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Cellulose nanocrystals from forest residues: An integrated techno-economic analysis and life cycle assessment

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ABSTRACT

Cellulose nanocrystals (CNCs) are renewable, high-value nanomaterials with broad industrial applications. Based on laboratory-scale experimental data, this study demonstrates the feasibility of utilizing sugar maple forest residues for 10 metric tons per day (MTPD) production of CNC through an integrated techno-economic analysis (TEA) and life cycle assessment (LCA). The minimum selling price (MSP) of CNC was estimated at \$16.03/kg, with a global warming (GW) impact of 28.60 kg CO_2 eq/kg CNC. Sensitivity analysis identified CNC yield and pretreatment solids loading as key drivers for the economic and environmental performance of the process. Monte Carlo simulations yielded 90% MSP confidence interval of \$13.33–19.23/kg, while key impact categories including GW, marine eutrophication, smog formation, and ozone depletion showed low variability, indicating model robustness. The environmental risk assessment revealed that forest residues offer a sustainable valorization pathway with the process accompanied by risks tied to chemical usage and waste management.

1. Introduction

The increasing global demand for sustainable materials has intensified the search for alternatives to conventional resources, particularly those derived from fossil fuels, which are associated with significant environmental consequences. Among the emerging candidates, bio-based nanomaterials have garnered considerable attention due to their potential to offer environmentally benign solutions across a wide range of applications. Cellulose nanocrystals (CNCs), derived from cellulose – the most abundant natural polymer on Earth – represent a particularly promising class of such materials (Heinze, 2015). The growth in agricultural and forestry practices has significantly increased biomass residues (Anwar et al., 2021; Langholtz et al., 2024), presenting opportunities for their utilization as valuable raw materials. If these residues are not properly managed, they can lead to resource loss and environmental issues. For example, accumulated dry biomass can serve as highly combustible fuel, increasing both the likelihood and intensity of wildfires, which in turn can lead to further ecological degradation and resource depletion. Nevertheless, transforming these residues into value-added products such as CNCs can enhance resource efficiency and mitigate environmental impacts (Liu et al., 2023; Moriana et al., 2016; Yu et al., 2024). Forest residues represent a significant economic and environmental opportunity in the United States. In the western U.S. alone, approximately 210 million dry tons of small-diameter wood and harvest residues are available, with an estimated value of \$5.97 billion (Davis et al., 2024; Page-Dumroese et al., 2022). Utilizing forest residues to produce CNCs offers dual benefit: reducing the accumulation of combustible biomass in North American forests, thereby mitigating wildfire risks, and contributing to the circular bioeconomy through the creation of high-value materials.

CNCs are rod-like nanomaterials derived from plant cellulose, characterized by their high crystallinity and at least one dimension within the 1–100 nm range (Habibi, 2014; Moon et al., 2016). CNCs are typically produced through acid hydrolysis, wherein strong mineral acids such as sulfuric, hydrochloric, or phosphoric acid are utilized to selectively dissolve the amorphous regions of cellulose fibers, leaving behind the more crystalline CNCs. Sulfuric acid is often preferred due to its high efficiency in hydrolysis and its ability to introduce negatively charged

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sulfate groups on the surface of CNCs, which enhances their dispersibility in water (Gao et al., 2022; Gu et al., 2013). While sulfuric acid hydrolysis is commonly used, alternative methods using organic acids or combined approaches have been investigated (Bondancia et al., 2022; Hoo et al., 2024; Zhang et al., 2025).

Reported examples of CNC production from low cellulose containing forest materials include the use of sulfuric acid hydrolysis on *Paulownia tomentosa* (empress tree) sawdust, yielding 7.62-8.34% of rod-shaped crystals with high crystallinity (Welter et al., 2024). Softwood logging residues have also been successfully used to extract CNCs with yields exceeding 13%, exhibiting high aspect ratios and increased crystallinity (Moriana et al., 2016). Acid hydrolysis of beech and cedar sawdust resulted in CNCs with varying lengths and crystallinities depending on the sawdust type (El Hajam et al., 2022). *Triplochiton scleroxylon* (ayous) sawdust yielded 37.84 $\pm$ 0.99% of isolated nanocrystals through sulfuric acid hydrolysis (Alifa et al., 2024). Spruce bark treated with sulfuric acid produced rod-shaped CNCs with high crystallinity and good thermal stability, achieving a yield of 39.78% (Le Normand et al., 2014). Apricot pomace (bark) yielded needle-shaped CNCs of nanometric size with a 34.56% yield via sulfuric acid hydrolysis (Dinçel Kasapoğlu et al., 2023). Kumar et al. reported a yield of 8-25% for CNC produced from spruce wood pulp using sulfuric acid hydrolysis and optimization of process parameters (Kumar et al., 2022).

By effectively valorizing waste biomass, promoting enhanced resource efficiency, and minimizing the overall environmental impact associated with material production and consumption (Dalbanjan et al., 2024; Lazaridou et al., 2021; Mair and Stern, 2017), the production of CNCs from forest residues represents a promising pathway towards the development of sustainable, high-performance nanomaterials with a wide array of applications across diverse sectors. Prior studies have demonstrated the viability of CNC production from high-cellulose feedstocks such as eucalyptus pulp and dissolving wood pulp (Bondancia et al., 2020; de Assis et al., 2017; Rajendran et al., 2023; Rosales-Calderon et al., 2021; Yang et al., 2019). However, there are no integrated assessments for underutilized forest residues with low cellulose content, which are more abundant but technically more challenging to process. Consequently, the economic and environmental trade-offs of using these abundant residues remain unquantified. To the best of our knowledge, this is the first study that reports a comprehensive TEA and LCA for the production of CNCs from forest residues. This study addresses this research gap by integrating laboratory-scale experimental data for low-cellulose containing forest residues into industrial-scale TEA and LCA with environmental risk assessment. This combined approach provides critical insights and enables the rapid identification of key economic and environmental hotspots associated with upgrading lower-quality biomass feedstocks such as forest residues for CNC production.

2. Methods

2.1. Process modeling for industrial-scale production of CNC

An industrial-scale process for producing CNCs from forest residues was developed based on laboratory-scale experimental data for CNC yields, including mass balances and process operating conditions, provided by researchers at the SUNY College of Environmental Science and Forestry (SUNY ESF), USA (Hossain et al., 2026).

The lab-scale experimental data was scaled up to industrial production by accounting for typical industry scaling factors and equipment efficiencies and a comprehensive steady state simulation model was developed in SuperPro Designer v12 to simulate the industrial scale process. The developed process simulation model facilitated detailed material and energy balance assessments and provided the inventory data for carrying out thorough techno-economic analysis (TEA) and life cycle assessment (LCA). In addition, sensitivity and uncertainty analyses were conducted to quantify the variability in these scale-up assumptions, thereby providing robust insights into the process's viability. Heat integration was carried out using the virtual energy recovery feature in SuperPro Designer, which enabled the utilization of residual heat from process streams for both heating and cooling purposes, thereby reducing the overall energy demand of the system. Details regarding equipment sizing, costing, scaling factors, and material selection, are provided in the Supplementary Information (SI). A simplified process flow diagram for the conceptualized process is shown in Fig. 1. In the base case scenario, the plant was designed with an annual production capacity of 10 metric tons per day (MTPD) of CNC, operating for 7884 hours per year. The mass flow diagram for the process is shown in **Fig. S1**.

2.1.1. Process Description

Sugar maple forest residues were utilized as the feedstock to produce CNC, with North America as the selected geographic location. Based on the experimental studies carried out by Hossain et al., the composition of the feedstock was modelled as follows: 39.98 wt.% cellulose; 17.5 wt.% hemicellulose; 21.17 wt.% lignin; 0.95 wt.% ash; 5.44 wt.% extractives, 10.06 wt.% other solids, and 4.91 wt.% moisture (Hossain et al., 2026). For the base case scenario, the feedstock cost was considered as $48.83/ODMT, which includes the cost of aggregating forest residues at a centralized location (28.3%), initial size reduction (40.3%), and transportation (31.4%) (Bisson et al., 2016). The impact of feedstock cost on process economics was further explored by carrying out a sensitivity analysis.

The process begins with mechanical size reduction of forest residues to 2 mm particles. A mild hydrothermal pretreatment at 100 °C for 20 minutes facilitates the removal of extractives and inorganic components. The solid fraction is separated via belt filtration and subjected to alkaline pretreatment using 1 M NaOH at 80 °C for 2 hours, enhancing lignin accessibility by disrupting biomass structure. Subsequently, bleaching with 2.5% $NaClO_2$ at 100 °C for 1 hour under acidic conditions removes lignin, yielding a cellulose-rich solid. Each pretreatment step includes filtration and washing, with 5 wt.% solids maintained throughout. Wash waters are treated using nanofiltration (Arkell et al., 2013) and electrodialysis (Song et al., 2021; Tian et al., 2024; Yan et al., 2015) to recover and recycle NaOH and $NaClO_2$. The nanofiltration step was modeled using reported component-specific retentions, with 99.5% and 99.9% retention of lignin and sugars, respectively, and 30% retention of NaOH (Arkell et al., 2013).

Following pre-treatment, the isolated cellulose undergoes acid hydrolysis with 55 wt.% H_2SO_4 at 50 °C for 45 minutes, selectively cleaving amorphous regions to produce CNCs at a 32.5% yield. Post acid hydrolysis, the mixture is diluted with water and centrifuged to separate the CNC suspension from dissolved sugars and sulfuric acid. The supernatant is processed using ultrafiltration (UF) and nanofiltration (NF) to remove sugars, with the retentate sent for neutralization. The permeate, containing dilute H_2SO_4, is concentrated to 55 wt.% in a five-effect multi-effect evaporator and recycled back to the acid hydrolysis reactor for reuse. This internal acid recycling loop reduces fresh acid consumption and improves the process viability. The retentate from UF and NF is neutralized with NaOH to produce 99.95 wt.% sodium sulfate as a co-product, recovered through crystallization, rotary vacuum filtration, and drying. Filtrates from diafiltration and ultrafiltration units are combined and processed by reverse osmosis for water recovery. CNCs are purified via diafiltration and ultrafiltration, concentrated to 8 wt.% (de Assis et al., 2017), and spray-dried to obtain 99.9 wt.% CNC powder.

2.2. Techno-economic analysis

A TEA was carried out to evaluate the economic viability of CNC production from forest residues by employing a discounted cash flow (DCF) analysis framework based on established n^{th}-plant assumptions and following the methodology detailed in the National Renewable Energy Laboratory (NREL) design report (Humbird et al., 2011). The

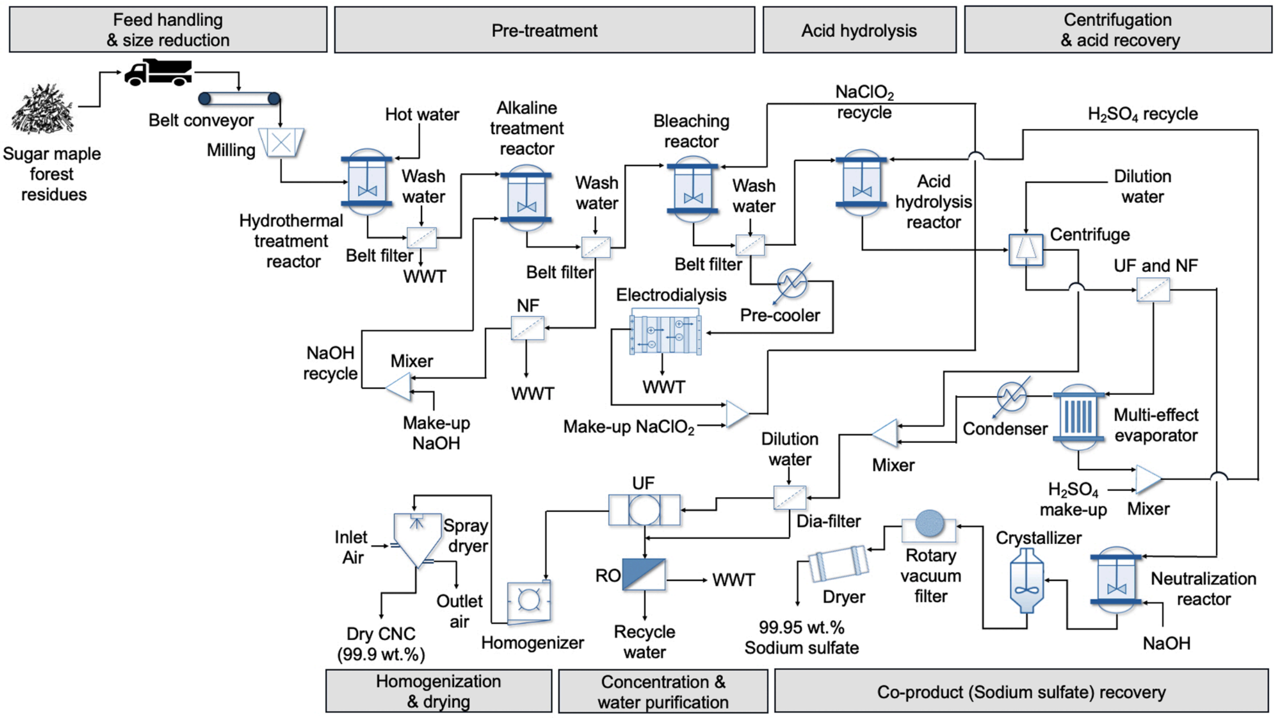

Fig. 1. Simplified process flow diagram to produce cellulose nanocrystals from sugar maple forest residues. Wastewater treatment abbreviated as WWT.

nth-plant economics assumes a mature stage of technology deployment, where multiple facilities employing the same technology are already constructed and operational, rather than describing a pioneer plant (Humbird et al., 2011). The TEA involved estimation of total capital investment and annual operating costs, derived from mass and energy balances obtained through detailed process modeling. For more details regarding the estimation of the total capital investment, annual operating cost and labor costs, refer to the SI.

2.2.1. Minimum selling price, sensitivity and uncertainty analysis

For the assumed financial parameters (as shown in **Table S1**), the selling price of the product is iterated until the net present value (NPV) of the plant is zero, thereby yielding the minimum selling price (MSP) of the CNC product. Univariate sensitivity analysis was performed to quantify the impact of key technical and economic parameters on the process. To assess the robustness of the estimated MSP, a Monte Carlo simulation–based uncertainty analysis (10,000 iterations) was performed. The economic parameters, along with their associated probability distributions and corresponding minimum, maximum, and most likely values, are summarized in **Table S8**. The parameter bounds were consistent with those used in the univariate sensitivity analysis. The analysis produced a probability distribution, from which the 90% confidence interval (defined as the 5th and 95th percentiles) was derived. This interval represents the expected range of minimum and maximum MSP values under realistic conditions.

2.3. Life-cycle assessment

2.3.1. Goal and Scope

The goal of this study was to conduct a cradle-to-gate LCA to quantify the environmental impacts of CNC production from forest residues in compliance with the ISO 14040 and 14044 standards. The use and end-of-life phases of the CNC product were not included in this study. For this study, 1 kg of dry powder CNC produced from forest residues is defined as the functional unit for the environmental impact analysis. **Fig. S2** shows the system boundary for the cradle-to-gate LCA analysis performed in this study.

2.3.2. Life cycle inventory

A cradle-to-gate life cycle assessment (LCA) was performed using SimaPro 10.2 software, with background data sourced from DATASMART and ecoinvent v3.11 databases (LTS, 2025; Wernet et al., 2016). Foreground data, encompassing material inputs and energy utilization, were compiled from the process mass & energy balances, peer-reviewed publications and industry reports (**Table S11**). Data concerning forest residues, including harvesting, collection, and transportation, were sourced from existing literature (Oneil et al., 2017; Sahoo et al., 2021, 2019) and utilized to estimate the life cycle inventory (LCI) associated with fuel consumption and transportation needs during forest residue harvesting (**Table S10**). The inventory for cooling water (**Table S12**) was adapted from NREL's Materials Flows through Industry (MFI) modeling tool that tracks the material, and energy demands and associated greenhouse gas emissions from manufacturing supply chains (Hanes and Carpenter, 2017). In addition, the LCA study adopted the “avoided product” and “system expansion and substitution” approach for allocation of environmental impacts following the ISO 14044 recommendations, thereby ensuring a thorough and comprehensive evaluation of the environmental implications across the lifecycle of the process.

2.4.3. Impact assessment, sensitivity and uncertainty analysis

Life cycle impact assessment (LCIA) categories were quantified using the TRACI 2.2 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) methodology (Bare, 2011) and focused discussion on the following 10 impact categories: Ozone depletion (kg CFC-11 eq), global warming (kg CO_2 eq), smog formation (kg O_3 eq), acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), marine eutrophication (kg N eq), carcinogenics (CTUh), non-carcinogenics (CTUh), respiratory effects (kg $PM_{2.5}$ eq) and ecotoxicity (CTUe).

Univariate sensitivity analysis was performed to study the impact of key technical parameters (CNC yield, pretreatment solids loading, plant capacity, steam consumption, co-product production, NaOH consumption and $NaClO_2$ consumption) on the evaluated LCI categories. Furthermore, the uncertainties in the impact categories were quantified via Monte Carlo simulation-based uncertainty analysis using SimaPro

10.2 software.

3. Results and Discussions

3.1. Economic and environmental impact assessment

3.1.1. Techno-economic analysis

The total capital investment for a plant designed to produce 10 MTPD of CNC (dry basis) from forest residues is estimated at $225.7 MM with a total installed cost of $117.7 MM. A breakdown of installed capital (Fig. 2) reveals that the highest contribution to the total installed capital cost is from the acid recovery process area at 23.2% ($27.3 MM). This is primarily due to the inclusion of membrane filtration and multi-effect evaporation systems. The pre-treatment process area accounts for 18.8% ($22.2 MM) of the total installed cost, arising from high-cost pre-treatment reactors and belt filters, required for effective solid–liquid separation and isolation of cellulose from hemicellulose and lignin fractions prior to acid hydrolysis. The outside battery limits (OSBL) accounts for 20% of the total installed cost and includes piping, instrumentation, and other infrastructure required to connect over-the-fence utilities to the plant. The co-product (sodium sulfate) recovery and centrifugation process areas account for 11.3% and 8.1% of installed costs, respectively. The installed cost contributions from the other process areas include concentration and water purification (7.5%), homogenization & drying (4.2%), acid hydrolysis (3.7%), and feed handling & size reduction (3.2%). Detailed capital cost breakdowns for specific unit operations and process sections on a 2023 cost basis are provided in **Table S2**.

In addition to the capital costs, the plant incurs annual operating costs of $24.10 MM. As shown in Fig. 3, the annual operating costs are dominated by the cost of raw materials, mainly driven by the high NaOH requirements for maintaining a solid loading of 5 wt.% in the alkaline pre-treatment reactor. The potential for operating expenses (OPEX) reduction through the implementation of higher solids loading (10 wt. %) in the pre-treatment step was further investigated in the sensitivity analysis. Process utilities, predominantly steam consumption in the pretreatment and acid recovery process areas, represent the next major OPEX component. It is important to note that the cost contributions for these chemicals & utilities are partially offset by the recovery of sodium sulfate, which generates additional revenue for the process when sold as a co-product. Further details of the annual operating costs are described in **Table S3**.

The base case scenario considers acid hydrolysis of sugar maple forest residues to yield CNC as the primary product and sodium sulfate as a co-product. Including revenue generated from the sale of the co-product, CNC achieves an MSP of $16.03/kg with the two largest contributions coming from the capital charge (54% of overall MSP) and raw materials (33% of overall MSP), shown in yellow and red, respectively in the simplified MSP breakdown chart (Fig. 3). The detailed MSP breakdown with combined capital and operating cost contributions from each process area is shown in **Table S4**. As a point of reference, Lan et al. applied nth-plant assumptions and reported MSPs for CNCs produced from dissolving wood pulp via acid hydrolysis. Without acid recovery, the reported MSPs ranged from $7.90 to $7.30/kg, while incorporating acid recovery reduced the MSPs further to between $5.40 and $4.00/kg, based on production capacities ranging from 25 to 100 MTPD, respectively (Lan et al., 2024).

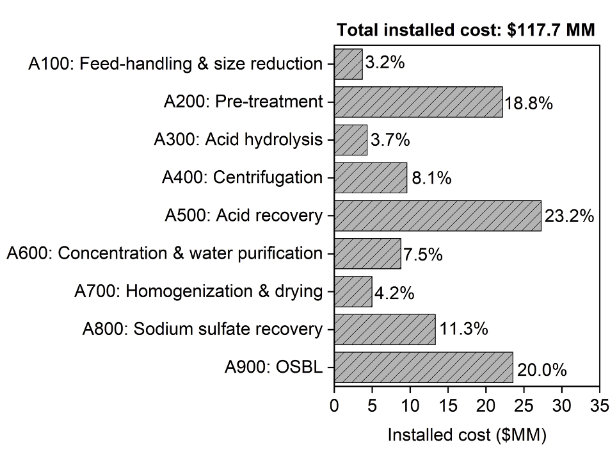

Fig. 2. Installed capital cost breakdown for production of CNC from forest residues. For detailed breakdown, refer to Table S2 in SI. Outside battery limits abbreviated as OSBL.

3.1.2. Life cycle assessment

The LCA results, evaluated using the TRACI 2.2 methodology, are presented in Appendix Table A1. For the base case scenario, the GW impact of the process is estimated at 28.60 kg CO_2-eq per kilogram of dry powder CNC produced. As seen in Fig. 4**A**, most of the environmental impacts are driven by a few key inputs. NaOH emerges as the dominant contributor, responsible for 17.0% to 81.9% of the total impacts across the evaluated categories. Other main contributors include sulfuric acid (0.8%–55.4%), steam (1.0%–51.0%), and $NaClO_2$ (4.4%–32.7%). Additional but comparatively smaller contributions originate from wastewater treatment (0.1%–22.0%), process water (0.9%–11.3%), electricity (0.02%–0.9%), and cooling water (0.01%-0.1%).

Furthermore, three cradle to gate LCA scenarios were considered to compare the environmental impacts of CNC production (Fig. 4**B**). In Case A, CNCs are produced from forest residues using fossil-derived steam for process heating. Case B examines CNC production from dissolving wood pulp by incorporating the recovery of sulfuric acid (H_2SO_4) within the process (Lan et al., 2024). Case C is identical to Case A but considers a future decarbonization scenario in which renewable natural gas (RNG) is used for steam generation in place of fossil-derived steam to supply the required process heat. Across all three cases, downstream processing comprising acid hydrolysis, acid recovery, neutralization, and purification, remains largely consistent; thus, environmental performance differences are driven primarily by upstream feedstock treatment and energy inputs. Case A, the base scenario using fossil-derived steam for process heat, shows the highest impacts in global warming, fossil fuel depletion, acidification, smog formation, and eutrophication. These are driven primarily by the energy-intensive pretreatment steps required to process low-purity forest residues. In contrast, Case B avoids pre-treatment altogether due to its high-purity cellulose feedstock, resulting in lower energy & chemicals demand and therefore lower climate-related impacts. Replacing fossil-derived steam with RNG generated steam in Case C drastically reduces the carbon intensity of pretreatment, lowering fossil fuel depletion, global warming, respiratory effects, and smog-related impacts by 75%, 61%, 28%, and 31%, respectively compared to Case A. Although using RNG for steam generation reduces climate impacts, its supply chain introduces more emissions to land and water in comparison to fossil-derived steam, thereby resulting in slightly elevated ozone depletion, ecotoxicity, carcinogenic and non-carcinogenic impacts. This comparative analysis highlights clear trade-offs between feedstock purity (in terms of cellulose content) and energy sources. For forest-residue routes (Cases A and C), decarbonizing process heat and optimizing pretreatment chemistry are critical for impact mitigation. These insights can guide the development of more sustainable nanocellulose production systems across a diverse range of biomass feedstocks.

3.1.3. Sensitivity analysis

Key economic and environmental hotspots were identified using sensitivity tornado plots (Fig. 5**A** and 5**B**), along with detailed breakdown of MSP and environmental impacts by process-level contributors (**Table S4** and **S13**). These results highlight key technical and economic parameters that have the largest contribution to costs and

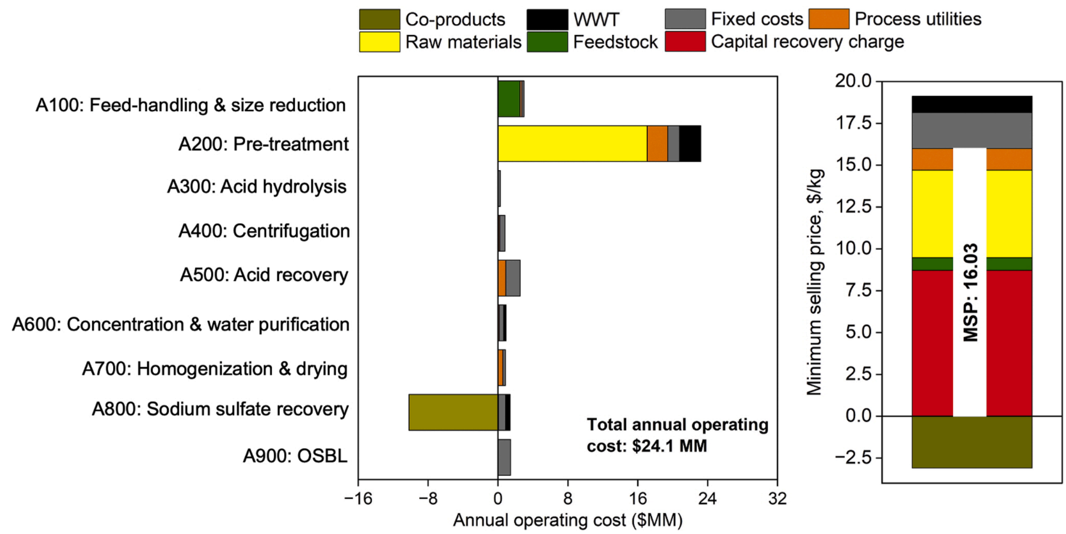

Fig. 3. Operating expense and minimum selling price breakdown. For detailed breakdown, refer to Tables S3 and S4 in SI. Wastewater treatment abbreviated as WWT.

environmental impacts, providing clear targets for process optimization. The sensitivity analysis results in Fig. 5**A** and Fig. 5**B** show the impact of key process and economic parameters on both the MSP and the GW impact of CNCs produced from forest residues. For the base case scenario, the MSP and GW impact are estimated at \$16.03/kg and at 28.60 kg CO_2-equivalent per kg of CNC produced, respectively. Among the process parameters analyzed, CNC yield had a big influence on both metrics. When the CNC yield during acid hydrolysis is reduced to 20%, the MSP increases by 47% (\$23.59/kg), while a higher CNC yield of 50% decreases the MSP by 26% (\$11.92/kg). For GW impact, a lower yield increases emissions by 48% (42.44 kg CO_2-eq/kg), while a higher yield reduces it by 26% (21.12 kg CO_2-eq/kg). This strong sensitivity highlights the critical role of maximizing CNC yield during acid hydrolysis for both cost and environmental performance.

Economic parameters also have a substantial impact on the MSP. The discount rate varied between 5% and 15% changes the MSP by ±19%, while FCI, ranging from \$150.3 MM to \$279.1 MM, results in a ±17% change. OPEX varied between \$16.9 to \$31.3 MM annually similarly impacts the MSP by ±14%. These findings indicate that strategic financial planning, cost control, and operational efficiency are central to economic viability. A reduction in the CNC production capacity from 10 to 5 MTPD increases the MSP by 20% (\$19.20/kg), while doubling capacity to 20 MTPD decreases the MSP by 10% (\$14.47/kg). This reflects the benefit of economies of scale, which are particularly important in capital-intensive biorefineries.

The pretreatment solids content of 5 wt.% reflects conditions used in the underlying laboratory-scale experiments (Hossain et al., 2026). This baseline was used for the industrial-scale TEA and LCA to ensure that simulations are grounded in validated experimental data. Higher solids contents (10 wt.%) during pretreatment was explored in sensitivity analyses to evaluate potential improvements in cost and environmental performance. Increasing the pretreatment solids loading to 10 wt. %, reduces the MSP and GW impact by 15% and 29%, respectively. The higher solids loading decreases the overall volumes of slurry and reduces the make-up solvent requirements in the pretreatment reactors, which in turn reduces material and energy inputs, improves process economics, and lowers the overall carbon footprint.

Fig. 5**C** demonstrates that, within an n^{th}-plant techno-economic analysis framework, reducing plant lifetime from the base case scenario of 30 years to 10 years increases the MSP of CNC by nearly 27% from \$16.03/kg to \$20.34/kg. While shorter lifetimes could be beneficial in initial or pioneer plants to realize faster capital recovery, the n^{th}-plant scenario emphasizes cost reductions achievable through long-term operations, as fixed-capital investments are amortized over a longer period, improving overall economic viability.

For comparison, an additional scenario was considered, wherein the final CNC product is obtained as an 8 wt.% aqueous suspension, and the drying step is excluded. In this case, the MSP and the GW impact of the dry CNC product decreases by 3.7% (\$15.44/kg) and 10.7% (25.54 kg CO_2-eq/kg), respectively, compared to the baseline case involving the drying step. This reduction can be attributed to the energy demand of spray drying, which contributes to both operating costs and environmental burdens.

3.1.4. Cumulative energy demand (CED)

The cumulative energy demand (CED) for production of 1 kg of CNC from forest residues is estimated as 446.83 MJ, as shown in Appendix Table A2, which distributes the CED into six distinct categories. The CED shows a heavy reliance on non-renewable energy sources. Fossil fuels alone contribute 400.07 MJ, accounting for 89.5% of the total energy, while nuclear energy adds 27.88 MJ (6.24%). Renewable sources play a comparatively minor role, with biomass contributing 1.51 MJ (0.34%) and solar, wind, geothermal and hydropower in total, contributing to only 17.38 MJ (3.9%). This cumulative energy demand profile reflects a high environmental burden and indicates substantial opportunities for decarbonization through the adoption of cleaner, renewable energy inputs.

Further breakdown of the CED by process components (**Fig. S5A**) reveals that process steam is the most energy-intensive component, consuming 272.64 MJ per kilogram of CNC produced, which constitutes 48.2% of the total energy use. This is followed by NaOH at 191.43 MJ (33.8%). Other contributors include $NaClO_2$ (9.1%), H_2SO_4 (3.6%), electricity (2.5%), process water (1.7%), feedstock (0.6%), wastewater treatment (0.4%) and cooling water (0.02%). Employing a system expansion approach, the formation of sodium sulfate as a co-product provides a substantial energy credit of 119.30 MJ (21.1%) by displacing conventional sodium sulfate production. This further highlights the potential for co-product valorization to offset the overall energy burden.

The dominance of NaOH in the energy profile highlights it as a strategic target for process optimization. Reducing its usage or substituting it with lower-impact alternatives could significantly reduce the overall energy footprint. Additionally, the substantial energy attributed to steam underscores the potential benefits of transitioning toward cleaner, low-carbon energy sources in facility operations. As seen in **Fig. S5B**, when a future decarbonization scenario is considered and renewable natural gas is used in place of fossil-derived steam for process heating, there is a corresponding decrease in 6 out of 10 impact

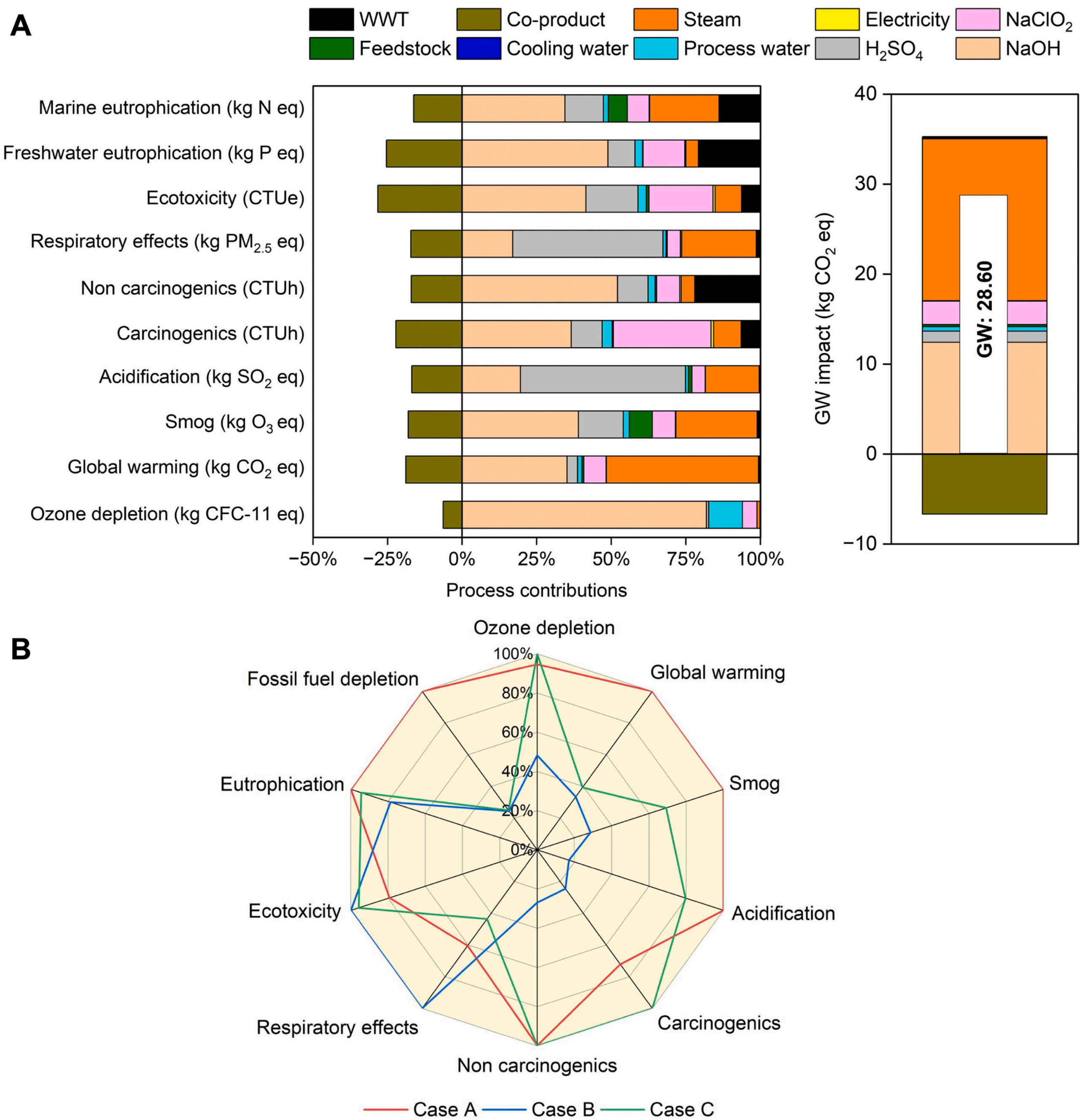

Fig. 4. (A) Process contributions to environmental impact categories and GW impact breakdown for CNC production from forest residues. Detailed breakdown of the primary contributors for all categories is provided in the SI (**Table S13**). Wastewater treatment abbreviated as WWT. (B) Radar chart showing the normalized LCA impact values for three different Cradle-to-Gate LCA scenarios. Results for cases A & C were recalculated using TRACI 2.1 to ensure consistency with the LCA results reported for Case B (Lan et al., 2024). All data shown in Fig. 4 are available in SI: **Table S13** for panel 4A and **Table S14** for panel 4B.

categories, with the GW impact decreasing by 61%. Renewable natural gas refers to upgraded biogas from sources such as landfills, animal manure, and crop residues. In our analysis, renewable natural gas is represented by the global ecoinvent dataset “market for heat, future” (version 3.11).

3.1.5. Uncertainty analyses

Uncertainty analyses via Monte Carlo simulations (10000 simulations) were performed to quantify the uncertainty in the MSP and evaluated environmental impact categories. As shown in Fig. 6, based on the uncertainty analysis carried out, the 90% confidence interval of the MSP was found to be between \$13.33 to \$19.23/kg with a standard deviation of 1.80. The key findings of the LCA uncertainty analysis results are presented in **Table S15**, including mean, standard deviation and other pertinent metrics. Among the evaluated impact categories, non-carcinogenic effects, freshwater eutrophication, and carcinogenic effects exhibit the highest relative uncertainty with coefficient of variation (CV) of 141%, 117% and 92%, respectively, suggesting considerable variability in underlying inventory data or model assumptions. Similarly, ecotoxicity (CV: 68%), acidification (CV: 64%), and respiratory effects (CV: 58%) show elevated uncertainties, highlighting these categories as areas that may benefit from more refined data collection or sensitivity analysis. In contrast, ozone depletion, marine eutrophication and smog formation demonstrate relatively low variability, suggesting

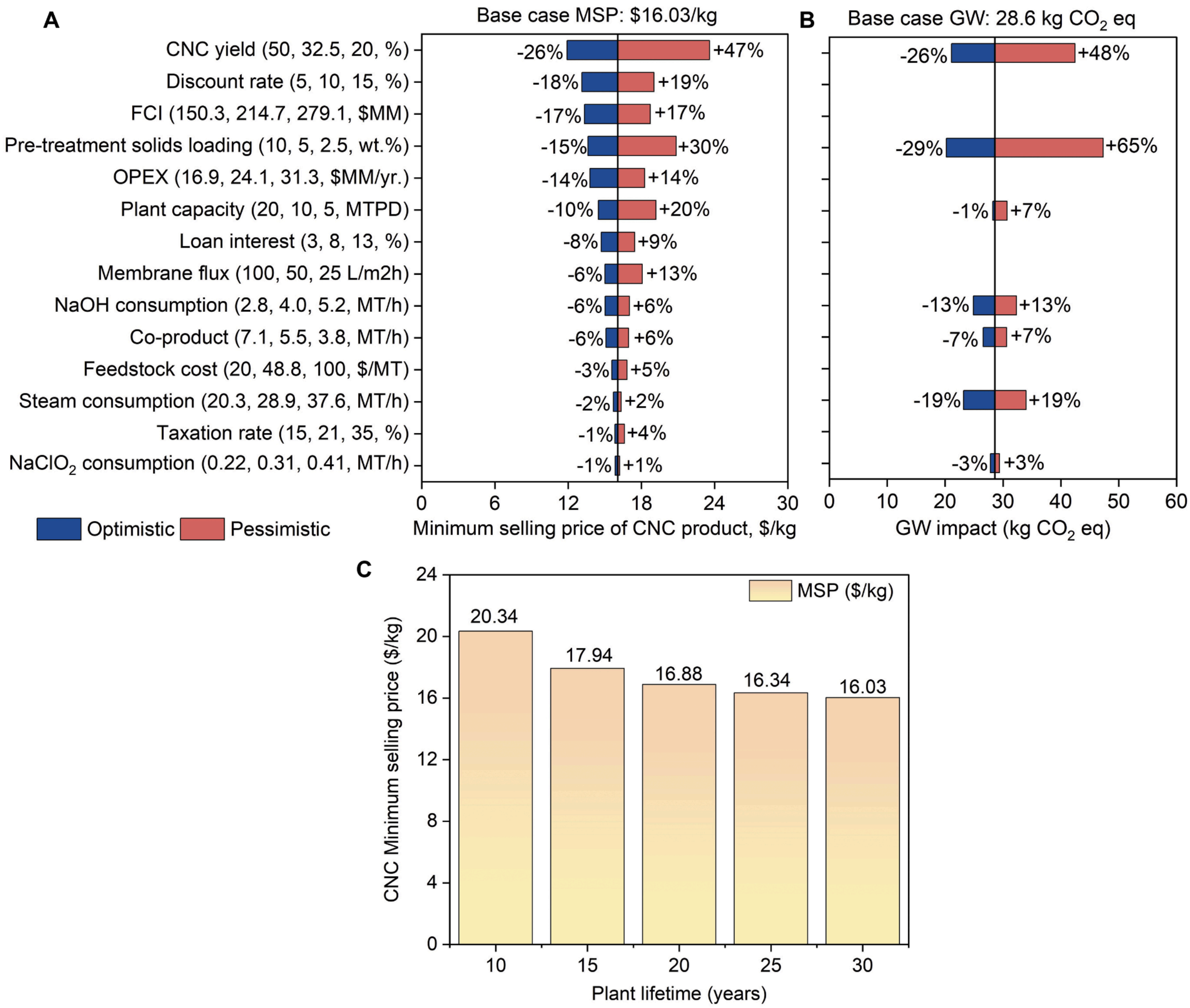

Fig. 5. (A) Univariate sensitivity analysis of the MSP of CNC produced from forest residues, considering various economic and process parameters. (B) Univariate sensitivity analysis of the GW impact associated with CNC production from forest residues, based on key process parameters. Refer to Table S9 in SI for sensitivity analysis results of rest of the life cycle impact categories. (C) Impact of plant lifetime on MSP of CNC Product. Data shown in Fig. 5 for panels 5A and 5B is available in Table S7 in SI.

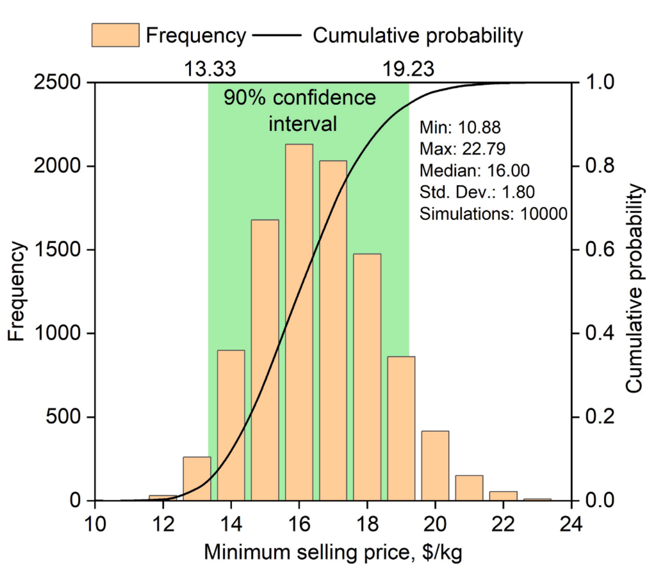

Fig. 6. Monte Carlo analysis results quantifying the uncertainty in the estimated MSP of CNC produced from forest residues.

stronger confidence in the reliability of the modeled results for these impact categories. Furthermore, GW impact, a critical environmental metric, has a narrow 95% confidence interval (2.50%–97.50%) ranging from 23.2 to 35.4 kg CO_2 equivalent per kg of CNC produced, reinforcing its robustness.

3.2. Assessment of environmental risks

A five-part enquiry-based framework (Uekert et al., 2024) was applied to evaluate the potential environmental risks of CNC manufacturing from forest residues during early-stage development, with a focus on chemical use, waste generation, supply chain equity, and end-of-life outcomes. A core environmental risk concern lies in the process's dependence on corrosive and toxic chemicals. The pre-treatment and acid hydrolysis steps utilize NaOH, which is highly corrosive—and sulfuric acid and sodium chlorite, both listed in the U.S. EPA's Toxics Release Inventory (TRI) (EPA toxic release inventory (TRI), 2024). These chemicals pose occupational safety risks and carry the potential for environmental contamination if not properly managed. Although less hazardous alternatives have been explored in literature, none provide equivalent performance in terms of CNC yield and purity at scales relevant to industrial-scale manufacturing. Therefore, the incorporation of closed-loop chemical recovery systems, acid/base neutralization units, and advanced worker safety protocols (e.g., fume hoods, PPE, process automation) is essential. Failure to implement mitigation strategies may result in heightened environmental impacts for communities located near processing sites.

Forest residues are considered benign and renewable feedstock. Nevertheless, sourcing strategies must guard against overharvesting and habitat changes. Although the residues are not associated with social exploitation, their use must be managed to ensure that forest biodiversity and carbon cycling functions are not compromised. To avoid unintended ecological impacts, residue procurement should adhere to established forest accountability (certification) schemes (e.g., Forest Stewardship Council, Wisconsin's Managed Forest Law program) and define clear sustainability thresholds based on forest regeneration capacity and soil nutrient retention (Brashaw and Bergman, 2021).

A key co-product of the CNC process is sodium sulfate, formed during the neutralization of sulfuric acid and NaOH. This byproduct is non-toxic and has commercial applications in the glass, textile, and paper industries. However, if market pathways are unavailable or oversaturated, large-scale generation of sodium sulfate may become a disposal liability and improper discharge into aquatic systems or landfills could lead to secondary environmental burdens. Therefore, early efforts should focus on developing strategic partnerships for sodium sulfate reuse, thereby aligning co-product management with circular economy principles.

The process is not associated with supply chains involving child or forced labor, based on assessments using the U.S. Department of Labor's ILAB database (List of Goods Produced by Child Labor or Forced Labor, 2024). Nonetheless, ethical sourcing policies should be maintained to mitigate future risks as raw material demand scales geographically. End-of-life considerations are relatively favorable. CNCs are biodegradable and offer improved environmental outcomes compared to fossil-derived nanomaterials or polymers, particularly in coatings and packaging applications (Andrade et al., 2022; Roman et al., 2024; Xu et al., 2024). Their degradability reduces the risk of long-term accumulation in landfills or aquatic systems and aligns with environmental justice goals by minimizing reliance on incineration or landfill infrastructure.

In summary, the CNC production process from forest residues offers a sustainable valorization pathway but is accompanied by environmental risks tied to chemical usage and waste management. Key recommendations include: (1) integrating chemical recovery and emissions control infrastructure early in process design, (2) sourcing forest residues from (certified) sustainable operations, (3) ensuring market pathways for sodium sulfate as a co-product, and (4) preserving product biodegradability through clean formulation strategies. By embedding these considerations in the early stages of technological development, CNC production can advance toward unbiased and environmentally sound deployment.

4. Conclusions

A plant scale process for 10 MTPD CNC production from sugar maple forest residues was conceptualized based on experimental data. TEA and LCA were carried out to quantify the economic and environmental performance of the process. Based on the TEA, the MSP of dry CNC product was estimated at $16.03/kg with a total capital investment and annual operating cost of $225.7 MM and $24.1 MM, respectively. The LCA results based on the TRACI 2.2 methodology estimated the GW impact of the process at 28.60 kg CO_2 eq/kg of dry CNC produced. The CED of the process was estimated at 446.83 MJ/ kg of dry CNC produced and the use of cleaner renewable energy for meeting process heating demand resulted in corresponding decrease in life cycle impacts of 6 out of 10 categories, with the GW impact reducing by 61%.

The sensitivity analysis revealed that the acid hydrolysis step benefits from higher CNC yields (50% and higher). In addition, when the pretreatment solids loading was increased to 10 wt.%, solvent requirements were minimized, thereby reducing costs and associated environmental burdens as well. In addition, changes in key economic parameters, such as the discount rate, FCI, OPEX, and plant capacity also had a significant impact on the MSP of the product. Uncertainty analysis using Monte Carlo simulations (10,000 iterations) quantified the economic and environmental impact of CNC, by yielding a 90% MSP confidence interval of $13.33 to $19.23/kg. and low variability in key environmental impact categories such as ozone depletion, marine eutrophication, smog formation, and GW.

While this study is based on experimental data specific to sugar maple, these results serve as a benchmark for the broader forest residue category. It is important to note the heterogeneity of forest biomass; specifically, softwood residues typically possess higher lignin content and different hemicellulose structures in comparison to hardwoods like sugar maple (Sjöström, 1993). Consequently, softwoods often exhibit higher recalcitrance, requiring higher severity during pretreatment (Zhu et al., 2010). This implies that a similar CNC production process using softwood residues would likely be more energy intensive and result in higher costs and associated environmental impacts. Therefore, the economic and environmental performance reported here represents a potentially more favorable scenario than other comparable processes utilizing high lignin containing softwood residues.

Based on this study, key technological bottlenecks include the low cellulose content of forest residues, low solids loading during pretreatment, and low CNC yields after acid hydrolysis. To further enhance economic feasibility and environmental performance, essential policy and support measures include integration of CNC production with existing biorefining plants to leverage existing infrastructure and reduce capital and operating expenses, establishing market pathways for sodium sulfate as a co-product and implementing closed-loop chemical recycling systems to improve waste management and reduce chemical usage. Furthermore, to avoid unintended ecological impacts, residue procurement should adhere to established forest accountability schemes.

CRediT authorship contribution statement

Rahul Prasad Bangalore Ashok: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard Bergman:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition. **Md Shahadat Hossain:** Writing – review & editing, Data curation. **Deepak Kumar:** Writing – review & editing, Validation, Data curation. **Prakash Nepal:** Writing – review & editing. **Troy Runge:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition.

Declaration of competing 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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.108778.

Appendix

Tables A1, A2

Table A1
Life cycle assessment results for cradle-to-gate production of CNC from forest residues, system expansion and substitution approach.

Impact category	Unit	Total
Ozone depletion	kg CFC-11 eq	1.44E-06
Global warming	kg CO_2 eq	28.60
Smog	kg O_3 eq	1.00
Acidification	kg SO_2 eq	0.19
Carcinogenics	CTU_h	9.06-07
Non-carcinogenics	CTU_h	6.45E-06
Respiratory effects	kg $PM_{2.5}$ eq	0.013
Ecotoxicity	CTU_e	73.88
Freshwater eutrophication	kg P eq	1.78E-03
Marine eutrophication	kg N eq	0.010

Table A2
Cumulative energy demand for 1 kg of CNC produced from forest residues across different impact categories, system expansion and substitution approach.

Impact category	Unit	Total	% contribution
Non-renewable (fossil)	MJ	400.07	89.53%
Non-renewable (nuclear)	MJ	27.88	6.24%
Non-renewable (biomass)	MJ	0.00	0.00%
Renewable (biomass)	MJ	1.51	0.34%
Renewable (wind, solar, geothermal)	MJ	1.18	0.26%
Renewable (water)	MJ	16.20	3.62%
Total	**MJ**	**446.83**	**100.00%**

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information file. Any additional data will be made available on request.

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