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Review

Techno-Economic Considerations on Nanocellulose's Future Progress: A Short Review

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Abstract: Nanocellulose (NC) is an emerging natural material that offers great potential for various applications due to its unique properties and renewable character. Nowadays, as NC production technologies are advancing, it is essential to evaluate their economic feasibility, technological maturity and commercialization potential using systematic techno-economic analysis (TEA). The present study considers both technical and economic aspects of NC production and analyzes them in two ways: first, by developing a new concept based on the production of different types of NC through the conversion of lignocellulosic biomass by chemical and mechanical technologies, and second, by a comparative review of existing TEA studies in the open literature. Three specific scenarios and two case studies are evaluated by comparing specific key performance indicators (KPIs), such as the production cost (PC) and minimum product selling price (MPSP) of NC. As a result, a short though comprehensive overview of the current state of NC production is provided, highlighting the main technical and economic challenges associated with it. Key areas for future research and innovation (R&I) are also identified to optimize the production processes and reduce relevant costs, in order to make NC competitive with existing materials and realize its full potential.

Keywords: nanocellulose; nanofibrillated cellulose (NFC); nanocrystalline cellulose (NCC); bacterial nanocellulose (BNC); techno-economic analysis; production cost; lignocellulosic biomass

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Citation: Penloglou, G.; Basna, A.; Pavlou, A.; Kiparissides, C. Techno-Economic Considerations on Nanocellulose's Future Progress: A Short Review. *Processes* **2023**, *11*, 2312. https://doi.org/10.3390/pr11082312

Academic Editor: Selestina Gorgieva

Received: 30 June 2023
Revised: 24 July 2023
Accepted: 27 July 2023
Published: 1 August 2023

1. Introduction

Nanocellulose (NC) is a versatile and sustainable material that can be derived from cellulose, the most abundant organic polymer on Earth; recently, NC has attracted much attention due to its unique properties and potential applications [1]. There are three main types of nanocellulose, each with its own special characteristics: (1) Nanofibrillated cellulose or cellulose nanofibrils or cellulose nanofibers (NFC) consist of long and thin fibers with high aspect ratio [2]. Therefore, NFC is excellent as a reinforcing agent in composites and as a thickening agent in coatings and adhesives [3]. (2) Nanocrystalline cellulose or cellulose nanocrystals (NCC), which are small, rod-shaped particles with high crystallinity and strength-to-weight ratio [4], are generally ideal for use in high-performance materials and composites. (3) Bacterial or microbial nanocellulose (BNC), which is produced by numerous bacteria and has a high degree of crystallinity and a unique 3D network structure [5], is commonly applied in biomedical and other niche applications. Microfibrillated cellulose or cellulose microfibrils (MFC) can be considered as the fourth type of NC, although with poor properties and characteristics compared to the original three types and possibly with end-use applications of lower value [6].

In principle, NC-based materials have the potential to revolutionize a wide range of industries, from packaging and textiles to biomedical engineering and electronics [7]. The raw materials used to produce NC are diverse and depend on factors such as availability, cost, and environmental impact [8]. The most commonly used raw materials for the production of nanocellulose include pulp obtained from wood chips by a chemical pulping process, agricultural residues such as corn husks, wheat straw and sugarcane bagasse, forestry residues, energy crops, bacterial cellulose, algae, cotton, etc. [9].

Nanocellulose can be produced by different technologies, each with its own advantages and limitations. One of the most common technologies is mechanical treatment, in which cellulose fibers are subjected to large shear forces that disintegrate them to smaller particles. This method is primarily used to produce NFC; however, NCC can also be produced by mechanical processing [10]. In this case, the resulting NC particles vary in size and shape, depending on the process steps and the conditions applied. Another common method for the production of NC is chemical treatment, in which cellulose is separated and dissolved and then precipitated in the form of NCC particles [11]. It is known that this technology can produce NC with high purity and well-defined properties, although it requires the use of harsh chemicals and can be energy intensive [12]. In contrast, bacterial synthesis of NC requires the use of specific strains to produce cellulose filaments; it also includes post-treatment methods in order to form BNC structures [13]. In addition to the above well-established technologies, there are numerous other typical or novel methods for NC production, e.g., TEMPO-oxidation, electro-spinning, enzymatic hydrolysis, ultrasonication, ionic liquid treatment, supercritical fluid processing, plasma, etc.; they have been reviewed previously [14]. Overall, each of these production technologies brings various benefits and constraints, and the final choice depends on the specific application and the desired properties of NC.

The importance of nanocellulose properties stems from the nanoscale dimension of particles and/or fibers [15]. Probably, the most remarkable properties of nanocellulose are (a) large surface-to-volume ratio; (b) high mechanical strength despite low weight; (c) optical properties, including high transparency and birefringence; (d) electrical properties, including high dielectric constant and piezoelectricity; (e) biocompatibility and biodegradability; and (f) sustainability, due to its natural origin and renewable character. In summary, and also according to a relevant review [16], the unique properties of NC make it a promising material for a wide range of applications. One of the key drivers for the NC market is the ever-growing demand for renewable and biodegradable materials, especially in the packaging industry [17]. NC offers several advantages over conventional packaging materials, including superior strength, barrier properties, and biodegradability. It is also lightweight and can be produced from renewable sources, making it an attractive alternative to petroleum-based plastics. Other industries where NC is increasingly applied are composites, electronics, and biomedicine [18]. In composites, NC is used to enhance the strength and durability of materials, while in electronics, it is being explored as a sustainable alternative to conventional conductive materials. In biomedicine, it is mainly used in drug delivery, tissue engineering, and wound healing [19]. These industrial applications, including also textiles, construction, food/feed, energy, water treatment, value-added products, cosmetics, biosensors, ultrafiltration, etc., and the future potential of NC-based materials have been discussed in detail elsewhere [20].

With the goal of harnessing the promising potential of NC, there is a growing number of companies involved in the production and commercialization of NC, ranging from startups to established corporations. For example, CelluForce from Canada is the world's largest manufacturer of NCC for coatings, adhesives, and composites. Firlean Technologies is a UK-based company that produces MFC for paper and boards, composites, and other applications. USA-based American Process Inc. is developing BioPlus, the brand name of a NC material used for packaging, paper and board, and composites. Stora Enso is a Finnish company that manufactures both MFC and NCC for similar applications. Melodea Ltd. is an Israeli company that has developed a proprietary technology for the production of NC from forestry wastes. Finally, Nippon Paper Industries from Japan and Innventia AB from Sweden produce NC from wood pulp. These are just a few examples of companies active in the NC industry [6–10,21–24]. As the demand for sustainable materials continues to grow, it is likely that more companies will enter the market and existing companies will expand their NC-based product offerings.

Driven by the increasing demand for renewable and high-performance materials, the nanocellulose market has grown rapidly in recent years. The global NC market size was valued at USD 319.5 million in 2021 and is expected to reach USD 1.063 billion by 2028, at a CAGR of 22.2% during the forecast period [25]. Geographically, the largest markets for NC are North America and Europe, owing to the presence of a large number of manufacturers and increasing investments in research and innovation (R&I) [26]. However, Asia-Pacific is expected to be the fastest growing market for NC in the coming years, driven by the increasing demand in the emerging economies of this region, such as China and India [27]. Despite its many advantages, the adoption of NC as a commercial material faces several economic barriers that should be addressed before widespread use. For example, one major barrier is the production cost, which can be relatively high compared to other materials, especially when NC is of bacterial origin [28]. The market price of nanocellulose currently varies widely and depends on several factors, including the type of NC, the raw materials, the production technology and the intended application [29]. To date, the price of NC can range from a few tens to several thousands of USD/kg, depending on the production scale and the quantity and quality of the product purchased. The price of NFC can range from approximately USD 10/kg to thousands of USD/kg. If enzymes are used for production, the price of NCC starts at USD 50/kg and in some cases exceeds USD 7000/kg [30]. It should be noted that these prices are subject to change in the near or distant future due to the dynamic market conditions and product availability.

Considering the above challenges as a prelude for R&I on NC, the present study aims to highlight the techno-economic barriers and identify possible future solutions for production at large technology readiness levels (TRLs). To this end, previously available studies (TEA) are consulted and a new preliminary feasibility study is conducted; the results are presented in the context of a short overview. Several economic factors, including capital and operating costs and KPIs, such as the production cost (PC) and the minimum product selling price (MPSP), are considered. A simple model is developed that simulates the entire production process under different operating scenarios and case studies. As a result, the economic feasibility of NC is evaluated in comparison with alternative production technologies, raw materials, and types. The study concludes with an analysis of all major economic and market barriers. In addition, conceptual options to improve the future potential of NC in terms of cost efficiency and sustainability are discussed.

2. Methodology

2.1. Overview of the Production Flow-Sheet

A preliminary techno-economic analysis is conducted to evaluate the feasibility of manufacturing and operating a nanocellulose plant. The technical analysis of the technology used and the main financial aspects are considered. The objective is to determine the technical and economic viability of the proposed plant and to identify possible options for improvement. Initially, a detailed flow-sheet was developed to outline the different steps of NC production and to present the different options in terms of technology applied and type of NC produced. The different NC production routes, identified as three distinct scenarios, were simulated based on in-house experimental procedures, and the parameter values were obtained from available experimental data. Figure 1 depicts the adopted flow-sheet, which was created in the form of a block diagram in Microsoft Visio; it contains the main process steps for isolating three types of nanocellulose (i.e., NCC, NFC, and MFC), assigned equally in number scenarios. *Phalaris aquatica* L., an energy crop with low lignin content, was utilized as lignocellulosic feedstock. It was provided in dried and ground form after cultivation, harvest and pretreatment.

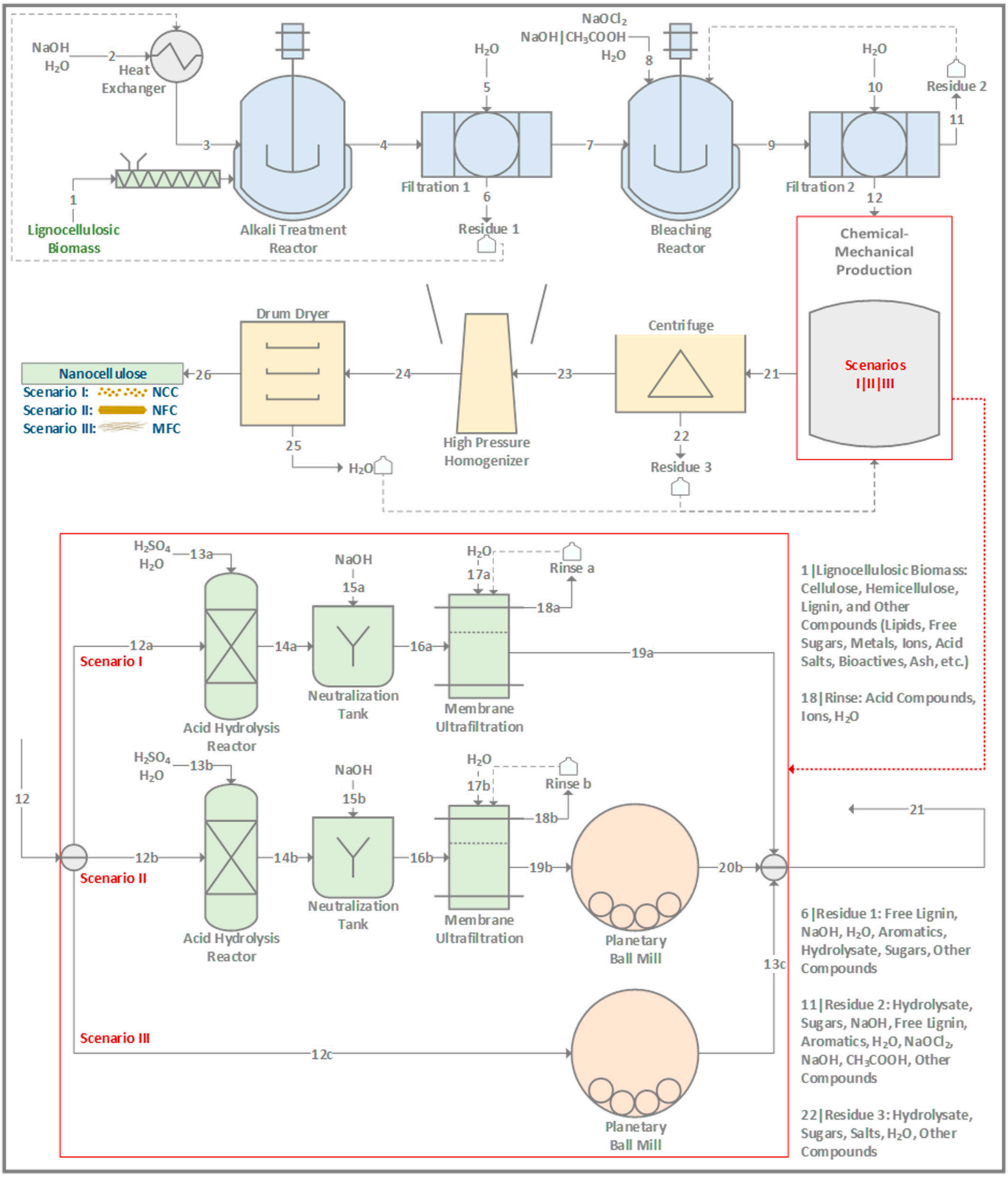

Figure 1. Process flow-sheet for the production of three types of nanocellulose (NC) following different scenarios. Scenario I: production of NCC via acid hydrolysis. Scenario II: production of NFC via acid hydrolysis and ball milling. Scenario III: production of MFC via ball milling.

As can be seen in Figure 1, lignocellulosic biomass (stream 1) was conveyed to the alkali treatment reactor, where also a NaOH solution (stream 2) was added after being preheated to 70 °C in a heat exchanger (stream 3); the reactor was operated at the same temperature. The alkali treated biomass (stream 4) was then filtered and washed with distilled water (stream 5) to neutral pH. Subsequently, the filtration residue was removed (stream 6), while the treated biomass was fed (stream 7) into the bleaching reactor (70 °C), together with the bleaching agent solution consisting of equal parts of acetate buffer and aqueous chlorite (stream 8). The bleached biomass (stream 9) was filtered and washed with distilled water (stream 10) to neutral pH. Filtration residues (stream 11) were also removed from this step. Thereupon, three different scenarios were defined.

2.2. Detailed Description of Nanocellulose Producing Scenarios

In Scenario I, acid hydrolysis of alkali-treated and bleached biomass (stream 12) was performed in a similar reactor to the two other previous chemical steps (45 °C), using an aqueous sulfuric acid solution as homogeneous catalyst (stream 13). The pH of the resulted suspension (stream 14) was neutralized with NaOH (stream 15), and the produced nanocellulose (in the form of NCC; stream 16) was washed with H_2O (stream 17) and purified via membrane ultrafiltration (stream 19); impurities were also removed (stream 18). In Scenario II, a planetary ball mill was included in the flow-sheet immediately after the membrane ultrafiltration step to facilitate the formation of NFC (stream 20). In Scenario III, the ball mill replaced all previous steps and was directly connected to the second filtration unit, thus leading to the formation of MFC. Subsequently, in all scenarios, the product suspension (stream 21) was concentrated by centrifugation and homogenized (stream 23), after the removal of final residues (stream 22). Finally, purified nanocellulose (stream 24) was dried to remove residual H_2O (stream 25) and recover the final NCC/NFC/MFC product (stream 26). Notice that significant attention should be given also to the method for and extent of nanocellulose drying, since it can negatively impact the physical, chemical, and end-use properties of the final produced material, according to a recent research study [31].

2.3. Economic Analysis and Case Studies

The process flow-sheet above provides the basis for solving the mass and energy balances and then determining the detailed capital (CAPEX) and operating (OPEX) costs of the plant. The profitability of the plant is then evaluated by the calculation of a number of economic KPIs (i.e., production cost, PC; minimum product selling price, MPSP; return on investment, ROI; pay-out time, POT; venture profit, V). In detail, the economic analysis is based on the cost–benefit analysis, in which the main capital investment and operational costs are broken down and the net benefit is defined. The methodology used for the economic analysis was adopted from previous relevant studies [32–40]. In addition, two basic environmental KPIs are calculated related to the consumption of energy and fresh water. A sensitivity analysis is also performed to analyze the influence of selected process parameters on the production cost of nanocellulose. All calculations for solving the plant mass and energy balances, as well as the financial analysis, are carried out in Microsoft Excel. Notice that for the equipment operating in batch mode in the research lab, the mass and energy balances are established by first flattening the operation to a “pseudo” continuous mode.

The base case study capacity of the plant, in terms of nanocellulose production volume, was set to 2000 tn/yr (see Section 3). An additional case study was also examined by considering an optimization case, where the values of selected key-process parameters were regulated to levels that minimize the NC production cost. Finally, the analysis of the TEA results, coupled with the results of similar TEA studies on nanocellulose production, facilitates the identification of technical and economic ‘hot-spots’ and opportunities to improve the relevant technology.

3. Analysis of New Scenarios for Nanocellulose Production

The economic feasibility of the proposed technology for NC production was analyzed via TEA of the three identified scenarios in two case studies. As explained in Section 2, the three scenarios differ in terms of the method used to form nanocellulose. In Scenario I, a chemical protocol was applied to produce NCC; in Scenario II, a combined chemical-mechanical process was used to produce NFC; and in Scenario III, the mechanical protocol replaced the chemical process to produce MFC.

Initially, the effect of plant capacity on NC production cost (PC) was investigated in the range 1–5000 tn/yr. The objective was to determine a plant capacity (for all scenarios) that minimizes operational and economic risk. This can be achieved by identifying a value (or even a range of values) with relatively low impact on the variation of PC; at the same time, the market demand for NC should easily cover the total amount of NC produced in this specific plant. As can be seen in Figure 2, this parameter has a large impact on PC for small plant capacity values (up to 1000 tn/yr). More specifically, the value of PC decreases sharply when the capacity increases slightly; this correlation is less strong when the capacity increases to values > 1000 tn/yr. Indicatively, the value of PC is USD 275.75/kg for 10 tn/yr of NC produced, USD 34.11/kg for 100 tn/yr, and USD 5.66/kg for 1000 tn/yr (for Scenario I). Looking at both the main and embedded graph in Figure 2, a clear plateau can be seen for larger capacities, i.e., >1500 tn/yr. Therefore, to minimize the impact of intentional changes or unintentional fluctuations in plant capacity, it is safe to select the value of 2000 tn/yr for the base (first) case study (CS1). For this specific plant capacity value, the PC of NCC, NFC, and MFC were calculated to be USD 3.67/kg, USD 4.39/kg, and USD 3.44/kg, respectively; similarly, the MPSP values of NCC, NFC, and MFC were USD 6.43/kg, USD 7.46/kg, and USD 5.81/kg, respectively (see also the small box in Figure 2). It should be noted that the production cost for NFC in Scenario II was the highest among all scenarios because of the addition of the planetary ball mill to the flow-sheet (compared to Scenario I). On the contrary, the cost of producing MFC in Scenario III had the lowest PC due to the absence of the acid hydrolysis reactor, the neutralization tank, and the membrane ultrafiltration unit.

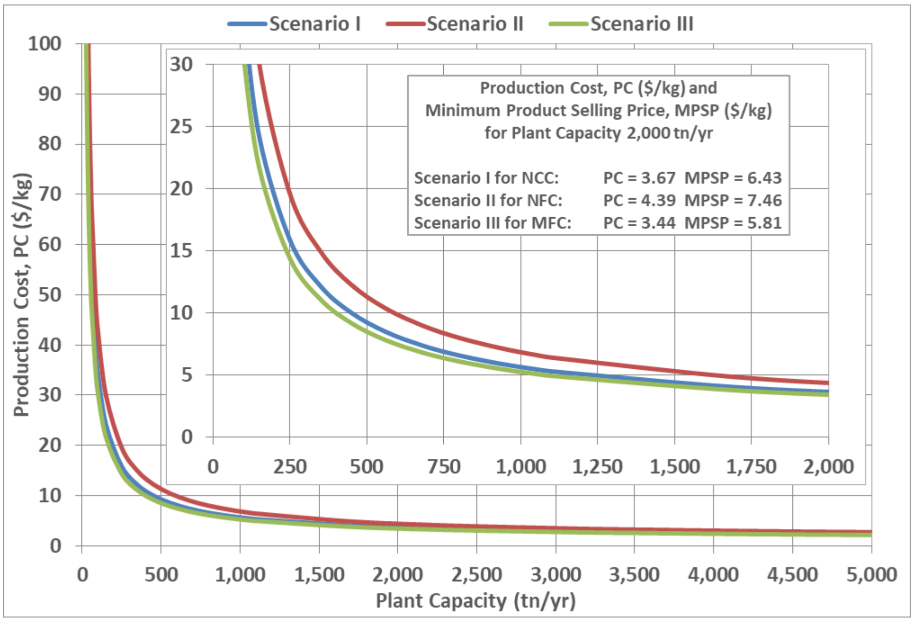

Figure 2. Effect of nanocellulose plant capacity on the production cost (PC) of NCC in Scenario I, NFC in Scenario II, and MFC in Scenario III.

After selecting 2000 tn/yr as the plant capacity of CS1, a detailed analysis of economic and environmental KPIs was performed. As a first step, the detailed costs of major equipment was calculated based on the solution of mass and energy balances. As shown in Figure 3, similarities and analogies can be observed in the equipment costs for the three scenarios, especially up to the bleaching-filtration process steps. On the other hand, the addition of the planetary ball mill increased the total cost of major equipment in Scenario II. More specifically, the total major equipment cost (MEC) was USD 2,959,817, USD 3,292,088, and USD 2,540,261 for Scenarios I, II, and III, respectively. Moreover, for all scenarios, the alkali treatment and bleaching reactors were among the most significant pieces of equipment in terms of purchase costs. In Scenarios I and II, the centrifuge and membrane ultrafiltration unit also contributed significantly to the total cost, while in Scenarios II and III, the planetary ball mill also played an important role. Based on the MEC values, the total CAPEX for the three scenarios was calculated by considering all direct, indirect and other costs (see Table 1). Overall, the total fixed capital expenditures (CAPEX) were calculated equal to USD 17,631,629, USD 19,610,493, and USD 15,132,338 for Scenarios I, II, and III, respectively.

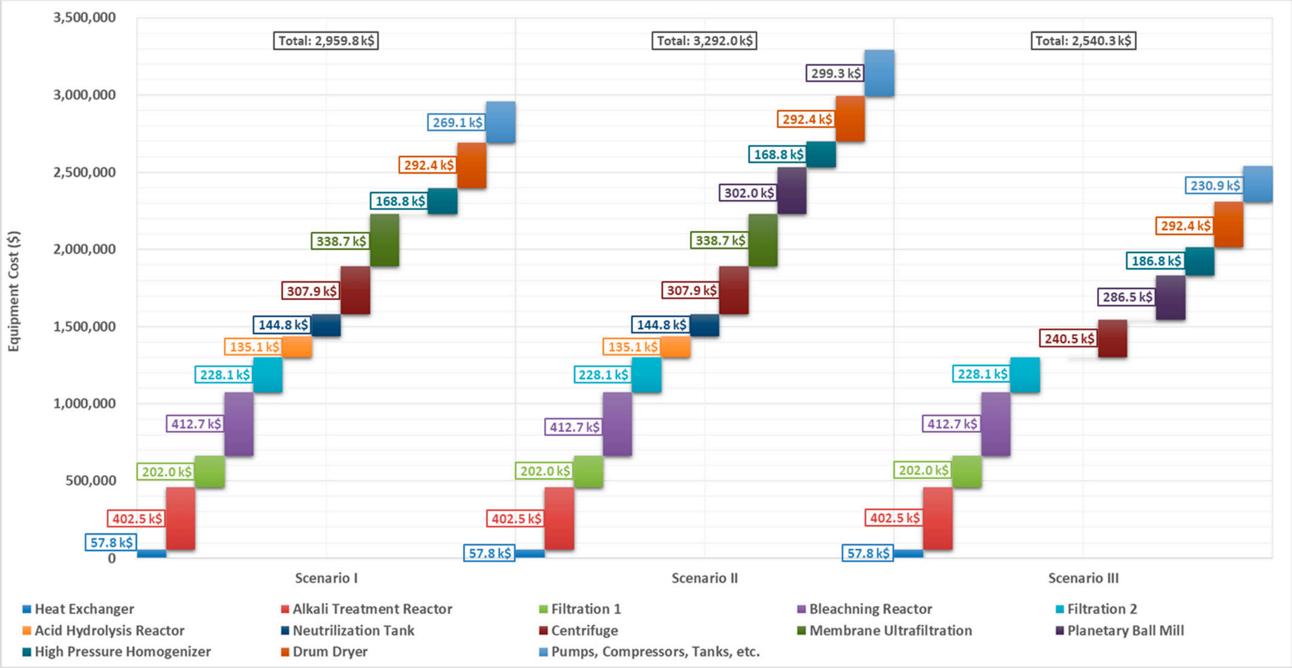

Figure 3. Distribution of major equipment cost (MEC) for the production of NCC in Scenario I, NFC in Scenario II, and MFC in Scenario III.

The detailed results of the base (first) case study (CS1) economic analysis are summarized in Table 1. Similarly to CAPEX, the order of OPEX values (from maximum to minimum) corresponds to the respective values of Scenario II (USD 8,789,837/yr), then I (USD 7,342,332/yr), and finally III (USD 6,883,896/yr). Again, the bulk of this effect is attributed to the planetary ball mill and in particular the associated energy consumption, especially for NFC production in Scenario II. Despite the simpler flow-sheet of Scenario III (as explained previously), a significant increase in the OPEX value is also observed, because of the energy intensive mechanical production of nanocellulose fibers, both at micro- and nanoscale. This conclusion is also reflected to the specific energy consumption values (SEC) calculated for Scenarios II and III (>1 $\mathrm{kWh_{el}/kg}$ for both), which are approximately 2.5 to 3 times larger than the value calculated for Scenario I (0.38 $\mathrm{kWh_{el}/kg}$). On the other hand, Scenario III is the most environmental-friendly scenario in terms of fresh water consumption since the specific water consumption (SWC) was calculated equal to 0.27 kg/kg of product due to the simplicity of the mechanical protocol used for MFC production.

The final economic evaluation of the three scenarios was made according to the estimated values of the selected economic KPIs. In addition to PC and MPSP, other KPIs were calculated to provide information on the profitability and expected economic impact of the proposed technology. Notice that the product price (PP) was set to 130% of the MPSP in all cases, i.e., USD 8.36/kg for NCC, USD 9.70/kg for NFC and USD 7.55/kg for MFC. This choice ensures minimal risk to market penetration of the three nanocellulose types/products and effectively prevents potential competition. It should also be emphasized that these prices are significantly lower than those used currently for the purchase of nanocellulose, particularly NCC (>USD 50/kg) and NFC (>USD 10/kg) [21]. Based on this analysis, all three scenarios showed positive and promising economic potential: in all cases, ROI was >20% and POT was <2.2 yr, while the venture profit (V) values were in the range USD 1,743,146–2,239,316/yr. Taking into account that the present price/value of NCC is larger than the price/value of the other two NC types, Scenario I can be considered the most promising overall. However, driven by the different applications that NFC and MFC can fulfil, a potential investment in a nanocellulose production plant according to Scenario II or III, respectively, can also be considered profitable and sustainable.

Table 1. Detailed economic analysis for the production of NCC in Scenario I, NFC in Scenario II, and MFC in Scenario III.

Cost/Value	Scenario I	Scenario II	Scenario III
Major Equipment Costs, MEC (USD)	2,959,817	3,292,008	2,540,261
Other Direct Costs, ODC (USD)	8,109,898	9,020,102	6,960,317
Direct Costs, DC (USD)	11,069,715	12,312,111	9,500,578
Indirect Costs, IC (USD)	2,190,264	2,436,086	1,879,794
Other Costs, OC (USD)	2,071,872	2,304,406	1,778,183
Fixed Capital Investment, FCI (USD)	15,331,851	17,052,602	13,158,555
Working Capital, IW (USD)	2,299,778	2,557,890	1,973,783
Total Fixed Capital Investment, CAPEX (USD)	17,631,629	19,610,493	15,132,338
Raw Materials Costs, RMC (USD/yr)	905,327	901,869	778,369
Utilities Costs, UC (USD/yr)	379,606	1,091,048	772,536
Labor Costs, LC (USD/yr)	147,660	147,660	147,660
Waste Treatment Costs, CWT (USD/yr)	148,039	148,039	110,636
Other Direct Production Costs, ODPC (USD/yr)	930,638	1,030,571	804,050
Direct Production Costs, DPC(USD/yr)	2,511,271	3,319,187	2,613,252
Annual Fixed Costs, AFC (USD/yr)	2,943,715	3,274,100	2,526,442
General Costs, GC (USD/yr)	176,471	192,216	155,837
Total Production Costs, OPEX (USD/yr)	7,342,332	8,789,837	6,883,896
Production Cost, PC (USD/kg)	3.67	4.39	3.44
Minimum Product Selling Price, MPSP (USD/kg)	6.43	7.46	5.81
Product Price, PP (USD/kg)	8.36	9.70	7.55
Total Revenue, TR (USD/yr)	16,720,338	19,407,406	15,107,268
Gross Profit, GP (USD/yr)	9,378,006	10,617,569	8,223,372
Net Profit, NP (USD/yr)	5,455,596	6,161,415	4,769,614
Return on Investment, ROI (%)	21.85%	21.69%	21.66%
Pay-out Time, POT (yr)	2.19	2.17	2.16
Venture Profit, V (USD/yr)	1,929,270	2,239,316	1,743,146
Specific Energy Consumption, SEC (kWh_{el}/kg)	0.38	1.03	1.02
Specific Water Consumption, SWC (kg/kg)	0.59	0.60	0.27

Following the above economic analysis of the three scenarios under CS1, a sensitivity analysis was also performed to identify the most significant (key-process) parameters and to investigate their impact on the production cost of nanocellulose. Upon preliminary considerations and calculations (data not shown), the following parameters were selected for this analysis: plant capacity, NC yield associated with the efficiency of acid hydrolysis and/or ball milling step(s), biomass cellulose content, biomass lignin content, alkali treatment yield, bleaching yield, and catalysts concentrations in terms of NaOH, $NaOCl_2$ and H_2SO_4. Accordingly, the values of these parameters were increased and decreased by 10% compared to the values used in CS1. The corresponding effects on the percentage change of PC are presented in Figure 4. As can be seen, despite the previous attempt to limit the effect of plant capacity, it still remains the most important parameter, followed by NC yield. Considering other technical parameters, such as the catalyst concentrations and yields of the other two chemical process steps (i.e., alkali treatment and bleaching), it is clear that additional efforts should be made to optimize and intensify the integrated process. In addition, the selection of lignocellulosic biomass type for conversion to nanocellulose is an equally important factor, as primarily cellulose content and secondarily lignin content have a strong impact on PC. Undoubtedly, the biomass source should have a sufficiently high cellulose content, combined with the lowest possible lignin content (e.g., *P. aquatica* lignocellulosic biomass used here).

Subsequently, the conclusions of the above sensitivity analysis were used to define an additional (second or optimized) case study (CS2). For this purpose, the values of all seven parameters were set to the level (10% increase or 10% decrease) that reduces the production cost of nanocellulose. Thereupon, the detailed economic analysis of CS2 was performed and compared with CS1 in Table 2. Notice that this analysis was performed only for Scenario I; however, similar conclusions can be drawn by examining the other two scenarios. In addition, the NCC product price for Scenario I was kept constant between the two cases studies to better compare the economic KPIs.

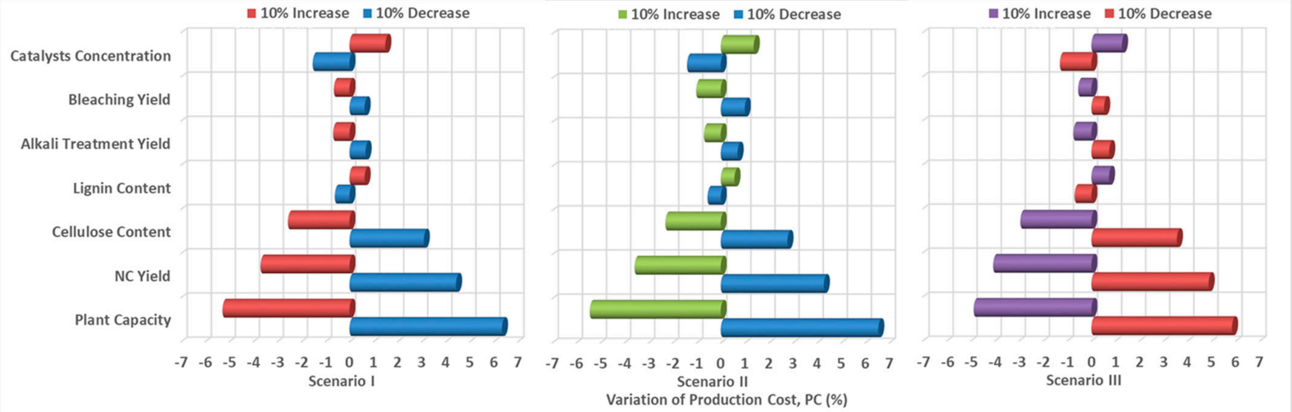

Figure 4. Sensitivity analysis of the effect of selected process parameters on the variation of the production cost (PC) of NCC in Scenario I, NFC in Scenario II, and MFC in Scenario III.

As expected, both the economic performance and the environmental footprint of the plant were significantly improved by CS2. The production cost was reduced to USD 3.36/kg, maximizing total revenues and, to some extent, improving gross and net profits. The POT was reduced to about 2 years and the ROI was increased to 24.34%; both values can be considered promising for this type of technology. Finally, the V value was increased by 22.63%, which is a clear indication of the even more positive economic evaluation of the plant under the optimized CS2. Beyond the economic KPIs, the two environmental KPIs considered were also improved: energy and water consumption per kg of NCC produced were reduced to 0.32 kWh_{el}/kg and 0.48 kg/kg, respectively.

Table 2. Comparison of base (CS1) and optimized (CS2) case studies for the production of NCC in Scenario I.

Cost/Value	Base Case Study (CS1)	Optimized Case Study (CS2)
Fixed-Capital Investment, FCI (USD)	15,331,851	14,625,463
Total Fixed-Capital Investment, CAPEX (USD)	17,631,629	16,819,282
Total Production Costs, OPEX (USD/yr)	7,342,332	6,723,320
Production Cost, PC (USD/kg)	3.67	3.36
Minimum Product Selling Price, MPSP (USD/kg)	6.43	7.46
Product Price, PP (USD/kg)	8.36	9.70
Total Revenue, TR (USD/yr)	16,720,338	16,720,338
Gross Profit, GP (USD/yr)	9,378,006	9,997,019
Net Profit, NP (USD/yr)	5,455,596	5,729,783
Return on Investment, ROI (%)	21.85%	24.34%
Pay-out Time, POT (yr)	2.19	2.03
Venture Profit, V (USD/yr)	1,929,270	2,365,926
Specific Energy Consumption, SEC (kWh_{el}/kg)	0.38	0.32
Specific Water Consumption, SWC (kg/kg)	0.59	0.48

4. Techno-Economic Considerations for Nanocellulose Production

Techno-economic analysis (TEA) is a methodology for evaluating the economic feasibility of a given technology or process [31]. When applied to nanocellulose production, TEA can help identify the key factors affecting production costs and determine the potential scaled-up production to achieve commercial viability.

4.1. Overview of Techno-Economic Analyses of Nanocellulose Production

Few TEA studies on NC production have been carried out so far, with different considerations depending on the raw material used, the production method, the type of produced NC, and the scale of production. A detailed overview of the existing TEAs from the open literature and the present study is presented in Table 3. In what is probably the first systematic attempt to evaluate the feasibility of nanocellulose production, de Assis et al. [32] conducted a TEA on NCC production using already available information from an existing pilot plant. Various operational scenarios were investigated for the proposed technology, which was based on standard mechanical and chemical pulping process steps. NCC production cost (PC) was calculated to be in the range USD 3.6–4.4/kg, with feedstock cost and capital investment being the main cost drivers for all scenarios. In addition, the authors discussed the possibility of improving the economics of nanocellulose by maximizing the biomass to nanocellulose yield, especially in the acid hydrolysis reactor, and by minimizing the raw material costs. In this case, alternative sources from wastes and residues could be considered.

Table 3. Overview and comparison of available techno-economic studies on nanocellulose production according to different technologies and research scenarios.

Ref. #	Raw Material	Production Technology	Research Scenarios	Capacity [1] (tn/yr)	Product Type(s)	Cost/ Price [1] (USD/kg)	Start Year	Country
[32]	Dissolving pulp	Size reduction and acid hydrolysis	Acid recovery and plant co-location or not	17,500	NCC	3.6–4.4 [2]	2019	USA
[33]	Bleached softwood Kraft pulp	Mechanical (milling) and acid hydrolysis	Standalone or integrated to an existing plant	30,000	MFC	1.8 [2]	2014	Finland
[34]	Bleached eucalyptus Kraft pulp	Acid and enzymatic hydrolysis	Alternative hydrolysis processes	4250	NCC	7.8–50 [2]	2017	Brazil
[35]	Sugarcane bagasse	Thermochemical pretreatment and alkaline/acid hydrolysis	Various pretreatment and extraction methods	400,000–460,000	Non-specified NC	0.7–3.1 [2]	2022	Colombia
[36,37]	Sugarcane bagasse	Pretreatment, enzymatic and acid hydrolysis	Organic and inorganic acid catalysts	1500–2400	NCC NFC	6.9–10.9 [3]	2021	Brazil
[38]	Oil palm fronds	Thermochemical pretreatment and acid hydrolysis	Base, best and worst case scenarios	25,000	NCC	1.2–1.5 [3]	2020	Malaysia
[39]	Miscanthus	Alkali treatment and bleaching	Biorefinery with multiple products	18,000–91,000	MFC	1.5–3 [2]	2019	Korea
[40]	Woodchips	Mechanical treatment and bleaching	Various biorefining scenarios	42,000	NCC NCF	1.7–2.5 [3]	2021	Canada
This study	*Phalaris aquatica*	Chemical and mechanical protocols	Different scenarios and types of NC	2000–2800	NCC NFC MFC	3.4–3.7 [2] 4.0–4.4 [2] 3.1–3.4 [2]	2023	Greece
[41]	Commercial saccharose	Fermentation and extrusion	Single scenario	60,000	BC film	63.8 [2]	2022	India
[42]	Beet molasses	Multi-step fermentation	Single scenario	500	BC	14.8 [2]	2016	Portugal

[1] Approximate values. [2] Production cost (PC). [3] Minimum product selling price (MPSP).

In a previous study, Vanhatalo et al. [33] analyzed the mechanical/chemical production of MFC in two alternative production plants, a stand-alone mill and a mill integrated into an existing pulp plant. They concluded that the integrated process offered greater economic benefits due to operational savings and reduced investment risk. It should be noted that the PC value calculated in this study (i.e., USD 1.75/kg) is of the lowest among all studies; however, MFC is considered the product of the lowest quality compared, e.g., to NCC or NFC. A similar feedstock (i.e., bleached eucalyptus Kraft pulp) was used years later by Rosales-Calderon et al. [34] for NCC production based on sulfuric acid and enzymatic hydrolysis technologies in stand-alone facilities. The results showed that the estimated nanocellulose PC by acid hydrolysis was significantly smaller than the corresponding PC by enzymatic hydrolysis (USD 7.8/kg and USD 49.3/kg, respectively) due to the high cost of enzymes. However, the particularly low capital costs of the enzymatic hydrolysis made it clear that this process is potentially profitable if drastically intensified in the future. In any case, the proposed technology offered the potential to operate competitively. It should also be noticed that water purification and wastewater treatment were the two process steps with the highest capital costs, indicating the general need to reduce fresh water consumption.

In one of the most recent TEA studies, Ospina-Varón et al. [35] studied the production of NC using lignocellulosic wastes (i.e., sugarcane bagasse) generated in Colombia. The design and analysis were based on different pretreatment methods for isolating cellulose and also different nanocellulose extraction methods. According to the economic results, the steam explosion pretreatment scenario had the lowest production cost (approximately USD 0.7/kg) and the largest economic margin. These values are quite promising for the feasibility of this specific plant, but there are clear risks with regard to the availability of biomass outside this area and the questionable market penetration due to the presumably unrealistically large production capacity. Sugarcane bagasse was also used by Bondancia et al. [36] for the preparation of both NCC and NFC, using different hydrolysis routes. Specifically, TEA (coupled with a life-cycle assessment, LCA) was performed to assess the economic performance of both organic and inorganic acid hydrolysis. The authors found out that the minimum product selling price (MPSP) values varied in the range USD 6.9–10.9/kg, simultaneously emphasizing the importance of recovery and reuse of the homogenous catalysts. Considering the comparatively small plant in terms of NC capacity (e.g., compared to the study in [35]), sugarcane bagasse can be seen as a promising feedstock, especially for NCC, but only in the sense of a biorefinery. This TEA investigation was based in part on a previous study by the same group [37], in which the importance of citric acid for nanocellulose production was first discovered technically and then verified economically. Eventually, in-house production of citric acid was suggested as a way to make the proposed technology sustainable. A feasibility study also based on an actual pilot plant for NCC production from agricultural wastes (i.e., oil palm fronds), was published by Qing et al. [38]. For nanocellulose production, a typical, albeit fully automated and controlled, process flow-sheet with a low estimated MPSP (USD 1.2–1.5/kg) was considered. Based on the results of various simulation scenarios, the authors assumed that the up-scaled NCC production facility can be economically sustainable for the established conditions in the Malaysian economy and market, provided that the availability of raw materials is ensured.

In a different approach, Lan et al. [39] developed and analyzed a biorefinery fed with an energy crop (Miscanthus) and operating under various scenarios. The economic KPIs were evaluated based on the co-production of xylose, xylo-oligosaccharides (XOS), and MFC for different biorefinery capacities. As expected, the results showed that the increasing biorefinery capacity can significantly reduce the production cost. Moreover, after a 12-step improvement analysis, all scenarios studied were promising enough to provide clear economic benefits. The best-case scenario was the one with the production of MFC at a PC of USD 2.5/kg. Another biorefining model, this time based on woodchips, was developed by Blair et al. [40]. This so-called forest biorefinery assumed the production of high-value materials, specifically NCC and NFC, in addition to cellulosic sugars and lignin. Of the two scenarios studied, only the second one included the co-production of nanocellulose. It was found that the estimated MPSP of nanocellulose (USD 1.7–2.5/kg) was significantly lower than the corresponding values of typical nanocellulose production methods. On the contrary, the characterization of NC revealed some unusual properties that raised doubts about the quality of the produced material. In all simulations, capital costs, product values, and energy costs had the greatest impact on MPSP.

Among the above studies, the technology proposed here was conceptually applied to chemically and mechanically produce three types of NC, namely NCC, NFC, and MFC. As discussed in detail in Section 3, the NC production cost for these products varied in the respective ranges: USD 3.14–3.67/kg, USD 4.04–4.39/kg, and USD 3.14–3.36/kg. By performing a sensitivity analysis and evaluating the impact of key-process parameters, an optimization case study was also conducted. This allowed the identification of clear economic and environmental 'hot-spots' for future intensification of the proposed technology. Beyond the plant capacity as a factor, the three chemical process steps (alkali treatment, bleaching, and acid hydrolysis, involved in all three scenarios) and the mechanical process step (planetary ball mill, involved only in Scenarios II and III) should be the subject of research and innovation for potential improvement and optimization. In addition, the choice of biomass and especially its composition is of paramount importance for the economic viability of the process. Finally, the consumption of energy and fresh water should be reduced by possible utilization of plant residues, e.g., in an anaerobic digestion plant for biogas production and recovery of thermal and electrical energy, and by efficient water purification and recycling steps.

Behera et al. [41] focused on bacterial cellulose (BC, not BNC) and conducted a TEA for a relatively simple plant based on a two-step fermentation process. BC filaments were produced at a production cost of approximately USD 63.8/kg, a value that seems prohibitively high compared to the other cases in Table 3. However, the authors exploited the large value of bacterial cellulose in general to demonstrate the economic feasibility of the plant. An appropriate sensitivity analysis identified the fermentation units as 'hot-spots' for future optimization to reduce the production cost. In a similar though earlier approach, Dourado et al. [42] collected numerous experimental data on bacterial cellulose from the open literature and combined them in a feasibility study. The production cost of BC was calculated to be USD 14.8/kg, a value significantly lower than the previous study, mainly due to the low-cost feedstock used as substrate (beet molasses). From the previous two TEA studies it is clear that the biotechnological processes for NC production are very capital intensive, associated with low to medium BC yields and high operating costs. Although only the process steps for the fermentative production of BC—and not the process steps for the successive conversion of BC to BNC—were considered, major economic barriers to the commercialization of BNC are already identified.

4.2. Nanocellulose Production Cost and Market Barriers

As highlighted in the previous section, NC production cost varies significantly depending on the feedstock, the production technology, the type of NC produced and the scale of production. These and other factors may limit the economic viability of NC, at least for certain applications, especially those that require large quantities of the material, such as materials for construction, paper packaging, and automobile parts [43]. In general, mechanical production technologies such as high-pressure homogenization and ball mill are more energy intensive and therefore more expensive than chemical methods [44]. In the former processes, the production is influenced by factors like the equipment used, the associated energy consumption and the quality of raw material [45]. For example, the use of specialized equipment like a high-pressure homogenizer or a planetary ball mill can significantly increase the production cost of NC, while the use of lower quality raw materials can result in lower conversion yields and poorer quality of the product. In addition, chemical technologies can be also expensive due to the cost of chemicals used in the process, such as sulfuric acid, hydrogen peroxide, organic acids, and TEMPO reagents [44]. These chemicals require also careful handling and disposal, which can drive up the overall production cost. Moreover, the drying of nanocellulose is also considered one of the most important issues in terms of production cost, storage and transportation [46]. However, as the demand for nanocellulose increases, there is a growing focus on developing more cost-effective and sustainable production methods. For example, researchers are exploring the use of enzymes and other natural catalysts as alternatives to chemical reagents, which could reduce the cost and, more importantly, the environmental impact of nanocellulose production [47]. Overall, NC production cost is expected to decrease as production methods become more efficient and sustainable, and as the economies of scale are achieved through increased demand and production volumes [48].

An additional economic barrier, apart from the actual production cost, is the limited availability of nanocellulose on a commercial scale. Although several NC production technologies exist, only a few companies are currently producing it on a large scale (see Section 1); this fact limits the general availability of nanocellulose and drives up its cost.

Moreover, there is a lack of standardization practices and general regulations for the production of nanocellulose, which can make it difficult for buyers to compare the quality and properties of the different materials available [49]. Potential investments for a new nanocellulose production plant are not easily justified and supported because of the unestablished market for nanocellulose. Although there is a growing interest in nanocellulose as a sustainable and high-performance material, there are still many industries and applications in which it is not yet used [50,51]. Therefore, it may be challenging for companies to predict the future demand for the material and eventually develop pricing strategies that are competitive with existing materials.

5. Conclusions

Nanocellulose can be produced from a variety of sources; the choice depends on factors such as availability, cost, and environmental impact, which greatly affect the NC production cost. In addition, the properties of the resulting product can vary depending on the feedstock and the production technology. These two factors can directly affect the suitability of NC for different applications and thus its market potential. As research and innovation continues in NC-based technologies, new sources and methods for nanocellulose production are expected to be identified and developed, further expanding its potential applications over the years. Overall, the value of nanocellulose lies in its potential to produce sustainable, high-performance, and value-added products in a wide variety of industries.

Some techno-economic studies on NC production have shown that the nanocellulose production cost can be competitive, especially in applications where the unique properties of nanocellulose offer significant advantages and economic value. However, other studies have identified several key economic barriers to the widespread adoption of nanocellulose, including high raw material costs, energy-intensive production methods, and lack of established markets for nanocellulose-based products. These barriers make it difficult for nanocellulose producers to achieve the economy of scale needed to compete with conventional materials. On the other hand, despite its high cost, nanocellulose offers the potential to add value and improve sustainability in a number of industries, which currently justifies its higher price for certain applications. In this sense, there are technical and economic limits to the entirety of NC production technologies and methods. In general, a particular manufacturing method can only be distinguished from the others in terms of the intended application and the desired properties of NC. Specifically, in the case of biotechnological routes for BNC production, the really high costs currently limit its application to high-value niche markets. Both NCC and NFC can be more cost-effective than BNC, although with significant challenges in production scale (i.e., plant capacity), market penetration, and even environmental impact.

In the coming years, innovative and intensified technologies for NC production are expected to continue to emerge and further expand the range of applications for this promising material. In addition, they are expected to reduce the overall NC production cost and make it more competitive in the short or medium term. In order to achieve this, and in general to overcome the technical and economic barriers mentioned above, the efficiency and scalability of NC production should be specifically improved. This includes alternative technologies to optimize the process flow-sheet with cost-effective production methods and to reduce the costs of raw materials, energy and equipment. It also includes establishing quality and performance standards and identifying new markets and applications for nanocellulose. These improvements can increase the profitability of relevant projects and investments and enhance their competitiveness in the market. To the extent that these barriers are overcome, it is likely that nanocellulose will become an economically viable and widely used material that will provide significant benefits to both industry and environment. For the latter goal, numerous environmental aspects should also be considered in the framework of life-cycle assessment (LCA) studies. Overall, the NC market is expected to continue to grow in the coming years, driven by industrial demand for sustainable and high-performance materials. As production methods become more efficient and cost-effective and new applications are discovered, it is likely that the market will continue to expand and provide new opportunities for growth and innovation.

Author Contributions: Conceptualization, G.P., A.P. and C.K.; methodology, G.P. and A.B.; validation, G.P., A.B. and A.P.; formal analysis, G.P. and C.K.; investigation, G.P., A.B. and A.P.; resources, G.P. and C.K.; data curation, G.P., A.B. and A.P.; writing—original draft preparation, G.P. and A.B.; writing—review and editing, G.P., A.P. and C.K.; supervision, G.P. and C.K.; project administration, G.P., A.P. and C.K.; funding acquisition, G.P. and C.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH—CREATE—INNOVATE (Project name: High Performance Industrial Materials based on Nanocellulose—HIPERION; project code: T2EDK-01394).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AFC	Annual Fixed Costs
BNC	Bacterial Nanocellulose
CAGR	Compound Annual Growth Rate
CAPEX	Total Fixed Capital Investment
CS	Case Study
CWT	Waste Treatment Costs
DC	Direct Costs
DPC	Direct Production Costs
FCI	Fixed Capital Investment
GC	General Costs
GP	Gross Profit
IC	Indirect Costs
IW	Working Capital
KPI	Key Performance Indicator
LC	Labor Costs
MEC	Major Equipment Costs
MFC	Microfibrillated Cellulose
MPSP	Minimum Product Selling Price
NC	Nanocellulose
NCC	Nanocrystalline Cellulose
NFC	Nanofibrillated Cellulose
NP	Net Profit
OC	Other Costs
ODC	Other Direct Costs
ODPC	Other Direct Production Costs
OPEX	Total Production Costs
PC	Production Cost
POT	Pay-out Time
PP	Product Price
R&I	Research and Innovation
RMC	Raw Materials Costs
ROI	Return on Investment
SEC	Specific Energy Consumption
SWC	Specific Water Consumption
TEA	Techno-economic Analysis
TEMPO	2,2,6,6-tetramethyl-1-piperidinyloxy
TR	Total Revenue
TRL	Technology Readiness Level
UC	Utilities Costs
V	Venture Profit

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