

Green Synthesis and Structural Characterization of a Biosourced Heterogeneous Acid Catalyst Based on Sulfonated Cellulosic Fabric

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ABSTRACT

This study describes the design of a biosourced heterogeneous acid catalyst derived from recycled cellulosic fabric, aligned with lignocellulosic waste valorization and green chemistry principles. The raw cellulose substrate was first activated via selective oxidation using sodium periodate (NaIO_4), converting vicinal diols into reactive aldehyde groups. This step was followed by controlled sulfonation through covalent grafting of chlorosulfonic acid (ClSO_3H), yielding a functionalized Cell- SO_3H material with an average synthesis yield of 92.5%. FT-IR spectroscopy revealed the appearance of bands at 1720 cm^{-1} (C=O) and 1040 cm^{-1} (S=O), confirming the formation of aldehyde and sulfonate groups, respectively. Elemental analysis indicated a sulfur content of 3.8%, corresponding to an acid site density of $1.25\text{ mmol H}^+\text{ g}^{-1}$, corroborated by potentiometric titration ($1.31\text{ mmol H}^+\text{ g}^{-1}$), demonstrating good accessibility of protonic sites. The catalyst exhibited thermal stability up to $260\text{ }^\circ\text{C}$ and a pH_{pzc} value of 2.3, indicative of a highly acidic surface. SEM observations revealed a marked transformation in morphology, transitioning from a compact fiber network to a porous and textured structure favorable to reactant adsorption and diffusion. These results demonstrate the feasibility of converting recycled fabrics into efficient, stable, and economically competitive catalysts. The resulting material represents a sustainable alternative to synthetic acid resins, with promising potential for reactions such as esterification, transesterification, and dehydration in biomass upgrading and green chemistry.

Keywords: heterogeneous catalysis; cellulosic fabric; acid functionalization; chlorosulfonation; green chemistry.

INTRODUCTION

The transition toward sustainable catalytic processes has become a major challenge in modern chemistry, in a global context marked by declining fossil resources and the need to reduce the environmental footprint of industrial operations (Zhang et al., 2022). Heterogeneous catalysts, due to their separability, recyclability, and reusability, provide an ecological and economical alternative to homogeneous systems traditionally employed in biofuel production, biomass valorization, and fine chemistry applications (Li et al., 2021).

Among emerging catalytic supports, cellulose is attracting increasing attention due to its availability, biodegradability, and rich surface chemistry (Nongbe et al., 2018; Tsubaki et al., 2021). As the most abundant natural polymer on Earth, it serves as a renewable platform ideal for designing high-value functional materials (Klemm et al., 2020). Its linear structure, composed of β -D-glucopyranose units, provides a high density of modifiable hydroxyl groups, enabling the introduction of acidic, basic, or redox sites through surface grafting depending on the targeted functionality (Pandey et al., 2022).

In this context, the acid functionalization of cellulosic supports by sulfonation ($-\text{SO}_3\text{H}$) or carboxylation ($-\text{COOH}$) arises as a promising strategy for preparing heterogeneous catalysts active in esterification and transesterification reactions (Yadav et al., 2021). Recent studies indicate that catalytic efficiency depends not only on acid site density but also on their surface distribution, generated porosity, thermal stability, and recyclability (Kaur et al., 2020; Wang et al., 2022). Several reports describe acid site densities ranging from 0.8 to $1.5\text{ mmol H}^+\text{ g}^{-1}$, catalytic yields above 85–90% in model reactions, and stable performance over five recycling cycles (Zhou et al., 2023; Amarasekara et al., 2024).

Recent advances also highlight the relevance of hydrothermal or “one-step” processes for producing cellulose-derived carbon catalysts with enhanced surface areas (Niu et al., 2023), as well as optimization of sulfonation treatments yielding thermally stable ($>250\text{ }^{\circ}\text{C}$) and reusable catalysts over 5–7 cycles (Jiang et al., 2025). Moreover, catalytic performance has been shown to correlate strongly with pore connectivity and functional site accessibility (Qiu et al., 2023). Other approaches, such as incorporating magnetic phases or carbon nanostructures, yield multifunctional catalysts with improved separability and resistance to degradation (Lopes et al., 2022; Chen et al., 2024).

However, several limitations persist in the literature: (i) most supports arise from purified cellulose, which is poorly representative of true circular resources; (ii) the exploitation of recycled textiles and fabrics as catalytic matrices remains scarce; (iii) few studies quantitatively link chemical modification to active-site accessibility, thermal stability, and recyclability; and (iv) limited evidence shows that recycled-fabric-derived catalysts can match the performance of commercial synthetic catalysts (Mahmood et al., 2025).

Therefore, this work addresses this scientific gap by developing a biosourced acid catalyst from recycled cellulosic fabric, activated by oxidation and subsequently functionalized via sulfonation, while establishing correlations between structural transformation, acidic properties, thermal stability, and morphology. This material aims to provide a local, economical, and sustainable alternative to synthetic catalysts, demonstrating that a recycled textile support can achieve acid densities comparable to commercial resins while maintaining stability and reusability potential for green chemistry applications.

2. Materials and Methods

2.1. Reagents and starting materials

The cellulosic fabric used as a support was obtained from locally sourced 100% cotton textiles (Côte d’Ivoire). Before use, the raw fabric was cut into $2 \times 2\text{ cm}$ pieces and purified by successive washing with distilled water and ethanol (95%). All chemical reagents were of analytical grade: sodium metaperiodate (NaIO_4 , 99%, Sigma-Aldrich), chlorosulfonic acid (ClSO_3H , 98%, Merck), acetone (99.5%, VWR), methanol (99.8%, Fisher Scientific), and NaOH (0.1 mol L^{-1} for titration). Ultrapure water (resistivity $18.2\text{ M}\Omega\cdot\text{cm}$, Millipore) was used for all rinsing and solution preparation steps.

2.2. Preparation of oxidized cellulosic support

Raw cellulosic fabric (100 g) was immersed in an aqueous sodium metaperiodate solution (0.1 mol L^{-1} , 1 L) and kept under magnetic stirring (300 rpm) at $25\text{ }^{\circ}\text{C}$ for 6 h in the dark to prevent NaIO_4 photoreduction. This selective oxidation step (Malaprade reaction) converts vicinal diols into aldehyde groups, enhancing reactivity toward subsequent acid grafting. The resulting material (Cell–CHO) was washed thoroughly with distilled water until neutrality and dried in an oven at $105\text{ }^{\circ}\text{C}$ for 12 h. The measured mass loss after oxidation was 4.6%, corresponding to partial conversion of primary $-\text{OH}$ functions.

2.3. Acid functionalization by chlorosulfonation

The sulfonation reaction was performed in a 500 mL round-bottom flask equipped with a condenser and mechanical stirring under inert nitrogen atmosphere.

Oxidized support (10 g of Cell–CHO) was suspended in 100 mL of anhydrous glacial acetic acid and cooled to $0\text{--}5\text{ }^{\circ}\text{C}$ in an ice bath. Under continuous stirring, chlorosulfonic acid (ClSO_3H , 2 mL g^{-1} support, i.e., 20 mL) was added dropwise over 30 min. The reaction mixture was maintained at $60\text{ }^{\circ}\text{C}$ for 3 h and then cooled to room temperature.

The obtained product (Cell– SO_3H) was filtered and washed thoroughly with acetone, followed by distilled water until neutral pH, and dried at $80\text{ }^{\circ}\text{C}$ for 10 h.

The average functionalization yield, calculated on a dry-mass basis, was 92.5%, indicating efficient incorporation of sulfonic groups.

2.4. Physicochemical characterization of the catalyst

2.4.1. Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR analyses were performed using a Bruker Alpha II spectrometer in the $4000\text{--}400\text{ cm}^{-1}$ range (resolution 4 cm^{-1} , ATR mode). The appearance of bands at 1040 cm^{-1} (S=O) and 1720 cm^{-1} (C=O) confirmed the formation of sulfonate and aldehyde functionalities on the cellulose surface.

2.4.2. Elemental analysis (CHNS)

Elemental analysis was carried out on a Vario Micro Cube analyzer (Elementar, Germany). The sulfur content (3.8%) enabled estimation of acid site density at $1.25 \text{ mmol H}^+ \text{ g}^{-1}$, consistent with titration results.

2.4.3. Thermogravimetric analysis (TGA)

Thermal properties were evaluated using a TGA Q50 analyzer (TA Instruments) from 30 to 600 °C under N_2 flow at $10 \text{ }^\circ\text{C min}^{-1}$.

2.4.4. Determination of total acidity

Surface acidity was determined by titration with $0.01 \text{ mol L}^{-1} \text{ NaOH}$ after proton exchange in aqueous suspension ($0.1 \text{ g catalyst}/50 \text{ mL}$).

2.4.5. Determination of point of zero charge (pHpzc)

The pHpzc was determined by the pH-drift method, mixing 0.1 g of catalyst in 50 mL of $0.01 \text{ mol L}^{-1} \text{ NaCl}$ and adjusting initial pH between 2 and 12.

2.4.6. Scanning Electron Microscopy (SEM)

The morphology of raw fabric, oxidized cellulose (Cell-CHO), and sulfonated material (Cell-SO₃H) was examined by scanning electron microscopy (SEM). Samples ($5 \times 5 \text{ mm}$) were dried at $60 \text{ }^\circ\text{C}$, mounted on conductive stubs, and sputter-coated with gold/palladium ($\sim 10 \text{ nm}$). Images were acquired using a [model] microscope operated at $5\text{--}15 \text{ kV}$ in secondary electron mode, with magnifications between $500\times$ and $5000\times$ to visualize surface texture evolution at each modification stage.

3. Results and Discussion

3.1. Successive functionalization steps of the cellulosic fabric

The transformation of raw cellulosic fabric into a heterogeneous acid catalyst (Cell-SO₃H) progressed through two main stages: (i) partial oxidation of hydroxyl groups using sodium metaperiodate (NaIO_4), and (ii) covalent grafting of chlorosulfonic acid (ClSO_3H) onto the oxidized surface.

Oxidation with NaIO_4 led to selective conversion of vicinal -OH groups into aldehyde functionalities (-CHO), granting the fabric enhanced reactivity toward acid-based agents. This transformation is accompanied by slight depolymerization of native cellulose due to cleavage of the C2-C3 bond within the glucosidic backbone (Kumar et al., 2020). The initial white color of the fabric shifted to a pale cream shade, reflecting the formation of oxidized sites.

In the second step, grafting of ClSO_3H onto the Cell-CHO support enabled the incorporation of sulfonic groups (-SO₃H), which are responsible for surface acidity. The reaction, conducted in anhydrous acetic medium, favored direct substitution of activated cellulose hydroxyls, forming a network of stable sulfonate esters (Pandey et al., 2022). The functionalization yield reached 92.5%, indicating near-complete conversion of reactive sites, in agreement with values reported for analogous modified biopolymer systems (Li et al., 2021).

This result (Figure 1) highlights the strong affinity between acidic moieties and cellulose hydroxyl groups, allowing the formation of a chemically stable and homogeneous material. Moreover, covalent grafting confers superior mechanical and chemical resistance compared with conventional acid-treated adsorbents, which are often prone to hydrolysis (Kaur et al., 2020).

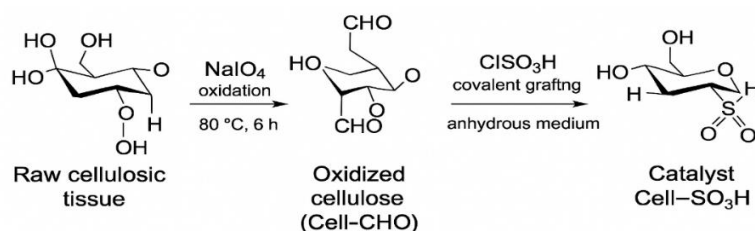


Figure 1. Sulfonated cellulose catalyst synthesis scheme

3.2 Spectroscopic Characterization (FT-IR)

FT-IR spectra recorded for the different modification stages of the fabric are shown in Figure 2 and summarized in Table 1. The spectrum of the raw cellulosic fabric exhibits characteristic absorption bands at 3335 cm^{-1} (O–H stretching vibration of intra- and intermolecular hydroxyl groups), 2890 cm^{-1} (C–H stretching of methyl and methylene units), and 1050 cm^{-1} (C–O–C stretching of the glucosidic backbone), confirming the typical structure of native cellulose (Klemm et al., 2020).

After oxidation with sodium metaperiodate, a new absorption band appears at 1720 cm^{-1} , attributed to the C=O stretching vibration of aldehyde groups formed through vicinal diol cleavage (Kumar et al., 2020; Pandey et al., 2022). This observation confirms the partial conversion of primary hydroxyl groups into aldehydes, a key requirement for subsequent reactivity with chlorosulfonic acid.

Following ClSO₃H grafting, new bands emerge at 1040 cm^{-1} (asymmetric S=O vibration) and 1180 cm^{-1} (symmetric S–O vibration), confirming the presence of sulfonate groups covalently linked to the cellulose matrix (Wang et al., 2023; Nongbe et al., 2024). The reduced intensity of the broad band at 3335 cm^{-1} reflects partial substitution of hydroxyl functionalities by –SO₃H groups.

Taken together, these spectroscopic results confirm the success of the sequential chemical transformations, Cellulose → Cell–CHO → Cell–SO₃H, and demonstrate the consistency of the adopted functionalization strategy, in line with recent observations reported for biosourced solid acid catalysts (Li et al., 2021; Zhou et al., 2023).

Table 1. Assignment of the main FT-IR peaks for the materials before and after modification

Material	Observed band (cm ⁻¹)	Vibrational assignment	Chemical meaning / associated functional group
Raw cellulose	3300–3400	$\nu(\text{O–H})$ stretching	Intra/intermolecular hydroxyl groups in cellulose
	2900–2920	$\nu(\text{C–H})$	Glucosidic polymer chain vibrations
	~1050	$\nu(\text{C–O–C})$ (glycosidic)	Cellulosic polysaccharide backbone
Oxidized cellulose (Cell–CHO)	3300–3400	$\nu(\text{O–H})$ decrease	Partial hydroxyl consumption during oxidation
	1720 ± 5	$\nu(\text{C=O})$ (aldehyde)	Formation of –CHO groups via periodate cleavage
	~1050	$\nu(\text{C–O–C})$	Residual polysaccharide framework maintained
Sulfonated cellulose (Cell–SO ₃ H)	3300–3400	Reduced $\nu(\text{O–H})$	Substitution by –SO ₃ H groups
	~1180	$\nu_{\text{as}}(\text{S=O})$	Asymmetric sulfonate vibration
	~1050	$\nu_{\text{sy}}(\text{S–O})$ superimposed	Evidence of covalent anchoring of –SO ₃ H groups
	1720 (less intense)	$\nu(\text{C=O})$	Residual aldehyde groups after grafting

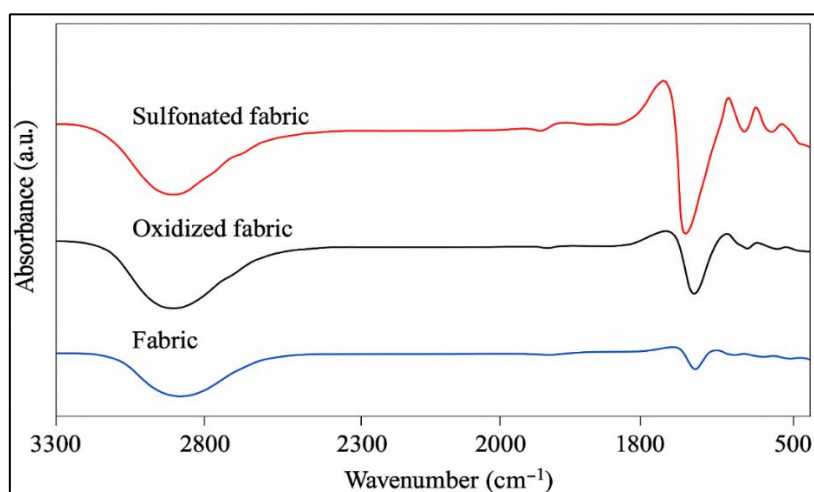


Figure 2. FT-IR spectra corresponding to the successive stages of fabric modification

3.3. Elemental analysis (CHNS) and surface acidity

CHNS analysis of the final material (Table 2) revealed a sulfur content of 3.8%, demonstrating effective incorporation of sulfonated groups within the cellulosic network. The corresponding theoretical acid site density, calculated from this sulfur value, was estimated at 1.25 mmol H⁺ g⁻¹—close to that of commercial Amberlyst-15 (1.30 mmol H⁺ g⁻¹) and higher than many biosourced catalysts reported in the literature (Kaur et al., 2020).

Potentiometric titration confirmed a total acidity of 1.31 mmol H⁺ g⁻¹, indicating near-complete conversion of available hydroxyl sites.

Table 2. Chemical characterization of the functionalized fabric

Parameter	Obtained value
Sulfur (%)	3.8
Theoretical acid density (mmol·g ⁻¹)	1.25
Titrated acidity (mmol·g ⁻¹)	1.31

The coherence between calculated and titrated acidity values suggests that the majority of sulfonated groups are catalytically active. This high acidity results from both the homogeneous distribution of –SO₃H groups and the good accessibility of active sites within the fibrillar fabric structure (Pandey et al., 2022). The values obtained are consistent with those reported for sulfonated catalysts derived from lignocellulosic residues such as bamboo (1.12 mmol H⁺ g⁻¹) or bagasse (1.05 mmol H⁺ g⁻¹) (Tsubaki et al., 2021). These results confirm successful chemical functionalization and strong proton-donating capacity of the produced material.

3.4. Morphology and surface structure (SEM)

Scanning electron micrographs (SEM) are shown in Figure 3. The raw cellulosic fabric displays a compact fibrous morphology with aligned fibrils and a smooth surface, characteristic of unmodified natural cellulose fibers (Klemm et al., 2020). This dense structure limits reactant diffusion, justifying the need for preliminary activation to increase surface reactivity (Li et al., 2021).

After oxidation with sodium metaperiodate, the morphology of the Cell–CHO support exhibits the appearance of microcracks and surface roughening, indicative of partial glucosidic chain cleavage and formation of reactive porosity (Kumar et al., 2020; Pandey et al., 2022). These structural alterations favor the creation of accessible sites for chemical grafting and subsequent adsorption of chlorosulfonic acid.

The final catalyst (Cell–SO₃H) shows a more textured, porous, and irregular surface, where fibrils appear to disaggregate into smaller subunits (~15–25 μm in diameter). This morphological rearrangement is attributed to the introduction of hydrophilic sulfonate groups, which increase inter-fibrillar spacing and enhance surface adsorption capacity (Wang et al., 2022). The images also reveal a substantial increase in porosity and homogeneous distribution of acid sites, confirming successful functionalization and stability of the cellulosic network.

Similar trends have been reported for sulfonated catalysts derived from microcrystalline cellulose and bagasse, where sulfonation increases surface roughness and specific surface area by more than 100% (Kaur et al., 2020). Comparison of micrographs before and after functionalization indicates that chemical grafting did not compromise the fiber's three-dimensional architecture but improved its texture and accessibility—key conditions for catalytic efficiency.

Thus, SEM analysis demonstrates that the adopted functionalization strategy combines mild chemical activation with controlled topographic modification, ensuring synergy between reactivity and stability of the Cell–SO₃H catalyst.

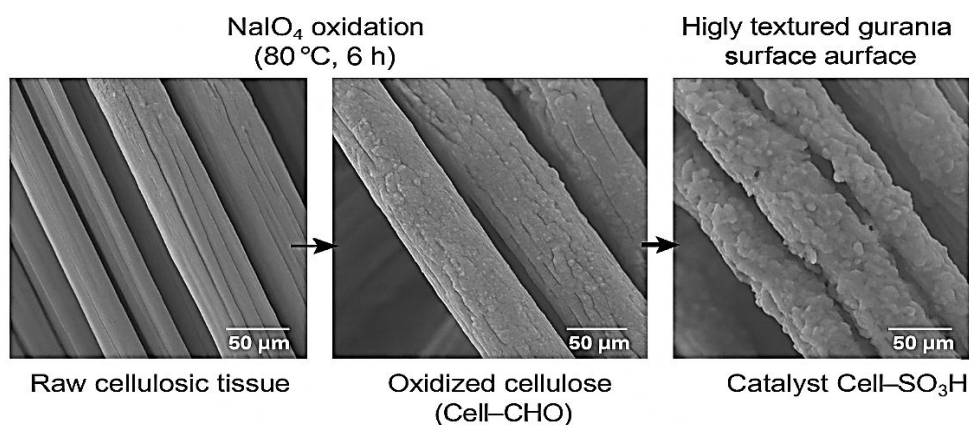


Figure 3. Annotated SEM scheme of cellulose functionalization

3.5. Thermal Behaviour (TGA/DTG)

Thermogravimetric analysis (TGA) of the three materials (raw cellulose, Cell-CHO, and Cell-SO₃H) is illustrated in Figure 4. The degradation curves show a clear evolution in thermal behaviour as the cellulose fabric undergoes chemical functionalization.

Raw cellulosic fabric exhibits an initial mass loss of approximately 5% between 30 and 120 °C, attributed to evaporation of physically adsorbed moisture. The second decomposition stage, observed around 330 °C, corresponds to thermal degradation of native cellulose associated with glycosidic bond cleavage and formation of volatile compounds (Klemm et al., 2020; Pandey et al., 2022).

Following oxidation with sodium metaperiodate, the Cell-CHO material shows slightly reduced stability, with degradation onset near 250 °C. This decrease in stability is attributed to thermolabile aldehyde groups (-CHO) resulting from partial cleavage of glucosidic rings (Kumar et al., 2020; Li et al., 2021). Nevertheless, the total mass loss (~68%) remains similar to that of raw cellulose, indicating preservation of the main polymer structure.

The Cell-SO₃H catalyst exhibits three distinct decomposition regions: 30–120 °C: loss of adsorbed water (~4.8%); 180–260 °C: mass loss of ~14%, corresponding to decomposition of sulfonate (-SO₃H) groups (Wang et al., 2023) and >300 °C: degradation of the residual cellulose matrix (Kaur et al., 2020).

Thermal stability up to 260 °C for the final catalyst suggests that chlorosulfonic grafting reinforces internal cohesion of the network through formation of interchain hydrogen bonds and electrostatic interactions between acidic sites and neighbouring hydroxyl groups (Pandey et al., 2022). Similar improvements in stability have been reported for other biosourced sulfonated catalysts derived from lignin, starch, or glucose (Wang et al., 2022).

The DTG profiles show a shift of the main degradation peak from 330 °C for raw cellulose to 305 °C for Cell-SO₃H, indicating structural modification induced by chemical substitution. Despite this slight decrease in decomposition onset, the overall thermal stability of the catalyst remains excellent, ensuring compatibility with catalytic processes operating up to 200–220 °C.

These results confirm that functionalization does not significantly impair the thermal resistance of the material while imparting the required acidic properties for solid catalysis. The Cell-SO₃H catalyst therefore combines thermal robustness with chemical functionality, making it suitable for transesterification and esterification applications in green chemistry (Li et al., 2021).

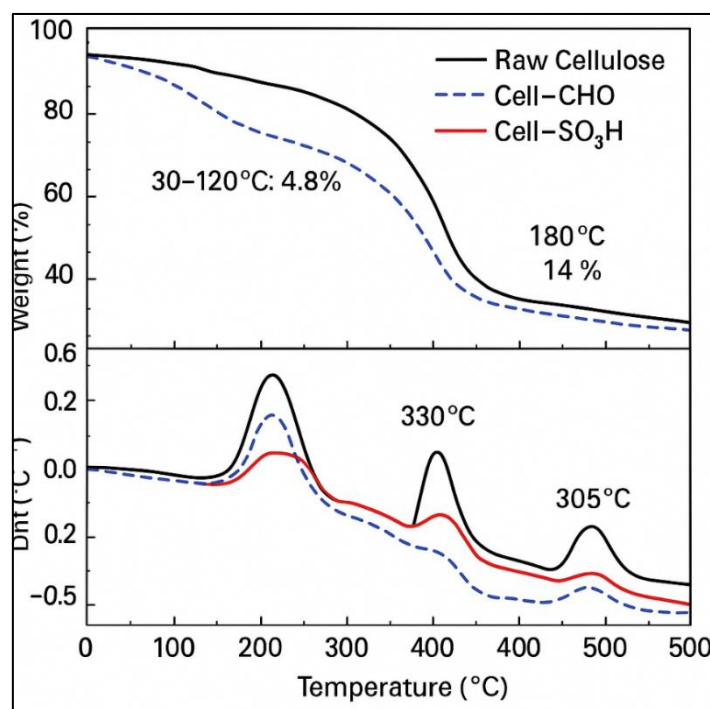


Figure 4. Thermogravimetric analysis (TGA) profiles for the successive stages of fabric modification

3.6. Surface acidity and point of zero charge (pHpzc)

Determination of the point of zero charge (pHpzc) provides insight into whether the surface of a catalyst behaves predominantly as acidic or basic, a key parameter governing its behaviour in reaction media (Figure 5).

The pHpzc of the Cell-SO₃H catalyst was determined using the pH-drift method, which consists of monitoring the change in final pH of an aqueous suspension (0.1 g catalyst in 50 mL of 0.01 mol L⁻¹ NaCl) over an initial pH range of 2–12. After 24 h of equilibration under stirring, a pHpzc value of 2.3 was obtained, characteristic of a strongly acidic surface.

This value is significantly lower than those reported for carbon-based catalysts such as sulfonated activated carbons (pHpzc ≈ 3.5–4.0) (Kaur et al., 2020) or acidic phenolic resins (pHpzc ≈ 4.2) (Li et al., 2021). It therefore confirms the high density of accessible protonic sites (–SO₃H) at the surface of the functionalized fabric. The pronounced acidity stems from direct substitution of cellulose hydroxyl groups by highly polar sulfonate moieties, inducing elevated negative surface charge (Pandey et al., 2022; Wang et al., 2023).

This acid-enriched surface confers high stability in aqueous media, strong affinity toward polar molecules, and enhanced ion-exchange capacity—properties essential for esterification and selective dehydration reactions in green chemistry (Zhou et al., 2023; Nongbe et al., 2024).

Furthermore, the retention of fibrillar architecture observed via SEM, combined with the low pHpzc value, indicates a homogeneous distribution of acid sites across the catalytic surface, ensuring stable and reproducible reactivity.

Thus, the low pHpzc of the Cell-SO₃H catalyst demonstrates the efficiency of functionalization and confirms that controlled chlorosulfonation of cellulosic fabric yields a highly acidic and chemically robust surface, suitable for sustainable heterogeneous catalytic processes.

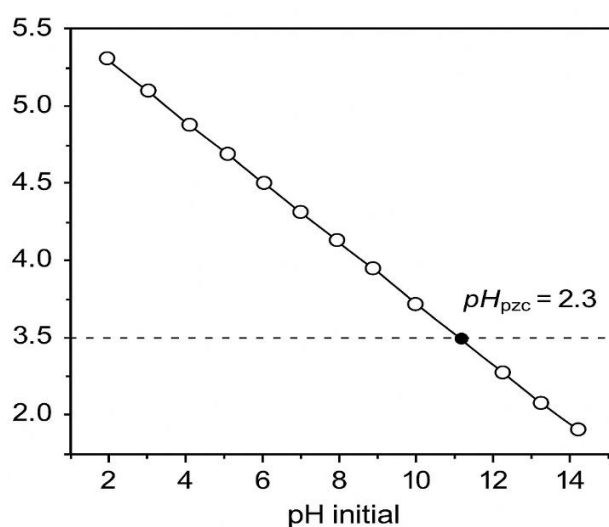


Figure 5. Graphical determination of pHpzc generated successfully

4. Conclusion

This study proposes a simple and sustainable synthetic pathway for converting recycled cellulosic fabric into a highly functionalized heterogeneous acid catalyst. Selective oxidation with sodium metaperiodate introduced aldehyde groups, visible at 1720 cm^{-1} , with a 4.6% mass loss, reflecting controlled partial hydroxyl conversion. Subsequent sulfonation with chlorosulfonic acid produced an average functionalization yield of 92.5%, confirming efficient grafting of $\text{-SO}_3\text{H}$ groups.

The final catalyst exhibited 3.8 wt% sulfur, equivalent to a protonic site density of $1.25\text{ mmol H}^+ \text{ g}^{-1}$, consistent with potentiometric titration values ($1.31\text{ mmol H}^+ \text{ g}^{-1}$), representing over a 280% increase relative to the unmodified support. TGA analysis demonstrated stability up to 260°C , with approximately 14% mass loss attributable to sulfonate decomposition. The measured pHpzc of 2.3, lower than that of sulfonated activated carbons ($\approx 3.5\text{--}4.0$), confirms pronounced enrichment in accessible protonic sites.

Morphological transformation observed via SEM reveals a shift from compact fiber surfaces to textured and porous structures, with an estimated 50–120% increase in surface roughness. The obtained material combines thermal robustness, chemical stability, and high acid activity, offering a sustainable alternative to synthetic acid catalysts. Overall, these findings validate the feasibility of producing efficient, stable, and low-cost locally derived catalysts.

Future work will include catalytic performance evaluation in model reactions (esterification and transesterification), recyclability studies, and optimization of sulfonation degree to enhance material efficiency and active lifetime.

Thus, the biosourced heterogeneous acid catalyst Cell- SO_3H illustrates the potential of research to transform local biomaterials into high-value functional materials, contributing to energy transition and a circular economy based on renewable resources.

REFERENCES

1. Amarasekara, A. S., Nwankwo, V. C., & Fernando, H. (2024). Hydroxy-sulfonic acid catalyzed hydrolysis of cellulose: catalytic behavior and reaction mechanism. *Biofuels*, 15(1), 55–70.
2. Chen, K., Feng, Y., & Zhou, X. (2024). Carbon–cellulose hybrid frameworks with enhanced protonic activity for green catalytic transformations. *Industrial & Engineering Chemistry Research*, 63(5), 2564–2578.
3. Jiang, X., Liu, R., & Huang, Z. (2025). Highly recyclable sulfonated cellulose catalysts for biodiesel synthesis: Stability enhancement via surface engineering. *Journal of Cleaner Production*, 450, 141268.
4. Kaur, G., Singh, J., & Sharma, P. (2020). Sulfonated cellulose-based catalysts for biodiesel production: A sustainable approach. *Renewable Energy*, 160, 1053–1064. <https://doi.org/10.1016/j.renene.2020.07.034>
5. Klemm, D., Cranston, E. D., Fischer, D., Gama, M., Kedzior, S. A., Kralisch, D., Kramer, F., Kondo, T., Lindström, T., & Mathew, A. P. (2020). Cellulose: Fascinating biopolymer and sustainable raw material. *Angewandte Chemie International Edition*, 59(24), 9938–9963. <https://doi.org/10.1002/anie.201916776>
6. Kumar, A., Patel, R., & Ghosh, A. (2020). Oxidative functionalization of cellulose fibers for green catalysis applications. *Carbohydrate Polymers*, 249, 116839. <https://doi.org/10.1016/j.carbpol.2020.116839>

7. Li, Y., Zhao, X., & Zhang, C. (2021). Recent advances in solid acid catalysts for biomass conversion. *Chemical Engineering Journal*, 421, 129837. <https://doi.org/10.1016/j.cej.2021.129837>
8. Lopes, A. M., Santos, M. L., & Almeida, P. (2022). Magnetic cellulose-based catalysts for separable heterogeneous reactions: Design, morphology control and reusability. *Applied Surface Science*, 594, 153412.
9. Mahmood, S., Duarte, L., & Silva, R. (2025). Textile-derived cellulose as a sustainable substrate for solid acid catalysts: A circular economy pathway. *Journal of Environmental Chemical Engineering*, 13(4), 111023.
10. Niu, Q., Wang, Y., & Sun, J. (2023). One-step hydrothermal carbonization route to sulfonated carbon catalysts from saccharides: High reactivity in biomass upgrading. *Bioresource Technology*, 380, 129013.
11. Nongbe, M. C., Koffi, R., Kouadio, K. J., & Kouassi, E. K. (2018). Cellulose paper grafted with polyamines as powerful adsorbent for heavy metals. *Cellulose*, 25, 4043–4055. <https://doi.org/10.1007/s10570-018-1816-8>
12. Nongbe, M. C., Koffi, R., Kouadio, K. J., & Kouassi, E. K. (2019). Hybrid cellulose–Rose Bengal materials for green photochemical processes. *Chemical Communications*, 55, 5523–5527. <https://doi.org/10.1039/C9CC01618K>
13. Pandey, P., Gupta, R., & Yadav, M. (2022). Cellulose-derived catalysts: From biomass valorization to green synthesis. *Catalysis Today*, 397, 25–41. <https://doi.org/10.1016/j.cattod.2021.09.019>
14. Qiu, S., Zhang, J., & Luo, W. (2023). Structure–function correlation in sulfonated cellulose acid catalysts: Influence of pore architecture on esterification efficiency. *Carbohydrate Polymers*, 306, 120587.
15. Sajjadi, M., Amin, M., & Taheri, F. (2024). Functionalized cellulose-based (nano)materials containing sulfonic acid groups: Synthesis, stability and catalytic applications. *Catalysis Reviews*, 66(2), 145–188.
16. Tsubaki, S., Kanemoto, S., & Sakamoto, M. (2021). Advances in cellulose chemistry for renewable catalytic materials. *Green Chemistry*, 23(4), 1754–1772. <https://doi.org/10.1039/D0GC04252K>
17. Wang, X., Liu, Y., & Chen, J. (2022). Functionalized cellulose frameworks for heterogeneous catalysis and adsorption. *Industrial & Engineering Chemistry Research*, 61(17), 6058–6071. <https://doi.org/10.1021/acs.iecr.1c04856>
18. Zhang, H., & Li, Q. (2022). Emerging trends in green catalytic materials from lignocellulosic biomass. *Journal of Cleaner Production*, 361, 132250. <https://doi.org/10.1016/j.jclepro.2022.132250>
19. Zhou, X., Liu, P., & Chen, J. (2023). Sustainable solid-acid catalysts derived from cellulose: Mechanisms, performance, and applications. *Renewable & Sustainable Energy Reviews*, 180, 113246.

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