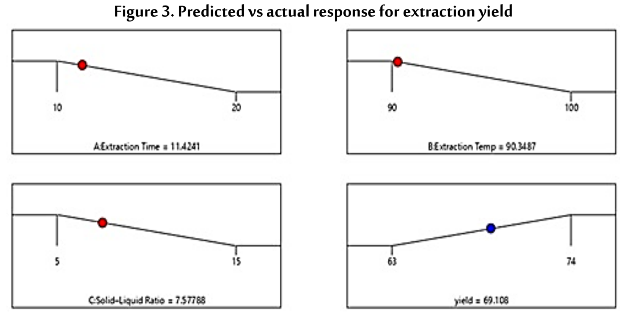


Table 4. Central Composite Design experimental matrix and corresponding yields.

Trials	Extraction Condition Yield (%)			
	A: Extraction Time (min)	B: Extraction Temp (⁰C)	C: Solid-Liquid Ratio (g/ml)	Response Yield (%)
1	20.00	100.00	15.00	70.00
2	15.00	86.59	10.00	68.00
3	10.00	100.00	5.00	63.00
4	15.00	95.00	10.00	74.00
5	15.00	95.00	18.41	67.00
6	15.00	95.00	10.00	73.00
7	15.00	95.00	10.00	74.00
8	15.00	95.00	1.59	63.00
9	10.00	100.00	15.00	68.00
10	15.00	95.00	10.00	73.00
11	15.00	103.41	10.00	69.00
12	20.00	90.00	15.00	65.00
13	10.00	90.00	15.00	67.00
14	0.59	95.00	10.00	67.00
15	15.00	95.00	10.00	74.00
16	20.00	100.00	5.00	68.00
17	10.00	90.00	5.00	64.00
18	20.00	90.00	5.00	67.00
19	23.41	95.00	10.00	69.00
20	15.00	95.00	10.00	74.00

3.2. Model Fit and Statistical Validation:

While the lack-of-fit test produced a p-value of 0.3189, which shows great correspondence between model projections and experimental results, analysis of variance (ANOVA) verified the quadratic model's significant importance ($p < 0.0001$) with an F-value of 85. 02 (Table 5a). An R^2 of 0.9871, an adjusted R^2 of 0.9755, a projected R^2 of 0.9301, and a proper precision value of 26.42 - well above the 4.0 acceptable threshold - evidence the great predictive power of the regression. Moreover, the CV of 0. 8485% (Table 5b) was low, pointing to exceptional model reproducibility. Together, these statistical measures verify that the model accurately forecasts extraction yield across the examined parameter space. The final predictive equation in coded form was:

Y=73.68+0.8321A+0.5625B+1.08C+0.7500AB−1.0000AC+0.7500BC−2.06A2−1.88B2−3.12C2

Where:

- Y = Predicted extraction yield (%)
- A, B, and C = Coded values of extraction time, extraction temperature, and solid-liquid ratio, respectively.

Table 5a. ANOVA quadratic model for extraction conditions with yield (%).

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	261.14	9	29.02	85.02	< 0.0001	Significant
A-Extraction Time	9.46	1	9.46	27.71	0.0004	
B-Extraction Temp	4.32	1	4.32	12.66	0.0052	
C-Solid–Liquid Ratio	15.88	1	15.88	46.54	< 0.0001	
AB	4.50	1	4.50	13.19	0.0046	
AC	8.00	1	8.00	23.44	0.0007	
BC	4.50	1	4.50	13.19	0.0046	
A²	61.21	1	61.21	179.37	< 0.0001	
B²	51.16	1	51.16	149.92	< 0.0001	
C²	140.43	1	140.43	411.50	< 0.0001	
Residual	3.41	10	0.3413			
Lack of Fit	2.08	5	0.4159	1.56	0.3189	Not significant
Pure Error	1.33	5	0.2667			
Corrected Total	264.55	19				

Table 5b: Summary of model fit statistics.

Model Type	Sequential p-value	Lack of Fit p-value	Adjusted R²	Predicted R²	Adequate Precision	Std. Dev.	Mean	C.V. (%)
Quadratic	< 0.0001	0.3189	0.9755	0.9301	26.42	0.5842	68.85	0.8485

3.3. Model Diagnostic Plot:

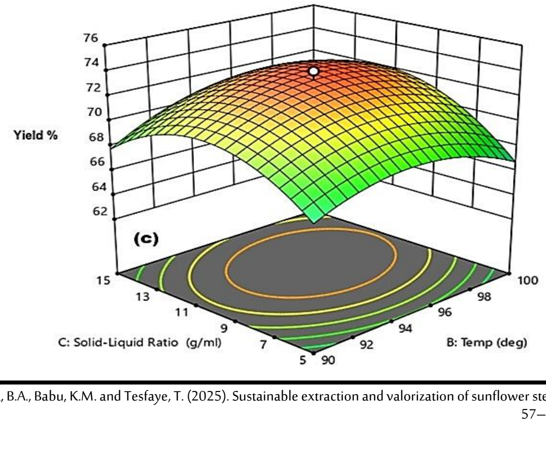
The model exhibited good predictive capacity with an R^2 of 0.98, indicating close correspondence between the predicted and experimental values. The points are closely parallel along the 45-degree line, indicating a high correlation between the observed and modelled results. The high agreement reassuringly affirms the strength and predictive capacity of the model across the range of experimental conditions. Low deviation from the line also confirms the model's reliability and lack of systematic error. The visual confirmation in this case is in tandem with the statistical results (Adjusted R^2 = 0.9755 and Predicted R^2 = 0.9301), reaffirming that the chosen quadratic model fits the response behavior of SSPP extraction yield to a great extent.

A one-factor-at-a-time analysis indicated that increasing NaOCl concentration and temperature enhanced EAC yield, while prolonged treatment slightly reduced yield due to pith degradation.

3.4. Response Surface Interpretation:

The Three-dimensional response surface plot (Figure 4) illustrates the interactive effect of the parameters of extraction on the yield. Among the interaction effects considered, the most powerful between solid-liquid ratio and temperature guided the optimal conditions of extraction. The most powerful interaction, as depicted in Figure 4, is that between solid–liquid ratio and temperature, where the high temperatures promote greater porosity and diffusion, but temperatures above 100 °C are accountable for the breakdown of the solvent system and hence lowering extraction efficiency.

Figure 4. Three-dimensional response surface plot showing the interactive effect between solid–liquid ratio and temperature on extraction yield. Moderate temperature (~95°C) and solid–liquid ratio (~10 g/mL) produced the highest yield.

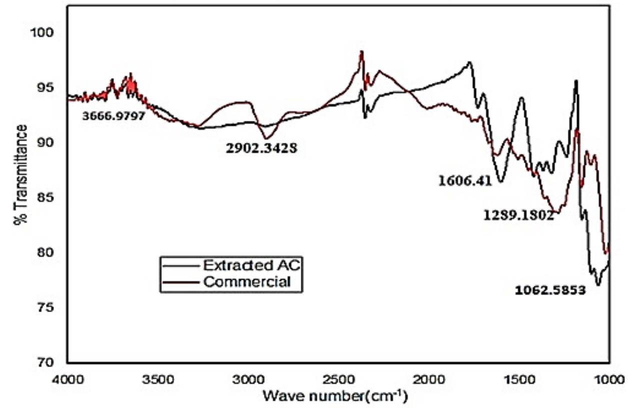


3.5. Functional and Thermal Characterization of Extracted Powder:

3.5.1. FTIR Spectral Analysis

FT-IR spectra of commercial absorbent core (CAC) and extracted absorbent core (EAC), as represented in Figure 5, exhibit characteristic bands for absorption related to cellulose and hemicellulose composition. A wide O–H stretching vibration band ranging from 3667 to 3200 cm^{-1} reveals rich hydroxyl groups available, which are an important aspect of water holding capacity and hydrogen bonding. The C–H stretching mode at 2902 cm^{-1} is attributed to the aliphatic $-CH_2$ groups present in the polysaccharide backbone. Remarkably, the aromatic C–O stretching band at 1289 cm^{-1} points towards ester and ether linkages prevalent in hemicellulose and lignin fractions, but bands between 1020-1075 cm^{-1} result from vinyl ether C–O vibrations specific to cellulose glycosidic bonds.

Figure 5. FT-IR spectra of extracted absorbent core (EAC) at optimized conditions (10 g/mL, 15 min, 95°C), demonstrating strong similarity with commercial absorbents, confirming effective delignification and cellulose preservation



The resemblance of the EAC spectrum to the CAC spectrum verifies that the NaOCl treatment effectively preserved the cellulose backbone and facilitated delignification and hemicellulose removal. The absence of any prevalent carbonyl (C=O) stretching bands close to 1730 cm^{-1} verifies that there was minimal oxidative degradation of the cellulose polymer during extraction. These results are consistent with previous reports indicating that NaOCl-mediated delignification can achieve a level of delignification efficiency comparable with or even greater than enzyme-assisted techniques, offering a chlorine-free method for the isolation of high-purity cellulose from lignocellulosic biomass (Joo, *et al.*, 2025).

3.5.2. Thermogravimetric Analysis (TGA)

Thermal analysis indicated that the processed absorbent core (EAC) showed a slightly higher thermal degradation onset compared to raw pith, possibly because of the destabilization of unstable organic contents by NaOCl treatment. The EAC experienced initial weight loss below 250 °C primarily due to the evaporation of physically bound water. This was followed by a major degradation stage between 350-400°C, corresponding to the breakdown of hemicellulose and cellulose. A final stage, observed between 390 - 470 °C, reflected the formation of char residues, coinciding with the breakdown of more stable polymeric fractions.

Above all, the thermal stability of NaOCl-treated EAC was marginally higher than for the CAC, with the onset of significant decomposition at around 470 °C compared to around 460 °C for the commercial counterpart. This higher thermal resistance is likely to be the result of increased cellulose crystallinity induced by the NaOCl treatment in combination with efficient removal of amorphous components such as lignin, pectin, and waxes. The highly ordered framework of the EAC matrix made it more resistant to thermal degradation before structural collapse. These findings validate that the EAC not only sustains but, in some aspects, surpasses the thermal excellence of commercial absorbent products, further witnessing to the viability of the EAC as a sustainable and high-performance alternative for use in absorbent hygiene products.

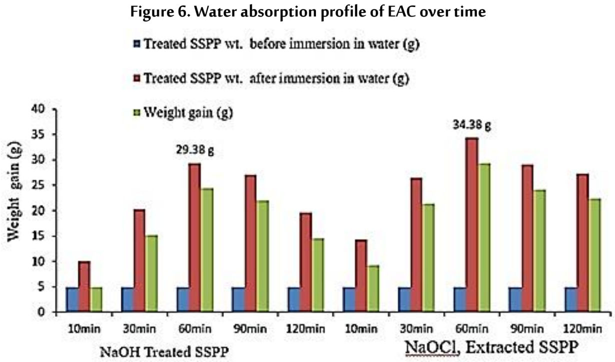
3.6. Performance Evaluation of Extracted Powder:

3.6.1. Water Absorption Time

Kinetics of water absorption for the obtained absorbent core extract (EAC), as indicated in Figure 6, exhibited a fast uptake phase in the first 15 minutes, where more than 59% of total water absorption was achieved. This reveals a rapid swelling capability, which is necessary for hygiene products requiring rapid fluid absorption. Among the treated variants, the 2% NaOCl-treated EAC showed the highest absorbency (29.38 g/5 g) compared to 24.38 g/5 g for 4% NaOH-treated samples. Maximum absorption was realized after approximately 60 minutes, and from that point on, the uptake tended to plateau, indicating saturation of the internal pore structure.

The enhanced absorbency of NaOCl-treated EAC can be explained by several complementary mechanisms. On the one hand, oxidative treatment has the consequence of increasing porosity and forming an open pore network that facilitates rapid capillary action. NaOCl treatment produced smaller particle sizes and larger surface area, enhancing fluid interaction and increasing potential fluid uptake. Finally, the effect of removing non-cellulosic constituents, such as lignin and that waxy outer layer of stem pith, also exposed more hydrophilic functional groups (such as –OH) over a larger surface area and bolstered overall hydrophilic character. Overall, these results demonstrated that NaOCl-mediated modification enhanced the water absorption capacity of sunflower stem pith, providing a foundation for a commercially viable and eco-friendly alternative to synthetic absorbents.

Figure 6. Water absorption profile of EAC over time



3.6.2. Free Swell Absorption

The EAC exhibited a free swell absorption capacity of approximately 12 g/g under non-restrained conditions and was comparable to that of conventional superabsorbent polymers (SAPs). This enhancement is attributed to the formation of highly connected pores and an extensive three-dimensional network structure within the cellulose matrix, which are both suitable for water absorption by capillary action. The NaOCl treatment effectively degraded the tight lignocellulosic structure, facilitated fiber loosening and increased void volume. These improved fluid transport and retention. The restructuring increased water accessibility to internal cellulose sites and prolonged swelling time, a desirable attribute in absorbent core products. These results are consistent with previous work on bio-based superabsorbents, where chemical pre-treatment was reported to improve porosity and hydrophilicity to improve swelling performance. The free swell behavior noted warrants the viability of employing NaOCl-modified SSP as an environmentally friendly alternative to conventional synthetic superabsorbent polymers in sanitary products.

3.6.3. Moisture Content (Moisture Absorption)

Moisture content was substantially higher in the NaOCl samples versus NaOH, principally from the removal of hydrophobic surface constituents like waxes and ash. Chemical treatment increased the exposure of cellulose domains containing hydroxyl groups. This produced cellulose with a more porous microstructure and improved the internal surface area and capillary channels. Accordingly, the samples treated exhibited greater equilibrium moisture absorption, possibly due to increased water vapor sorption and retention capacity. The greater hydrophilicity and availability of pores are responsible for the material's ability to hold greater moisture at ambient conditions. These results are consistent with earlier observations of the moisture retention characteristic of sunflower stem pith (SSP) and its potential application in sanitary absorbent products and bio-based insulation materials, where moisture management, biodegradability, and functional performance are crucial (Ahmed, *et al.*, 2025).

3.6.4. Sieve Analysis and Particle Size Distribution

Sieve analysis showed that most of the particles passed a 425-micron mesh, indicating fine particle distribution conducive to uniform layering in hygiene product matrices. Coarser fractions were minimal, enhancing even fluid distribution when the product was applied.

3.6.5. Comparative Performance of Extracted and Commercial Absorbents

A comparative assessment was conducted between NaOH-treated sunflower stem pith (SSP), NaOCl-treated SSP (EAC), and commercial superabsorbent polymers (SAPs). The NaOCl-treated EAC demonstrated performance metrics comparable to commercial SAPs while retaining complete biodegradability. This comparison clearly indicated that the EAC exhibits performance comparable to or slightly better than commercial SAPs in terms of moisture retention and thermal stability while maintaining complete biodegradability (Table 6).

Table 6. Comparison of performance characteristics between NaOH-treated SSP, NaOCl-treated SSP (EAC), and commercial SAPs

Parameter	NaOH-treated SSP	NaOCl-treated SSP (EAC)	Commercial SAP
Water absorption (g/g)	24.38	29.38	30–35
Free swell capacity (g/g)	10.2	12.0	12–15
Moisture retention (%)	62.5	68.4	70–75
Thermal degradation onset (°C)	460	470	465
Biodegradability	High	High	Low

4. Conclusion

This research confirmed that sunflower stem pith (SSP), an agro-industrial by-product, is valorised to a high-performance absorbent core through hydrolysis in the presence of sodium hypochlorite (NaOCl) under optimized conditions. With Response Surface Methodology (RSM), the best conditions for extraction - 10 g/mL solid–liquid ratio, 15-minute treatment time, and 95 °C extraction temperature - gave 68.85% extraction efficiency. Spectroscopic (FT-IR) and thermal (TGA) analyses ensured that the extracted absorbent core (EAC) retained structural characteristics similar to commercial absorbents. Functional performance testing, like water absorption, free swell, and moisture retention, enhanced performance of the EAC compared to NaOH-treated ones owing to enhanced porosity, reduced particle size, and enhanced hydrophilicity caused by NaOCl treatment. The findings of this research highlighted the potential of SSP as an environmentally friendly, biodegradable, and cost-effective raw material for hygiene applications. The environmental footprint of this process was significantly lower than that of conventional SAP production. The NaOCl-based hydrolysis operated under mild, energy-efficient conditions and produced neutralized effluents. Valorizing sunflower pith avoids agro-waste burning and supports circular bioeconomy principles. Also, the hydrolysis using NaOCl was a more sustainable and safer alternative to traditional acidic hydrolysis.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare no conflict of interest.

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