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Abstract

Nanocellulose is a renewable, biodegradable, and high-value biomaterial whose production can help valorize agro-industrial residues. Costa Rica generates substantial lignocellulosic waste from pineapple processing, but the techno-economic viability of converting pineapple peel residues into nanocellulose has not been rigorously assessed for a pilot-scale production scenario. A chlorine-free process was evaluated for a plant producing 48.000 kg/year of nanocellulose, primarily cellulose nanofibers, from approximately 140.000 kg/year of pineapple peel. The process comprises milling, alkaline pretreatment, hydrogen peroxide bleaching, high-pressure homogenization, and spray drying. The Netherlands and the broader European market were identified as priority targets for commercialization. The estimated total capital investment was 669.200 USD, while the total initial investment, including land, was 2,2 million USD. At an average selling price of 75 USD/kg, the corrected 10-year discounted cash flow model yields a Net Present Value of 6,7 million USD, an Internal Rate of Return of 199,4%, a Return On Investment of 61,5%, and a Payback Period of 19,5 months. Pineapple nanocellulose production from Costa Rican

pineapple peel residues is technically feasible and economically promising under the modeled assumptions. The case is strongest for a cellulose nanofibers-led product platform and should be strengthened before submission by validating product morphology, energy demand, wastewater characteristics, and firm market off-take conditions.

Keywords: nanocellulose; cellulose nanofibers; pineapple peel; techno-economic assessment; Costa Rica; circular bioeconomy; lignocellulosic waste; high-pressure homogenization

1. Introduction

With the growing global transition from fossil-based resources to renewable alternatives, nanocellulose has attracted considerable attention due to its renewability, biodegradability, abundance, and outstanding mechanical properties (1). Derived from cellulose, the most abundant natural polymer on Earth (1) nanocellulose is used in the food, cosmetic, pharmaceutical, biomedical, paper, and plastic industries (2,3), and its global market is projected to increase substantially over the coming decade (4–6). Beyond its attractive physicochemical properties, nanocellulose production offers an opportunity to valorize lignocellulosic residues generated by agricultural activities, transforming low-value waste streams into high-value advanced materials.

Costa Rica represents a particularly promising case for this type of valorization because of the large quantity of biomass residues generated by its pineapple industry. Approximately 640 kilotons of lignocellulosic waste are produced annually, mainly from pineapple stubble, crowns, and peels (7). These residues are continuously generated throughout the production cycle at rates of tons per day and currently pose significant logistical and environmental management challenges. Among the different biomass fractions, pineapple peels present several advantages for industrial processing, including easier handling and transportation, elimination of an initial grinding stage, and an adequate cellulose content combined with relatively low hemicellulose levels (8,9). These

characteristics make pineapple peels an attractive feedstock for pilot-scale nanocellulose production.

Industrial nanocellulose production generally requires two integrated stages. First, the biomass is pretreated to remove non-cellulosic components and generate a purified cellulosic fraction. Second, the purified fibers are mechanically or chemically disintegrated into nanoscale cellulose structures (10).

The first stage is commonly performed using alkaline pretreatment, which is considered more environmentally friendly than other conditioning methods, such as acid hydrolysis. Sodium hydroxide is generally used as the standard alkaline agent in both laboratory and industrial settings. During this alkaline digestion, glycosidic side chains, lignin, esters, and hemicellulose are removed, and the raw material is partially mercerized (11). This treatment alters the degree of polymerization of the biomass components, leading to changes in surface area, porosity, and crystallinity, thereby improving the material's suitability for subsequent fibrillation (12,13).

As part of this first conditioning step, the alkaline treatment is followed by a bleaching step to fractionate and remove hemicellulose and lignin residues. Traditionally, sodium hypochlorite has been used as a bleaching agent in the laboratory, but recent research has indicated negative environmental consequences associated with the use of chlorinated reagents, especially at pilot or industrial scales. These concerns arise primarily from the management of waste generated by these reagents (14,15). An alternative method was recently developed by Hafemann et al. (16), who reported a sustainable industrial-scale method using hydrogen peroxide for bleaching. In their work with rice husks, they reduced the lignin content from 20% to 3–5%. This approach not only effectively extracted and bleached the cellulose from rice husk but also employed mild process conditions, highlighting its potential for sustainable industrial applications.

High-pressure homogenization is widely used for the mechanical fibrillation stage because it is scalable, solvent-free, and compatible with aqueous processing. A cellulose suspension is forced through a narrow high-pressure zone, where impact, shear, and cavitation effects disintegrate the cellulose microfibrils into nanoscale fibrils (17). This route is most directly associated with cellulose nanofiber (CNF) production. The degree of cellulose fibrillation is determined by the applied pressure and the number of homogenization cycles. Nanocellulose crystals produced by this method generally exhibit a wide distribution of fibril diameter and length, as well as a high surface area, making them suitable for a variety of applications (18).

Previous techno-economic studies have shown that large-scale nanocellulose production from agricultural and forestry residues can be feasible under favorable biomass availability, labor costs, and market prices (19,20). Building on this literature, the present work assesses the techno-economic feasibility of a pilot-scale nanocellulose production plant using Costa Rican pineapple peel residues as feedstock. The analysis integrates market segmentation, process design, mass and energy requirements, capital and manufacturing costs, and discounted cash-flow indicators.

2. Methods

This study was designed as a desk-based techno-economic assessment of a pilot-scale nanocellulose production facility. The assessment combined market analysis, literature-based process design, equipment sizing, factorial capital-cost estimation, manufacturing-cost estimation, and discounted cash-flow analysis.

Market data were compiled from commercial supplier quotations, trade databases, market reports, and published sources cited in the reference list. These data were used to identify priority geographies, target sectors, competing suppliers, price benchmarks, and a plausible annual production volume for a pilot facility.

The process route was selected from the literature: alkaline pretreatment, hydrogen peroxide bleaching, and high-pressure homogenization. The mass balance assumes a 34% recovery of purified cellulosic material from pineapple peel based on reported yields for pineapple peel and related lignocellulosic materials (16,21,22). Fibrillation was modeled at 30 g/L, 60 MPa, and 10 homogenization cycles (23–27), assuming no mass loss during fibrillation.

Capital costs were estimated using the factorial method described by Robin Smith (28). These include Total Capital Investment (TCI, the overall financial resources required to bring the plant into operation, including both fixed and working capital), Fixed Capital Investment (FCI, the portion of investment associated with physical assets such as equipment, installation, and construction), and Working Capital (WC, the funds required to support day-to-day operations). Additionally, the Cost of Manufacturing (COM, which encompasses expenses related to raw materials, labor, utilities, maintenance, and other operational costs necessary to produce the final product) was estimated using the methodology described in the work of Richard Turton and coworkers (29). All calculations are performed in USD using an exchange rate of 519,6 CRC/USD (as of January 4, 2024, Central Bank of Costa Rica), and exchange rate trends are not considered. In addition, as the project is planned for a Free Trade Zone, the project's imports (raw materials and equipment) and revenue are tax-exempt for the first 10 years (the duration of the pilot-scale project).

Financial performance was assessed over a 10-year project horizon using a 12,5% discount rate. The corrected base-case cash flow includes land acquisition in year 0 and land recovery in year 10. The key financial indicators Net Present Value (NPV), Internal Rate of Return (IRR, also referred to as the Discounted Cash Flow Rate of Return), Return on Investment (ROI), and Payback time were calculated following the methodology proposed by Smith and coworkers (28).

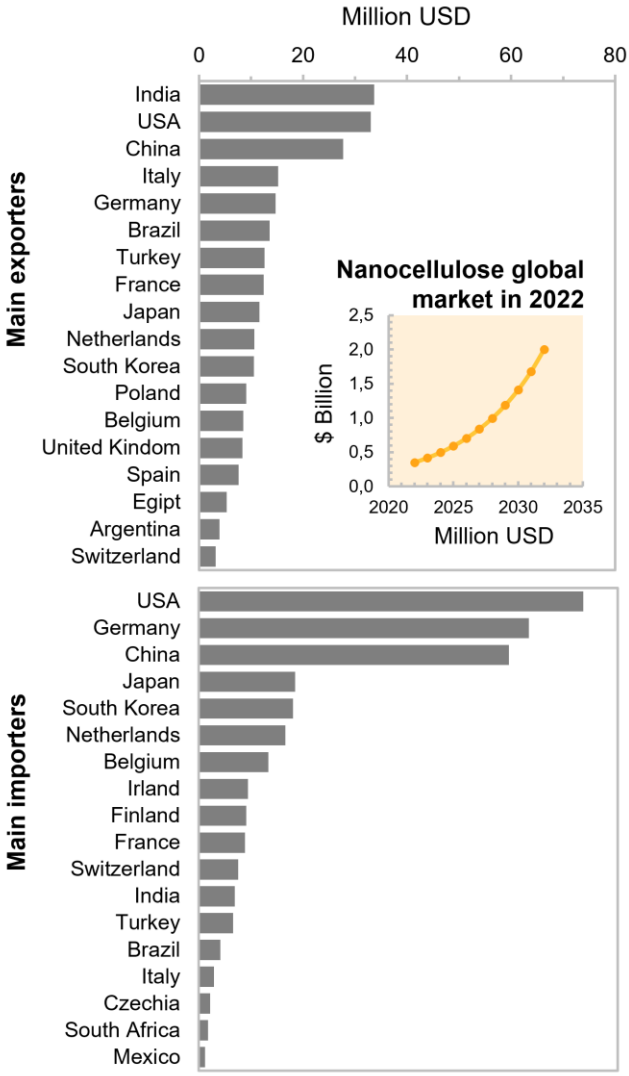
3. Results and Discussion

This section is organized into Market analysis, Process design and technical feasibility, Techno-economic performance, and Final remarks. Together, these sections define and discuss the target product, target market, production capacity, process configuration, cost structure, and financial robustness of the proposed pilot plant.

3.1. Market analysis

3.1.1. Nanocellulose market and commercial drivers

Global demand for nanocellulose has grown rapidly with the emergence of renewable materials for paper, packaging, composites, biomedical products, and other bioproduct applications. Market reports cited in this work project substantial growth from approximately 350 million USD in 2022 to nearly 2,0 billion USD by 2032 (4–6) (Fig. 1 – inset). As shown in Fig. 1, India, the United States, and China were the leading individual importers in the analyzed trade data, while Europe represented the largest regional importing market (30).



130

131 **Fig. 1** Main global nanocellulose importers and exporters (30). Inset: projected global
132 nanocellulose market growth based on market reports (4–6).

133 The main exporters identified in Fig. 1 are the United States, China, and Germany, with exports
134 between approximately 67 million USD and 83 million USD in 2022 (30). The United States
135 benefits from a strong research and development capacity, including the University of Maine's
136 nanocellulose program (31), while China is supported by industrial producers such as Sheng
137 Quan Group and IPG Chem (32).

Costa Rican imports and exports of cellulose and derivatives remain very small in the cited trade statistics, indicating that local nanocellulose production and demand are still in their early stages [26]. This creates both a market-development challenge and a first-mover opportunity for a regional pilot facility.

3.1.2. Competitors and price benchmarks

The global competitive landscape is summarized in Tables S1 and S2. Commercial prices vary widely with product type, concentration, order size, purity, supplier scale, and whether the material is sold as a powder or a hydrogel. Dry nanocellulose powders are commonly quoted at US$1,000–1,200/kg, whereas bulk or higher-volume products can be offered at substantially lower prices, including US$50–100/kg for some powders and lower apparent prices for dilute hydrogels.

The dimensions of nanocellulose particles available on the market also vary. Typically, particles range from 300 nm to 900 nm in length and from 10 nm to 20 nm in width. These dimensions are crucial, as they directly influence the properties and potential applications of nanocellulose, including its ability to form films, mechanical strength, and transparency.

3.1.3. Scale-up challenges

Industrial nanocellulose production still faces three major scale-up challenges: process scalability, quality control, and evolving regulation. Although recent techno-economic studies support industrial feasibility under appropriate conditions (19,20). Production routes remain energy- and water-intensive and require robust control of feedstock variability, pretreatment severity, fibrillation efficiency, and drying cost (33).

Another challenge is standardization and quality control. Currently, accurate characterization of nanocellulose in an industrial setting is challenging, as available nano-characterization methods are complex, require extensive analysis, and represent a significant investment in capital and

skilled personnel (34). Therefore, precise protocols and techniques are needed to characterize aspects such as dispersion, particle size, and morphology of nanocellulose.

Current regulations surrounding nanocellulose are limited and present another challenge. As a relatively new material, it is still in the process of establishing clear guidelines for its production and use. For industry stakeholders, adapting to these evolving regulations and potential new standards can be a significant challenge, as it involves adjustments to accepted industrial processes.

3.1.4. Market opportunities

The paper, cardboard, and packaging sectors represent the most immediate market opportunity because nanocellulose can improve barrier, strength, and coating properties, and because these sectors already operate at an industrial scale. Market reports cited in this work identify the pulp and paper segment as a leading area for nanocellulose applications (4).

Nanocellulose consumption in the medical and pharmaceutical sectors is expected to grow significantly, driven by the material's biocompatibility, low toxicity, and biodegradability. Factors such as an aging population, technological advancements, and the rise in chronic diseases are increasing demand in the healthcare industry. This trend is expected to foster the development of the nanocellulose industry as it seeks to meet the growing need for innovative healthcare solutions. The global biomedical and healthcare industries have been expanding significantly, with year-over-year growth rates of 10% to 14% since 2020, a trend expected to continue to drive demand for nanocellulose in the global market in the coming years (35). This field is also of interest to Costa Rica, as the country has a strong biomedical device manufacturing sector that could potentially demand local nanocellulose.

Regarding product type, cellulose nanofibers (CNF) accounted for the largest share of reported revenue in 2022 (6). Established cellulose-nanomaterial terminology distinguishes CNF from

crystalline nanocellulose (CNC) primarily by morphology, dimensions, and production route (6). This is consistent with the selected high-pressure homogenization route, which is better aligned with CNF production than with classical CNC production. CNC should therefore be treated as a potential future product only after particle morphology, dimensions, and crystallinity are experimentally validated (6,36,37).

A key opportunity is the existing interest of Dutch companies in the Costa Rican product. According to a 2018 market study by Nennie & de Boer of MVO Nederlands, in collaboration with various Costa Rican entities (38). Companies such as Avantium, Smurfit Kappa, and Schutpapier have expressed interest in purchasing nanocellulose.

At the local level, Costa Rica and the region have no large-scale nanocellulose producers, which presents a competitive advantage given the low level of competition in local and regional markets. Although nanocellulose consumption in the region is currently low, this presents an opportunity to introduce an innovative material to sectors such as paper, cardboard, and the medical industry, which are well-established in the country.

The geographical distribution of pineapple plantations and their processing facilities is another opportunity. Most of the industry is concentrated in the northern region of the country, especially in San Carlos. The region accounts for 80% of the country´s pineapple cultivation area (42.000 hectares) (39). Furthermore, many independent processing companies in the area have expressed willingness to negotiate commercial agreements to facilitate the acquisition of pineapple peel waste, thereby providing a sustainable and efficient source of raw material for nanocellulose production. San Carlos also has Muelle Free Zona and Business Park. This is a key infrastructure and location. Besides its location at the heart of the Costa Rican pineapple industry, it is also close and well connected to the Caribbean and Pacific Ports (168 and 69 km away, respectively), the main international airport (64 km), and the capital of the country, San Jose (74 km). The industrial park operates under the Free Trade Zone regime, offering significant

benefits, including tax exemption on profits and other earnings, with a 100% exemption for the first 12 years and 50% for the following 6 years, as stipulated by Law 8794. The free trade zone is equipped with an electrical grid designed to meet industrial needs, as well as telecommunications, water supply, and a water treatment plant (40)

3.1.5. Market segmentation and production volume

Based on the information compiled in this work, a target market was defined as shown in Table 1. The project focuses on the Netherlands as the primary market, given that Dutch companies have previously shown interest in nanocellulose. Europe and the United States are identified as attractive secondary markets, ranking second and third in order of priority, respectively. Regarding industry type, the focus is on the paper, cardboard, and packaging sectors, given their high demand for nanocellulose. The construction biomaterials, plastics, and other sectors are also included, leveraging the product's versatility. Finally, universities and research centers are included, given the high demand for nanocellulose across various technical applications. Furthermore, growth in nanocellulose consumption is observed in the pharmaceutical and biomedical sectors, justifying their inclusion in the strategy. Among the different types of nanocellulose, CNF is identified as the most sought-after and is therefore expected to be the primary product. Nonetheless, adjusting the fibrillation conditions during high-pressure homogenization is expected to yield both CNF and CNC. Consequently, CNC could also be produced and introduced to the market. Initial production will be geared towards small and medium-sized enterprises, in line with the pilot plant's production capacity. Finally, the behavioral target focuses on environmentally conscious companies committed to sustainability and the use of eco-friendly products. Nanocellulose, due to its environmentally friendly characteristics, is particularly attractive to this market segment. This strategy provides a comprehensive, well-defined approach to identifying the most promising markets for nanocellulose, aligning the project with current sustainability trends across industries.

Table 1. Market segmentation (in order of priority)

Geographic	Industrial	Type of nanocellulose	Industry size	Behavioral
1. The Netherlands 2. Europe 3. USA	1. Paper, cardboard, and packaging 2. Construction of biomaterials and plastics 3. Academic research 4. Pharmaceutical and biomedical industry	1. CNF 2. CNC	1. Small to medium enterprises	1. Environmentally conscious companies seeking bio-based materials

According to the analysis presented in this work, it is feasible to sell 48 tons of nanocellulose per year at pilot scale under the proposed conditions. This estimation considers the average Dutch imports of nanocellulose, which do not exceed 2.000 metric tons per year (30). It also considers the specific demands of key companies such as Avantium, Smurfit Kappa, and Schutpapier, which have shown preliminary interest in the product, as well as the exploration of other potential markets and the ability to secure sufficient raw material from the Costa Rican pineapple industry.

3.2. Process design and technical feasibility

The proposed production process is shown in Fig. 2. It begins with the milling of pineapple peel, followed by a sequence of alkaline and bleaching treatments to obtain microcrystalline cellulose (MCC). The resulting MCC is then fibrillated by high-pressure homogenization and spray-dried to produce dry nanocellulose powder (or a gel), with CNF as the primary product target. Detailed process conditions are provided in Table S3.

A key stage during the process is the alkaline and bleaching treatments. In addition to purifying and conditioning the cellulosic material, this stage determines the process yield. In this work, the yield during this stage is expected to be around 34%. This is based on previous reports on the use of pineapple peel and other lignocellulosic materials with cellulose content between 20 and 40% (16,21,22). No other losses of cellulosic material during the rest of the process are considered. This implies that, per year, 140.000 kg of pineapple peel should be processed to meet

the proposed production of 48.000 kg of nanocellulose. On a daily scale, this is equivalent to processing 387 kg of lignocellulosic waste to get 133 kg of product. In Table S4, the mass balance of the entire process is tabulated.

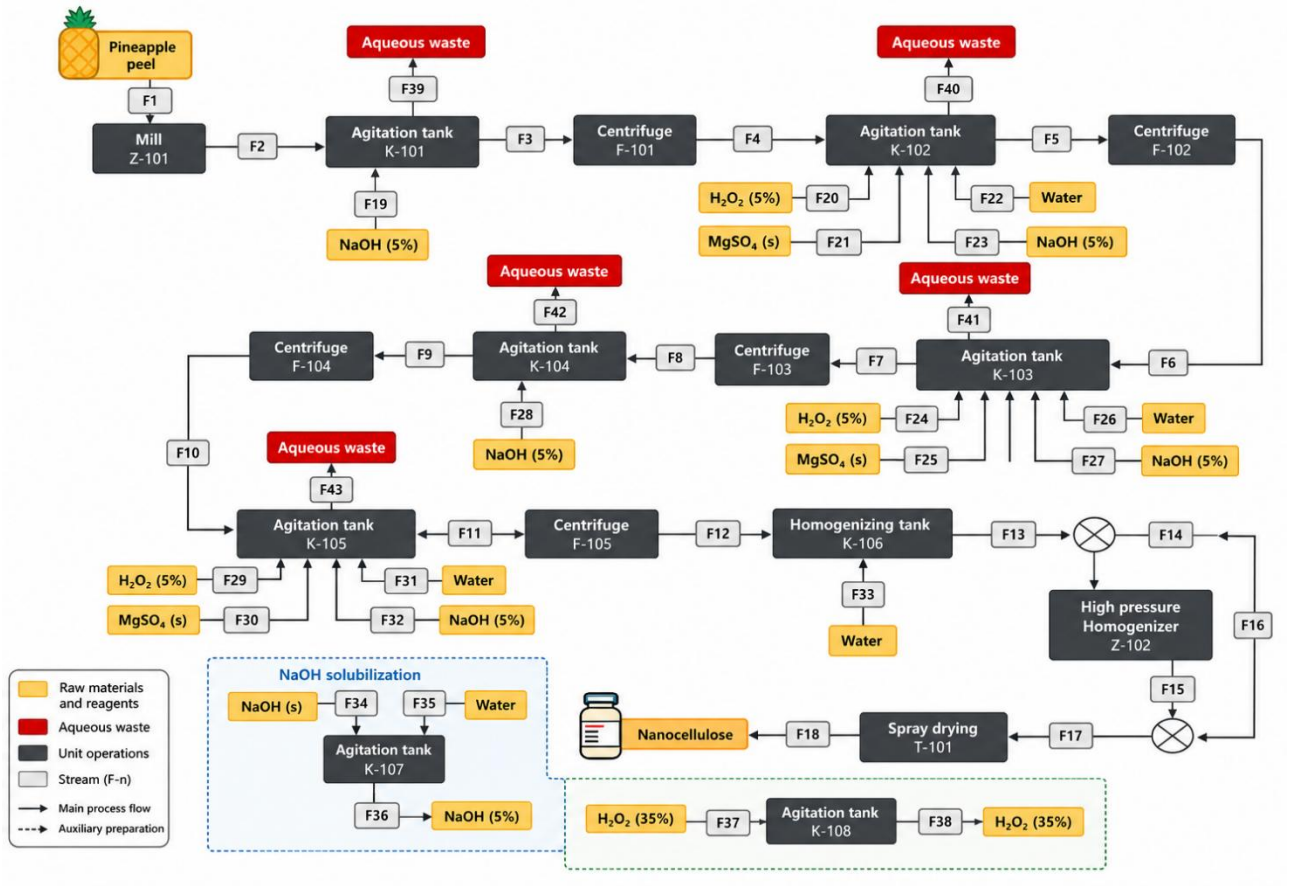


Fig. 2 Block flow diagram of the proposed nanocellulose production process.

The second key stage is fibrillation of MCC. Literature values indicate suitable solid concentrations of 10–30 g/L and operating pressures of 50–140 MPa, while the required number of homogenization cycles depends strongly on pretreatment efficiency and feedstock structure [37-41]. The base case (24) uses 30 g/L, 60 MPa, and 10 cycles. With the selected homogenizer capacity of 8.000 L/h, the daily suspension volume of approximately 4.400 L can be processed within approximately 10 h for 10 cycles, leaving operational margin for additional cycles if

267 required. The specifications of the homogenizer and the remaining infrastructure required for the
268 pilot plant are described and sized in Table S5.

269 A major environmental advantage of the proposed route is the avoidance of chlorinated bleaching
270 agents. The modeled aqueous residues are expected to contain water, dissolved lignocellulosic
271 components, hemicellulose fragments, Na^+, Mg^{2+}, and SO_4^{2-} and should be neutralized or treated
272 before discharge. This aqueous waste can be treated by the water treatment plant at the proposed
273 location, Muelle Free Zone and Business Park. The solid residue consists mainly of residual
274 lignocellulosic material and should be managed in accordance with local waste regulations.
275 Similarly, solid waste is also non-hazardous. It consists of lignocellulosic residues from the
276 pineapple peel, which can be disposed of as ordinary waste in compliance with the San Carlos
277 Municipal Integrated Waste Management Plan. Pilot testing should verify wastewater pH,
278 chemical oxygen demand, salt loading, and treatment compatibility.

279 *3.3. Techno-economic performance*

280 *3.3.1. Cost estimation*

281 The Total Capital Investment (TCI) was estimated using Eq. 1, where C_e refers to the cost of each
282 equipment delivered to the site, and the different correction factors are defined as: f_m, material; f_p,
283 pressure; f_t, temperature; f_{pip}, piping; f_{er}, equipment erection; f_{inst}, instruments and controls; f_{elec},
284 electrical; f_{util}, utilities; f_{os}, off-sites; f_{build}, buildings; f_{sp}, site preparation; f_{dec}, design, engineering,
285 and construction; f_{cont}, contingency; and f_{wc}, working capital.

286 $$TCI = \sum_i \left[C_e \cdot f_m \cdot f_p \cdot f_t\left(1 + f_{pip}\right)\right]_i + \left(f_{er} + f_{inst} + f_{elec} + f_{util} + f_{os} + f_{build} + f_{sp} + f_{dec} + f_{cont} + f_{wc}\right) \sum_i C_{e,i} \quad \text{(Eq. 1)}$$

287 Since all the equipment was quoted directly by the provider, material, pressure, and temperature
288 correction factors are assumed to be 1. The remaining values of the correction factors are used
289 as described by Smith for plants processing mostly fluids (28). These values are tabulated in
290 Table S6, and the calculation is shown in Table S7, yielding a TCI of 669.200 USD.

The Fixed Capital Investment (FCI) is calculated similarly to TCI, but without the working capital correction factor (Eq. 2). The calculation is also shown in the Supporting Information (Table S8) and yields an FCI of 584.000 USD.

$$TCI = \sum_i \left[C_e \cdot f_m \cdot f_p \cdot f_t\left(1 + f_{pip}\right)\right]_i + \left(f_{er} + f_{inst} + f_{elec} + f_{util} + f_{os} + f_{build} + f_{sp} + f_{dec} + f_{cont}\right) \sum_i C_{e,i} \quad \text{(Eq. 2)}$$

The Working Capital (WC) is estimated as the difference between TCI and FCI, which is $ 85,200.

Land acquisition was modeled separately from plant capital. Although land is often estimated as 1–2% of TCI in early cost estimates (41). A Costa Rica-specific value of 1,5 million USD was used to avoid unrealistically low land-cost assumptions. Thus, the total initial cash outflow is 2,17 million USD. The land is treated as a non-depreciable asset and is recovered at the end of the project horizon.

The Cost of Manufacturing (COM) is estimated using Eq. 3, and Table 2 shows the definition of terms in the equation. It also includes the estimated annual contributions for raw materials, waste treatment, utilities, and labor, along with the section of the Supporting Information that describes the estimation in detail. Using the values in Table 2, the resulting COM is 2.265.500 USD/year.

$$COM = 1.23 \cdot (C_{RM} + C_{WT} + C_{UT}) + 2.73 \cdot C_{OL} + 0.280 \cdot FCI \quad \text{(Eq. 3)}$$

Table 2. Definition and yearly estimation of the terms used in Eq. 3.

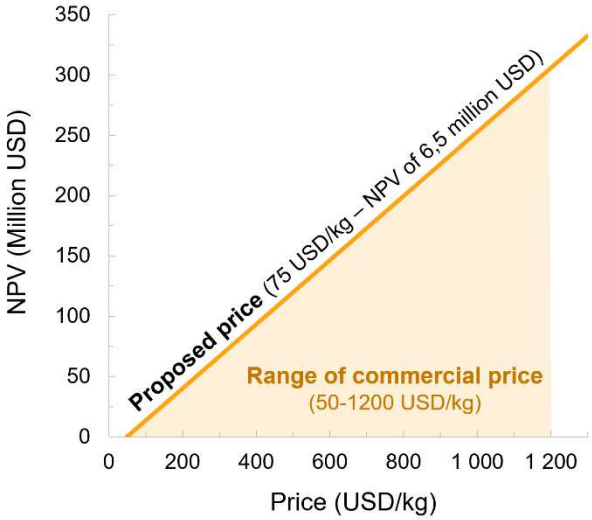
	Term	Yearly cost ($)	Detailed in
C_{RM}	Raw material cost	633.500	Section S1.1
C_{WT}	Waste treatment cost	0	Section S1.2
C_{UT}	Auxiliary services cost	736.700	Section S1.3
C_{OL}	Labor cost	152.600	Section S1.4

3.3.2. Financial evaluation

In this section, the selling price of nanocellulose powder is established based on the market analysis. Additionally, key financial indicators—Net Present Value (NPV), Internal Rate of Return

311 (IRR, also referred to as the Discounted Cash Flow Rate of Return), Return on Investment (ROI),
312 and Payback time. These parameters are subsequently used to evaluate the project's economic
313 feasibility. The calculation of these financial indicators is described in detail in Section S2 of the
314 Supporting Information.

315 Fig. 3 illustrates the relationship between the product's selling price and the NVP. The graph also
316 indicates the current market price range for nanocellulose sold as dry powder, which spans from
317 50 to 1.200 USD/kg. The minimum viable selling price is estimated at 49,62 USD/kg. At this point,
318 the IRR equals the assumed discount rate (12,5%), meaning that the project reaches its break-
319 even condition, generating neither profit nor loss. Notably, this value coincides with the lowest
320 price identified in the market analysis for commercially available nanocellulose. However, this
321 price corresponds to orders exceeding 5 kg. More commonly, market prices range between 1.000
322 and 1.200 USD/kg. Although lower prices have been identified, with the lowest being 100 USD/kg
323 for purchases of less than 5 kg.



324

325 **Fig. 3** Variation of the Net Present Value as a function of the price of power nanocellulose.

326 According to the literature (28), an IRR of 20% is acceptable for low-risk projects. At this IRR, the
327 required selling price is estimated at 50,45 USD/kg, which is basically the most competitive price

identified in this study. However, this scenario yields a relatively low NPV of 222.600 USD. In contrast, projects with more associated risk (such as the pilot plant considered in this work) typically require an IRR of around 50%. Under these conditions, a selling price of 54,28 USD/kg is obtained, which remains competitive and yields a more attractive NPV of 1.238.000 USD. Based on this analysis, nanocellulose could be sold in bulk at approximately 55 USD/kg. Nevertheless, smaller volume orders may be marketed at higher prices, closer to those observed in the current market. For instance, a selling price of 100 USD/kg would correspond to an IRR of 379% and an NPV of approximately 13.400.000 USD. However, it is not expected that the entire production output would be sold at such small scales. Therefore, a representative average selling price of 75 USD/kg is selected for the project's financial evaluation. This assumption reflects a scenario in which most of the production is sold at scale (55 USD/kg), while a smaller fraction is sold at higher prices (100 USD/kg or more) for low-volume orders. The resulting financial indicators, summarized in Table 3, include an IRR of 199,4%, indicating efficient use of invested capital; a 6.745.400 USD NPV, indicating high profitability; a 61,5% ROI, considered attractive; and an appealing 19,5-month Payback time. Overall, these results demonstrate that the project is highly profitable and financially feasible for implementation.

Table 3. Estimated financial indicators

Net Present Value (NPV)	6.745.400 USD
Internal Rate of Return (IRR)	199,4%
Return on Investment (ROI)	61,5%
Payback time	19,5 months

3.3.3. Sensitivity analysis

Sensitivity analysis allows the evaluation of changes in project profitability in response to fluctuations in process-related variables. This makes it possible to assess the project under

different conditions that may deviate from the expected scenario. The sensitivity analysis considered the following factors: initial investment, COM, selling price, and sales volume (i.e., product manufactured and sold). Fig. 4 illustrates how NPV and IRR are negatively affected as the evaluated factors vary by up to 50%.

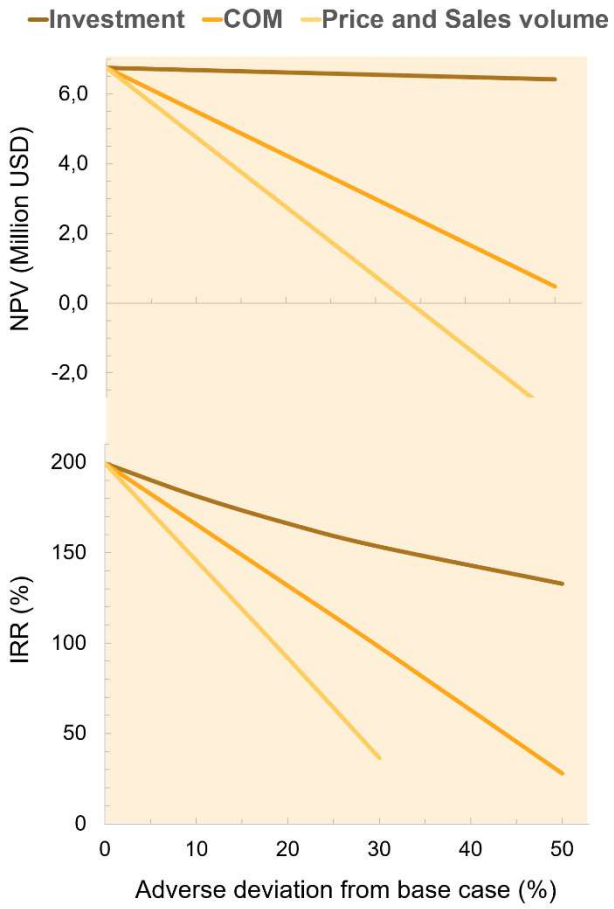


Fig. 4 NPV and IRR as the initial investment, COM, price, and sales volume negatively deviate from the expected case.

As shown in Fig. 4, variations in the initial investment have a relatively minor effect on project feasibility. Even if the initial investment were 50% higher than the base case, the NPV would decrease only slightly to 6,4 million USD, while the IRR would remain at a highly favorable 133%. In contrast, the COM has a greater impact on the project's economic feasibility. A 40% increase

in COM would still result in a profitable project, with an NPV of 1,7 million USD and an IRR of 64%. However, when the COM increases by 50%, the IRR falls below 50%, suggesting that the project might not be worth a high risk.

Among the variables evaluated, selling price and sales volume have the greatest influence on project feasibility. Either variable can decrease by up to 20% while still maintaining a profitable project, yielding an NPV of 2,8 million USD and an IRR of 92%. Nevertheless, reductions greater than 28% render the project insufficiently attractive relative to its risk. The selling price and sales volume are represented by a single line in Figure 4 because both variables produce identical results. This occurs because Eq. S8 was modified by reducing the term Annual production × Price, with the first factor corresponding to sales volume and the second to selling price.

Overall, the sensitivity analysis demonstrates that the most influential variables are the selling price and sales volume, followed by the COM. Nevertheless, these carefully estimated parameters would each need to vary by at least 28% to make the project economically unattractive, and by more than 32% to make it unprofitable. Nonetheless, these results show that the base case requires credible off-take agreements and conservative price validation.

3.4. Final remarks

This work supports the strategic relevance of pineapple peel valorization in Costa Rica by linking a local residue stream to a high-value bioproduct market. The proposed route aligns with the scope of bioproducts from biomass and can be framed as a circular bioeconomy opportunity rather than solely as waste management.

The strongest scientific limitation is product definition. High-pressure homogenization is a robust route to CNF, but CNC production generally requires additional chemical or enzymatic strategies and must be supported by microscopy, particle-size distribution, crystallinity, and surface

chemistry data. Therefore, CNF is identified as the first commercial target, and CNC as a future product development option.

The strongest business limitation is market execution. The financial model is attractive at 75 USD/kg, but the sensitivity analysis shows that price and sales volume dominate the project's risk profile. Thus, before investment, the project should obtain letters of intent, define product specifications, and compare bulk dry powder with hydrogel sales, as drying is a major utility burden.

The environmental advantages of the proposed project are credible but model-based. The absence of chlorinated bleaching agents is favorable, yet wastewater composition, chemical oxygen demand, sodium loading, peroxide residuals, and treatment compatibility should be experimentally verified. Future work should include pilot trials and a cradle-to-gate life-cycle assessment.

4. Conclusions

This work evaluated the techno-economic feasibility of a pilot-scale nanocellulose production plant using pineapple peel residues generated by the Costa Rican pineapple industry. The study integrates market analysis, process design, and financial evaluation to assess the conversion of an abundant agro-industrial residue into a high-value biomaterial.

The market analysis indicates favorable commercialization opportunities in Europe and the United States, particularly for CNF applications in paper, packaging, biomaterials, and research. Costa Rica offers strategic advantages, including a steady supply of pineapple residue, proximity to the San Carlos pineapple-processing region, export connectivity, and potential benefits of a Free Trade Zone.

The technical assessment indicates that 48.000 kg/year of dry nanocellulose could be produced from approximately 140.000 kg/year of pineapple peel, assuming a 34% recovery. The proposed process avoids chlorinated bleaching agents and is therefore environmentally preferable to routes that generate chlorinated effluents, although pilot wastewater characterization remains necessary.

The financial evaluation confirms that the project is economically promising. At an average selling price of 75 USD/kg and using a land-inclusive cash-flow boundary, the project achieves an NPV of 6,75 million USD, an IRR of 199%, an ROI of 61,5%, and a payback time of 19,5 months. Sensitivity analysis identifies selling price and sales volume as the key risk drivers, followed by COM.

Overall, pineapple peel-derived nanocellulose production in Costa Rica is technically feasible, economically attractive, and environmentally promising under the modeled assumptions. The next critical steps are pilot validation, CNF product characterization, wastewater testing, drying energy optimization, and market validation with potential buyers.

List of abbreviations

CNF, cellulose nanofibers; CNC, cellulose nanocrystals; COM, cost of manufacturing; FCI, fixed capital investment; IRR, internal rate of return; MCC, microcrystalline cellulose; NPV, net present value; ROI, return on investment; TCI, total capital investment; WC, working capital.

Declarations

Ethics approval and consent to participate

Not applicable. This study did not involve human participants, human data, human tissue, or animals.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this article and the supporting information.

Competing interests

The authors declare that they have no competing interests. This statement should be confirmed by all authors before submission.

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Authors' contributions

MRA, FO, BCMM, RCR, and JRV-B contributed to conceptualization, data curation, process design, techno-economic analysis, manuscript drafting, and revision. All authors read and approved the final manuscript. Specific author contributions should be confirmed before submission.

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Use of AI-assisted tools

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