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Technoeconomic assessment of bacterial nanocellulose production from second generation sugars derived via the OxiOrganosolv pretreatment process

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Abstract

The techno-economic performance of bacterial nanocellulose (BNC) production by *Komagataeibacter* sp has been evaluated in a process utilising second generation sugars, more specifically glucose derived from forestry residues via their delignification pretreatment and subsequent enzymatic hydrolysis towards sugars. Two distinct scenarios were evaluated. In the first scenario, the end product was BNC with 15 wt. % moisture, it involved a drying step. In the second scenario, the end product was a BNC hydrogel containing 99 wt. % water. To achieve a payback period (PBP) of 8 years minimum selling prices of 202.9 €/kg and 2.07 €/kg were calculated for scenarios A and B respectively. A sensitivity analysis showed that the main contributor to the process cost was the fixed capital investment (FCI) and more specifically the cost of the seed growth reactors and the tray bioreactors that accounted for around 77 % of the FCI. In terms of annual costs, peptone as a raw material, electricity costs and wastewater treatment costs were the main contributors. Designing a more efficient process with lower cost bioreactors, higher automation and shorter fermentation cycles can help cut down the total product cost. In addition, understanding how dewatering and drying of the BNC affect its properties and designing an efficient drying section is key to minimizing process costs. Strategies for wastewater treatment also need to be considered as there are high volumes of wastewater that necessitate its efficient and sustainable treatment so that ideally fresh water consumption is minimized.

List of Acronyms

- BNC: Bacterial Nanocellulose
- CNF: Cellulose Nanofibers
- CNC: Cellulose Nanocrystals
- COL: Operating Labor Expenses
- CRM: Raw Material Expenses
- CUT: Utilities Expenses
- CWT: Wastewater Treatment Cost
- DCF: Discounted Cash Flow
- DD: Delignification Degree
- DM: Dry Matter
- FCI: Fixed Capital Investment
- FOB: Free-on-Board
- HS: Hestrin–Schramm
- MACRS: Modified Accelerated Cost Recovery System
- MARR: Minimum Acceptable Rate of Return
- MSP: Minimum Selling Price
- NPV: Net Present Value
- OD: Optical Diameter
- PBP: Payback Period
- PC: Plant Cellulose
- TEA: Techno-Economic Evaluation
- TPC: Total Product Cost
- VVM: Vessel Volumes per Minute

Keywords: technoeconomic evaluation, sensitivity analysis, bacterial nanocellulose, biorefineries, second generation sugars

Highlights

- BNC production resulted in a selling price of 202.9 €/kg and a PBP of 8 years.
- NPV was estimated at 21.5 M € for a total plant lifetime of 30 years.
- The Fixed Capital Investment was the main contributor to the selling price of BNC.
- Seed growth reactors and bioreactors costs accounted for 77 % of equipment cost.
- Raw materials and wastewater treatment costs are critical to the process design.

1. Introduction

1.1 Background and Importance of Bacterial Nanocellulose (BNC)

There is an increasing demand for sustainable and biodegradable materials, chemicals and fuels that has resulted in increased interest in biorefinery technologies that can provide appropriate solutions. In this context, plant cellulose (PC) is considered a valuable resource due to its availability, renewability, and natural degradability. PC can be recovered from different types of lignocellulosic biomass such as forestry and agricultural residues (Moniri et al. 2017). A more interesting variant of cellulose is nanocellulose.

Overall nanocellulose is divided into two types, cellulose nanofibers (CNF) and cellulose nanocrystals (CNC), both of which are derived from plant sources (Wong et al. 2025). Typically, CNF and CNC are produced with an array of treatment/extraction processes from plant cellulose including mechanical, chemical, and enzymatic methods (Zhou et al. 2021; Jirathampinyo et al. 2023; Hu et al. 2024). However, lignocellulosic biomass is not the sole source of cellulose; it can also be produced from microorganisms, such as Gram-negative and Gram-positive bacteria, e.g. *Acetobacter* and *Agrobacterium* and *Lactobacillus*, that have been found capable of synthesizing cellulose (Gromovkykh et al., 2017, Jonas and Farah, 1998; Saleh et al., 2022). Bacterial nanocellulose (BNC) is produced predominantly by acetic acid bacteria of the genus *Komagataeibacter* (e.g., *K. xylinus*), that convert carbon sources such as glucose directly into cellulose microfibrils during aerobic fermentation (Brugnoli et al., 2025; Rajasekharan et al., 2021). Moreover, BNC has no lignin, pectin or hemicelluloses in its structure (Skočaj 2019; Abol-Fotouh et al. 2020). In addition, BNC is well within the nanoscale with fiber diameters ranging from 20 to 100 nm and demonstrates exceptional properties and unique characteristics, including higher crystallinity, liquid absorption capacity, degree of polymerization, superior mechanical properties, high strength, Young's modulus, significant surface area and biodegradability, making it highly sought after for applications in advanced composites, packaging, biomedical engineering, filtration membranes, and sustainable materials research (Chen et al. 2016; Barja 2021).

A distinct advantage of BNC is that it may be grown on external scaffolds and thus be shaped in different ways and sizes facilitating the fabrication of tubes, spheres, scaffolds or membranes according to tailored specifications and niche applications such as materials and biomedical applications (Luo et al. 2019; Wang et al. 2020; Sreedharan et al. 2024). Typically formed as a hydrated pellicle containing over 99 % water, BNC is extensively utilized in biomedical scaffolds, wound dressings, cosmetic masks, food coatings and biodegradable packaging. Its biocompatibility and tunable properties open avenues for green technological applications in healthcare and sustainable materials (Barja 2021; R et al. 2021; Ong et al. 2023).

1.2 Production Processes and Challenges

Industrial BNC synthesis typically employs feedstocks that resemble the Hestrin–Schramm (HS) medium, formulated with 20 g/L glucose, along with yeast extract, peptone, and mineral salts to supply essential nutrients and cofactors for vigorous bacterial growth and cellulose biosynthesis. The process initiates with medium sterilization, inoculation with an actively growing bacterial culture followed by incubation in shallow reactors or trays to maximize oxygen transfer at the air-liquid interface (Makharita et al., 2025; Phan et al., 2024). Aerobic conditions, controlled pH (5–6), and temperatures around 30°C are maintained, with fermentation periods extending up to 7–10 days, depending on the reactor configuration and productivity requirements (Chen et al. 2019).

During this process, bacteria use glucose both as an energy substrate and as the carbon skeleton for cellulose synthesis. The produced BNC hydrogel, which comprises >99 % water, is subsequently harvested, washed with hot alkaline solutions (typically 0.5 M NaOH at 60°C) for cell removal, and thoroughly rinsed to remove residual impurities (Jagtap and Dastager 2024a). The resulting hydrogel may be further dried under controlled conditions to obtain either films with defined moisture (~15 %) or wet gels for tailored downstream applications.

Despite the high purity and performance of BNC, its industrial-scale production faces significant technical constraints: oxygen transfer limitation due to aerobic fermentation, long batch fermentation cycles necessitating multiple reactors for continuous production and high energy consumption during drying of the hydrogels. The oxygen mass transfer rate and bioreactor design critically govern productivity, while the week-long batch process constrains the throughput. Additionally, drying energy for removing over 100 times the dry mass in water is a major cost driver, although the critical drying effect is not in terms of cost but rather in terms of how it affects the nanocellulose properties (Andree et al., 2021).

1.3 Technoeconomic Aspects, Current Bottlenecks and Market Potential

Technoeconomic analyses consistently identify feedstock cost (glucose or alternative carbon sources), media components (peptone, yeast extract), and energy demands (drying, sterilization) as primary factors influencing production cost and profitability. Glucose and nutrient media typically account for 35–45 % of operating expenses, followed by energy utilities at 25–35 %. Sensitivity studies highlight that improving yield, reducing glucose cost, and optimizing energy consumption are critical levers to enhance economic viability. Using low-cost feedstocks such as lignocellulosic hydrolysates offers promising cost reductions but requires addressing associated inhibitors and process complexity (Blair and Mabee 2021). In addition, sensitivity analyses highlight that accelerating fermentation and enhancing drying efficiency are the largest levers for cost reduction (Phan et al., 2024; Rajasekharan et al., 2021).

Despite elevated production costs relative to plant cellulose derivatives, the unique purity and biocompatibility of BNC support high-value applications in medical, cosmetic, and packaging sectors. This niche market justifies ongoing research and investment in process innovation and scale-up. Recent advances focus on continuous or fed-batch fermentation, process intensification, and integration of energy recovery systems to offset utility demands (Kargupta et al. 2023; Wong et al. 2025). There is also great interest in composite materials, hybrid scaffolds, and nanostructured BNC-based systems (Jonas and Farah 1998; Moniri et al. 2017; Folmann Lima et al. 2023).

Despite economic hurdles, the unmatched combination of properties and the potential for biotechnological advancements position BNC at the forefront of next-generation sustainable

biomaterials research and commercialization. Ongoing research into new feedstocks, metabolic engineering of producing strains and new reactor architectures will be vital for future breakthroughs.

1.4 Review of Previous Technoeconomic Evaluations

Technoeconomic models for BNC production have been developed in the literature, typically based on batch fermentation using synthetic (glucose-based) or renewable (lignocellulosic hydrolysate) substrates. Low overall carbon conversion efficiencies are noted (~0.25 kg BNC/kg glucose) and the necessity for substantial batch capacities to achieve economies of scale (Blair and Mabee 2021). Moreover, high cost sensitivity to substrate, energy, and culture medium composition was noted while there seem to be opportunities for substantial cost reductions with continuous processes, improved reactor aeration, and valorization of side streams (Chen et al. 2019; Kargupta et al. 2023; Putranto et al. 2025). Alternative carbon sources and bioprocess innovations hold the key to more competitive and sustainable BNC supply chains, provided technical and regulatory challenges can be addressed.

There are a few technoeconomic assessments in the literature that have analyzed BNC production from different carbon sources, focusing on costs, process configurations, and scalability. Most studies model a batch fermentation process using synthetic glucose media with varying assumptions on bioreactor size, aeration efficiencies, and downstream processing. Capital expenditures are heavily influenced by bioreactor design and drying equipment due to batch operation and the volumetric oxygen transfer needs.

For instance, Dourado et al. found that for an industrial plant with a capacity of 504 tons of wet BNC per year, the total capital investment was around US\$ 13 million. Around 71 % of this corresponded to direct costs (DC) from equipment and relevant installation auxiliary costs such as piping, instrumentation, electrical facilities, building costs, and land. Indirect costs were around 29 % of the total capital cost and consisted of engineering and construction costs. To achieve profitability, the market price for BNC was assumed to be US\$ 25 per kg and resulted to net profit amounts of US\$ 3.3 million per year and a payback period of 4 years. It should be highlighted that the selling price of US\$ 25 per kg refers to wet BNC that contains around 99% water; on a dry basis this price increases by at least 100-fold. Clearly, BNC can be profitable when it finds niche application that can justify its high selling price. Another critical parameter in BNC production technologies is the use of water. Forte et al. (2021) assumed that 36 tons of water are used per kg of dry BNC that is produced, indicating the intensity of the process in terms of use of water resources; 98 % of the used water was assumed to be returned to the environment without further treatment. They also found that around 31.6 MJ per kg of dry BNC was needed, indicating the energy demands of the process; 27 % of the energy demand was during the static culture fermentation. These are critical constraints as wastewater treatment can be a significant cost contributor and needs to be carefully considered.

2. Materials and Methods

In this section, a detailed analysis of the critical steps of the technoeconomic analysis is presented, focusing on providing details on the biomass source and how the second-generation sugars were produced, the actual production setup that was used to convert the sugars to nanocellulose and the main assumptions that were made.

2.1 Description of biomass source and pretreatment

In previous work a novel pretreatment process was developed, a variant of the organosolv pretreatment process, named OxiOrganosolv. OxiOrganosolv, is an oxidative organosolv pretreatment method that replaces traditional homogeneous acid catalysts with oxygen gas to delignify biomass, enabling a milder, acid-free approach. The process uses water-organic solvent mixtures (30–70 % v/v) at 150–200 °C and employs O₂ gas to drive delignification. It has been demonstrated to effectively delignify both beechwood (hardwood), pine (softwood) where traditional organosolv process typically fails to achieve high delignification degrees (DD) and corn stover (agricultural residue) in prior work (Katsimpouras et al. 2017, 2018; Kalogiannis et al. 2020; Asimakopoulou et al. 2021). In summary, the key underlying mechanisms and advantages are the fact that the primary mechanism involves oxidative cleavage and removal of lignin facilitated by oxygen, increasing cellulose accessibility while preserving cellulose integrity. This approach aims to avoid acid-catalysis, reducing corrosion and acid-stream handling requirements. In addition, the process is very flexible, able to use different solvents, temperatures, times, and O₂ pressures, pretreating efficiently different types of lignocellulosic biomass. The design goal was a versatile fractionation process capable of adapting to various biomass inputs. The main milestones and achievements of the OxiOrganosolv were high DDs 95 %, close to 100 % cellulose recovery in a low-lignin pulp, production of highly fermentable cellulose pulps suitable for downstream bioprocessing, minimal formation of sugar degradation products such as 5-hydroxymethylfurfural (HMF) and furfural (Kalogiannis et al. 2020). The OxiOrganosolv pretreatment process offers significant advantages for generating high-purity fermentable sugars from lignocellulosic biomass, ideal for subsequent bacterial nanocellulose (BNC) production using *Komagataeibacter medellinensis*, a strain noted for its robust glucose utilization and high BNC yields. Unlike conventional acid or alkaline pretreatments, OxiOrganosolv achieves >90% cellulose-to-glucose conversion while minimizing inhibitory byproducts like furfural or hydroxymethylfurfural that hamper *Komagataeibacter* fermentation (Zou et al. 2017).

Based on previous work, wheat straw leftover biomass was successfully delignified with the OxiOrganosolv process resulting in a cellulose rich pulp that was used as a sugars source. More specifically, wheat straw was pretreated with the OxiOrganosolv process utilizing a water and acetone (50:50) mixture, oxygen as the reaction gas, and a reaction temperature of 175°C for 120 min. The process resulted in a solubilization rate of 55.2% and significant delignification, achieving 88.1% lignin removal. The pretreated wheat straw pulp had a cellulose content of 84.4 % and a reduced hemicellulose content of 8.9 %. Residual lignin was 1.9 % and 0.9 % for the acid-insoluble and acid-soluble fractions respectively. This highlights the effectiveness of the pretreatment in enhancing cellulose accessibility while removing non-cellulosic components. This optimized OxiOrganosolv pretreated wheat straw served as the substrate for subsequent enzymatic treatments to isolate and functionalize cellulose.

2.2 Glucose production method from lignocellulosic biomass

The cellulose-rich solid fraction obtained from the OxiOrganosolv pretreatment was saccharified via enzymatic hydrolysis, following a previously described method. Hydrolysis was carried out using the commercial cellulolytic cocktail Cellic® CTec2 (Novozymes A/S, Denmark), quantified at 95.6 mg/mL protein content via Bradford assay. Reactions were set up in 250 mL Erlenmeyer flasks at 50 °C, shaken at 160 rpm, with an initial dry matter (DM) content of 9 % (w/v) and an enzyme dosage of 9 mg g⁻¹ solids in 80 mM phosphate buffer (pH 5), targeting a hydrolysate sufficiently rich in sugars to support *Komagataeibacter medellinensis* growth. The wheat straw hydrolysate had a sugar concentration of 58.70 ± 4.3 and 5.74 ± 0.4 for glucose and xylose respectively, as evaluated via HPLC.

2.3 Bacterial nanocellulose production setup

Komagataeibacter medellinensis cells together with the associated nanocellulose were harvested from fresh agar plates, resuspended in HS medium that was produced from the hydrolysates of wheat straw. They were then mechanically dispersed to detach the polymer, followed by centrifugation and adjustment of the supernatant to OD₆₀₀ = 1.2 to standardize the inoculum. Cultures were inoculated at 0.1 % (v/v) into fresh HS medium and incubated statically at 26 °C for 15 days with a 1:5 liquid-to-flask ratio, promoting reproducible bacterial nanocellulose pellicle formation that was favored at the air-liquid interface. Throughout the incubation period, no agitation was applied, allowing the bacteria to develop stable cellulose pellicles and optimizing the structural integrity of the produced nanocellulose. The productivity was found to surpass 5 g/L of dry BNC and this is the value we used for our technoeconomic analysis, a value that can be further increased in the future with optimization. After cultivation, BNC pellicles were purified by alkaline treatment (5 % w/v KOH), extensively washed to neutral pH and freeze-dried to constant weight.

2.4 Technoeconomic analysis methodology: parameters, cost assumptions, models

In this work an industrial process for bacterial nanocellulose production was designed and evaluated based on experimental findings. To simplify this study, some assumptions were made. First of all, the sugar streams are considered a raw material that can be bought from the market rather than including the pretreatment process in the technoeconomic evaluation (TEA). The aim was to focus the study and discussion on the nanocellulose production scheme without the added complexity and uncertainty introduced by the production of second generation sugars. A cost for the sugars of around 450 euros per ton is assumed, similar to the cost of first-generation sugars, this however is not the case for second generation sugars that are still not competitive in terms of pricing as the various lignocellulosic pretreatment technologies are still under development. The production capacity of the plant is 100 tonnes of dry bacterial nanocellulose per year, however, the final product is also considered to contain 15 wt. % moisture as completely drying the bacterial nanocellulose can have a detrimental effect on some of its properties (Andree et al., 2021). Therefore, the actual production in terms of end product is 117.64 tonnes of bacterial nanocellulose containing 15 wt. % moisture.

This TEA is preliminary (accuracy up to ± 30 %) targeting the estimation of the Fixed Capital Investment (FCI) and the Total Product Cost (TPC). The FCI was estimated by multiplying the Free-on-Board (FOB) equipment purchase cost with a Lang factor of 5, to showcase the novelty and hence uncertainties of the technology (Dheskali et al. 2017). The TPC was calculated on an annual basis and covers the period that the industrial plant operates. The TPC was determined considering the FCI, the operating labor expenses (COL), the raw material expenses (CRM), wastewater treatment cost (CWT) and the utilities expenses (CUT) using equation (1) taken from Turton et al. (Turton et al. 2008):

$$TPC=1.22(CUT+CRM+CWT)+2.66*COL+0.195*FCI \quad (1)$$

The cost of utilities used in this study (Table 2) has been taken from Turton et al. (2008), while the CUT was estimated by multiplying the utility requirements presented in Table 2 with the unitary costs. The cost of raw materials and the corresponding annual quantities are used for the calculation of the CRM. The COL has been estimated considering the workers per shift required for the plant operation, the total number of workers required in the industrial plant based on the annual plant operation (multiplied by 4.5), the working time of each worker and the average annual labor cost.

A discounted cash flow (DCF) analysis was performed to assess the profitability of the proposed process. The assumptions for performing the DCF analysis were adopted by Humbird et al. as follows: the interest rate is 10 %, the plant lifetime is 30 years (not including the 3 year construction phase), the equity financing is 50 %, the depreciation is 7 years based on the Modified Accelerated Cost Recovery System (MACRS), the corporate tax rate is 35 %, the duration of the plant construction is 3 years, the percentage of project costs is 8 %, 60 % and 32 % for the 1st, the 2nd and 3rd year of the plant construction period respectively, the working capital is 5 % and the salvage value and land purchase costs are considered zero (Humbird et al. 2011). The techno-economic indicators used for the assessment of process profitability are the Net Present Value (NPV) and the Minimum Selling Price (MSP) that corresponds to a PayBack Period (PBP) of 8 years. A sensitivity analysis took place to better understand the effect of the main cost contributors, such as FCI, cost of raw materials and electricity, on the NPV.

3. Results and Discussion

In this section, a thorough discussion takes place, focused on the nanocellulose production scheme, material and energy balances, equipment sizing and costs, detailed costs breakdown leading to economic and sensitivity analyses.

3.1 Bacterial Nanocellulose Production Scheme

The process diagram of BNC production begins with the feeding of raw materials from storage tanks into a mixing vessel for the preparation of the culture medium. The prepared medium then passes through a continuous sterilization system, which consists of two heat exchangers and a holding tube. Upon exiting, it is cooled to fermentation temperature and is ready to be introduced into the seed production reactors and the tray bioreactors.

In this production scheme, well known industrial practices were chosen for growing the initial bacteria that will later produce the nanocellulose. More specifically, the inoculum protocol described by Humbird et al. (2011) was adopted; in this case there is a direct transfer of cells without a cell concentration step. The process starts off with a small-scale bioreactor that is fed part of the sterilized culture medium. The required inoculum volume corresponds to 10 % of the culture medium volume in each bioreactor. The very first bioreactor is a laboratory scale one that produces the first inoculum. In this process scheme 6,000 liters of inoculum are required, corresponding to the $6 \times 10^3 \text{ m}^3 = 60,000$ liters of medium needed daily from the 6 bioreactors that start a fresh production cycle. Therefore, the first vessel needs to produce 60 liters of inoculum that will be fed to the next bioreactor that will in turn produce 600 liters of inoculum that will feed the reactor that will produce the 6,000 liters needed for the tray bioreactors. Bioreactors of total volume of 100 liters, 1,000 liters and 10,000 liters are sufficient to produce the corresponding inoculum for each step. These reactors are part of the two seed

reactor trains presented in figures 1 and 2. To simplify the production scheme, the 100-liter bioreactor is not taken under consideration; due to its lab scale volume, it can work separately from the rest of the production process and is also cheap to obtain and operate. In addition, the culture medium that is spent for the initial growth of the inoculum in each step is also contributing in the final BNC production and therefore, no additional raw materials are needed. This is a rational hypothesis as BNC-producing bacteria such as *Komagataeibacter xylinus* have been found to accumulate intracellular precursors like UDP-glucose during the growth phase. These are then polymerized into cellulose chains even as external carbon sources are exhausted. This enables a second phase of pellicle formation in static cultures, where bacteria shift to stored metabolites or alternative metabolic pathways for sustained biosynthesis (Jacek et al. 2019).

A critical parameter in the design of the production scheme is the fermentation time necessary for each step. Typically, the seed or bacteria growth stage needs between 1 and 3 days. *Komagataeibacter xylinus* and similar bacteria primarily undergo adaptation and growth with minimal or no nanocellulose production, transitioning to BNC synthesis in the exponential or stationary phase thereafter. In glucose-based cultures, glucose decreases slowly during the first day, corresponding to the lag growth phase where BNC synthesis is negligible; rapid consumption and production follow over days 2-4. Studies confirm a lag phase of ~6 hours to 3 days before significant BNC mass increase, with pellicle formation aligning with the late exponential/early stationary transition around 24-72 hours (Bagherniya et al., 2021; Melani et al., 2025; Shavyrkina et al., 2021). Each seed growth reactor, the 1,000 L and 10,000 L ones, require 2 days residence time in total. Therefore, given that the production cycle of the tray bioreactors is 8 days, 2 seed trains consisting of a 1,000 L and a 10,000 L bioreactor each can cover the needs of all 48 bioreactors, these are detailed below. In contrast to the tray bioreactors, the seed reactors need not be static ones but can rather be batch agitated and aerated vessels. The objective in these bioreactors is to grow the initial bacteria and not produce the nanocellulose. It has been found that growing BNC under agitation results in small particles rather than well-formed sheets. In addition, BNC produced in agitated culture has a lower degree of polymerization, lower crystallinity, lower mechanical strength, lower content of Ia cellulose (Watanabe et al. 1998). Other issues noted were strain instability, high viscosity, and non-Newtonian behavior of the culture medium due to the production of exopolysaccharides (Bagherniya et al. 2021).

However, this is not an issue during the initial stage of the bacteria growth as the nanocellulose film begins to form after the first 48 hours (Humagain 2018). This was also in accordance to experimental campaigns that were conducted on second generation sugars. Figure 1 presents a Gantt chart of the production scheme of the seed growth and fermentation reactors. The horizontal axis is in days. The light and dark blue bars represent the scheduling of the first seed train, while the grey and black bars represent the second seed train. As explained above in both seed trains the inoculum is grown for 48 hours in each 1,000 L and 10,000 L seed reactor before it is fed to the tray bioreactors; their scheduling is represented by the green bars lasting 8 days each, this includes the preparation of the bioreactor, the growth stage and the unloading of the product and clean up. This is a fairly optimized scheme as there is essentially zero downtime for the most expensive and important equipment, the seed trains and the tray bioreactors. The upstream and downstream equipment is considered to work in a continuous mode, hence there is no need for any type of scheduling. As discussed later on, minimizing the time spent in each of these steps can considerably improve the process economics.

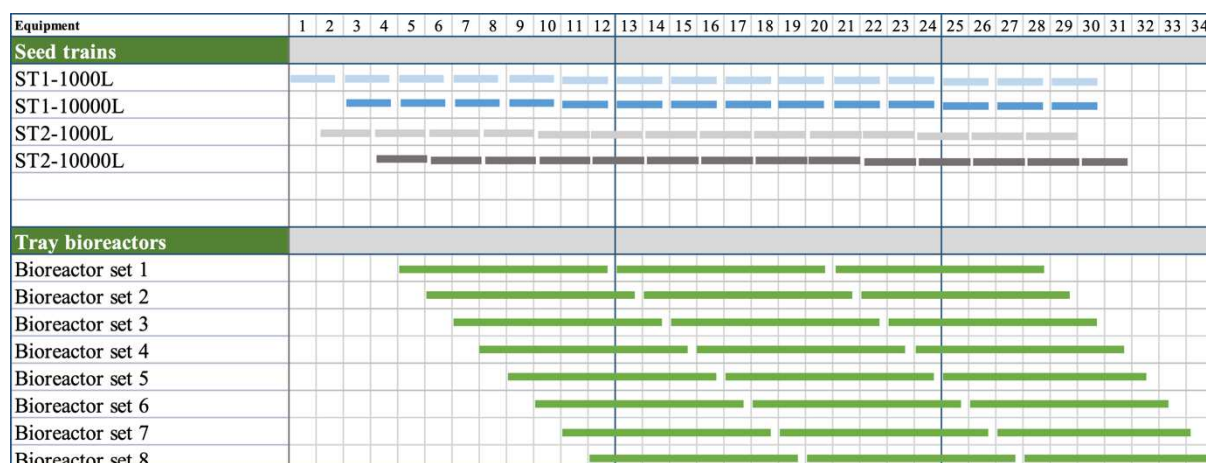


Figure 1. Gantt chart of scheduling of seed trains and tray bioreactors.

The fermentation stage is carried out under static conditions on specially designed trays placed inside a chamber that provides the appropriate conditions (e.g., aeration, humidity, and temperature) for bacterial growth. This static cultivation lasts for 7 days, yielding 5 g/L of BNC (on a dry basis). A complete operational cycle of the bioreactor in this case spans 8 days. To achieve the target annual production of 100 tons of dry BNC, 48 identical bioreactors, each with a capacity of 10 m³, were used. These bioreactors host the culture medium, consisting of second generation sugars, peptone, yeast extract, disodium phosphate, and citric acid. This medium provides the essential nutrients and the appropriate pH for BNC biosynthesis, which occurs as a pellicle at the air–liquid interface.

At the end of the cultivation, the resulting BNC pellicles are transported via conveyor belts at a controlled speed to the washing stage. Here, they are sprayed for 2 hours with a 0.5 M NaOH solution at 60 °C, to remove residual cells and proteins. After alkaline washing, the BNC pellicles continue along the conveyor system and undergo neutralization with deionized water until their pH reaches neutrality and any remaining alkali or impurities are removed. The final stage of the process is drying, which is performed in conveyor dryers. At this stage, the freshly produced BNC, which initially consists of approximately 99 % water, is dried at 50 °C under circulating dry air until the final moisture content is reduced to 15 %, where the remaining 85 % is the dry BNC. The goal of this stage is to achieve the desired moisture content without significantly altering the product's properties. After drying, the BNC is packaged and made available for market distribution. It should also be noted that the production plant is equipped with its own deionized water system (DIS) due to the large quantities required both for washing and for the preparation of NaOH solutions. To simplify the production process, well known technologies for washing and drying were adopted; they employ conveyor belt systems that are reliable and cheap and have been used extensively in relevant industries such as the food industry. Figure 2 presents the flow diagram of the entire bacterial nanocellulose production process.

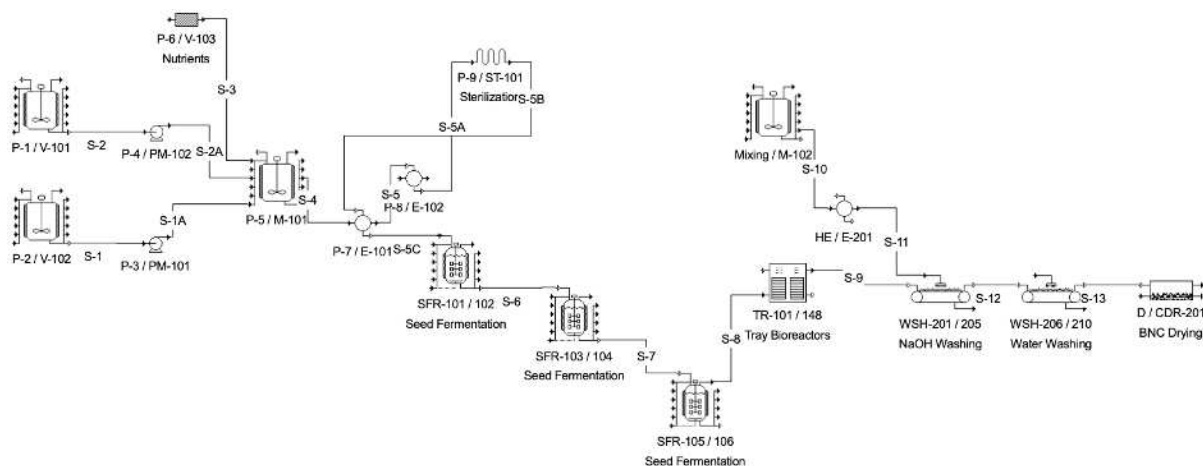


Figure 2. Flow diagram of the bacterial nanocellulose (BNC) production process. P/ PM stands for Pump, V for Vessel, for SFR for Seed Fermentors, ST for Steriliser, TR for Tray Reactor, M for Mixer, WSH for Washer, D/CDR for Conveyor Dryer

3.2 Material balances of the process

In this section the material and energy balances are summarised in the main process steps of the production scheme. A more detailed breakdown of the material balances can be found in the supplementary material; here the most critical aspects are presented.

3.2.1 Medium preparation – Fermentation stage

The most commonly used formulation of the cultivation medium for BNC production is the HS medium, an aqueous solution composed of glucose (2 % w/v), peptone (0.5 %), yeast extract (0.5 %), disodium hydrogen phosphate (Na_2HPO_4 – 0.27 %), and citric acid (1.15 g/L) (Schramm and Hestrin 1954). The medium is prepared in a mixing tank and prior to being transferred to the bioreactors, it undergoes sterilization using the standard method applied in industry, as illustrated in Figure 2.

Vessel V-101 is used for storing glucose (in a 15 % solution), that is fed (stream S-2) into V-103, a mixing tank. Together with the remaining nutrients of the medium supplied via stream S-3 and water provided by the network (stream S-1), these are mixed in V-103 to prepare the cultivation medium. The outlet from the mixing tank is then directed to the continuous sterilization system.

For the mass balance calculations, it is noted that, according to the bench scale results, the yield of the culture is 5 g of dry BNC per liter of cultivation medium. This is a conservative estimate as up to 6.2 g of dry BNC per liter of cultivation medium was achieved in our work. The duration of each fermentation batch, based on literature data and confirmed by our own work, is 7 days, carried out at 30 °C. Fermentation takes place in static bioreactors (trays) with a working volume of 10,000 L, housed in a specially designed chamber that maintains optimal conditions of temperature and aeration for culture development.

The amount produced per batch is calculated to be 50 kg of dry BNC, which represents 0.05 % of the total annual BNC production target. Therefore, to achieve the target of 100 tons of dry BNC per year, it is necessary to conduct 2,000 batches annually. Considering that the plant operates 340 days per year, this corresponds to approximately 6 batches per day. One bioreactor operating 340 days/year with an 8-day full cycle produces 42.5 batches annually). For this reason, 48 identical bioreactors are used, operating in parallel, with 6 bioreactors starting and 6 finishing each day, thereby achieving a production of 300 kg of dry BNC per day; this corresponds to the annual production target of 100 tons.

To simulate the continuous operation of the plant, the mass balance calculations were initially carried out in kg/h, and then converted to the required quantities per batch. First, given that the yield of BNC is 5 g of dry BNC per liter of cultivation medium, the required volume of cultivation medium was calculated to meet the target production of 100 tons of dry BNC per year.

$$V_{medium} = \frac{100,000 \text{ kg/y}}{0.005 \text{ kg/L}} \Rightarrow V_{medium} = 20,000,000 \frac{\text{L}}{\text{y}} \text{ or } V_{medium} = 20,000 \text{ m}^3/\text{y}$$

Having calculated the annual requirement of the cultivation medium and taking into account its composition, as described above, the corresponding flow rates of the remaining nutrients were determined. These results are presented in Table 1.

Table 1. Consumption of components from the HS medium on an annual basis.

Component	g/L	t/y
Glucose	20.00	400.0
Peptone	5.00	100.0
Yeast extract	5.00	100.0
Na ₂ HPO ₄	2.70	54.0
Citric acid	1.15	23.0
Water	966,10	19,323.0
Total		20,000.0

Table 2 presents the aeration requirements of the fermentation stage; the detailed breakdown can be found in the supplementary file.

Table 2. Aeration requirements during the fermentation stage.

Parameter	Value	Unit	Comments
Production of dry BNC	100,000	kg/year	Annual production target
Aeration	0.5	VVM	From literature data
Volumetric air flow rate	300	m ³ /h	During 7 days
Air density	1,164	kg/m ³	At 30 °C and 1 atm
Annual air consumption	117,331	t/y	For the entire plant
O ₂ content in air	21	% (vol)	Typical atmospheric value
O ₂ consumption	63	m ³ /h	During 7 days

3.2.2 Washing stage with NaOH and Deionised Water

Another critical process step is the washing and purification of the produced BNC in a special belt-type filter using a 0.5 M NaOH solution at 60 °C for two hours (de Araújo e Silva et al. 2020; Girard et al. 2024). The purpose of this step is to remove impurities such as cell debris, residual sugars, and proteins. Furthermore, the process following fermentation is considered continuous, with an outlet stream of BNC from the bioreactors equal to 1,250 kg/h (WSH-101). This is consistent with the total daily amount processed by the unit, i.e., 30,000 kg of wet BNC from 6 daily batches, corresponding to 300 kg of dry BNC per day. For every kilogram of dry BNC, 1.13 kg of pure NaOH is required (Forte et al., 2021).

The BNC is subsequently washed with deionized water to remove residual alkaline compounds as well as trace amounts of cellular debris; these are considered negligible in the mass balance calculations. The process is carried out in a manner similar to the NaOH washing stage. The BNC, conveyed at a controlled speed via the WSH-102 conveyor belts, is sprayed with deionized water for a period of 2 hours until it is fully neutralized. After exiting this stage, the now neutral BNC is ready for the drying step and the recovery of the final product. According

to Forte et al., the required amount of washing water is approximately 5 times the mass of the wet BNC (Forte et al., 2021). Thus, a total of ~6,313.5 kg/h of deionized water is required, this corresponds to a daily demand of 151,500 kg. The purified wet BNC exits the neutralization stage (stream S-12) at ~1,250 kg/h, ready for the final drying stage.

3.2.3 Drying stage

For the estimation of the required air quantity as well as the air properties at 50 °C, data from the literature were used (Dute et al., 2025). The volumetric airflow was calculated as 13,448.76 m³/h.

3.3 Energy balances breakdown

The energy balances of the process are presented in detail in the supplementary material. In summary, roughly around 930 kW are needed by the heat exchangers (E-101 and E-102), around 36.5 kW are needed for heating up to 60 °C the NaOH solution (stream S-10) for the washing stage and around 1,098.5 kW are needed for the drying of the BNC in the conveyor belt dryer. The aeration and the agitation electricity costs were considered.

3.4 Equipment sizing

In this section, the results regarding the equipment sizing are briefly presented. Details for more general equipment such as storage and mixing tanks, heat exchangers and pumps are not provided for brevity, however the main assumptions, literature data used and an overall synopsis of this section are provided.

3.4.1 Static Reactors with trays

For the design of the static bioreactors, data from the techno-economic study of Dourado et al. (Dourado et al., 2016) were used, along with reasonable assumptions regarding the thickness of the medium inside the trays, which are summarized in table 5. Each bioreactor was calculated to be able to process 10 m³ of culture medium to achieve an annual production of 100 tons of dry BNC, corresponding to 50 kg of dry BNC per batch. This corresponds to 800 trays, each with a surface area of 0.25 m² (50 cm × 50 cm), resulting in a total active cultivation surface of 200 m² per reactor. With a medium layer height of 5 cm/m², each tray contains 12.5 L of medium, giving a total active culture volume of 10 m³ per reactor, producing approximately 2.5 cm thick BNC per tray. The plant includes 48 bioreactors, each completing a full fermentation cycle in 8 days, thereby enabling the completion of 6 batches per day, with an outlet flow rate to the subsequent stages of about 1,250 kg/h. Table 3 presents the sizing details for the 48 bioreactors. It is important to note that the term static bioreactor refers to a chamber with controlled parameters (temperature, humidity, and aeration), inside which the trays are housed, and the cultivation process takes place.

Assuming a spacing between trays of 0.115 m, and a typical chamber height of 2.4 m, each column can contain 20 trays. Therefore, one reactor with 800 trays will accommodate 40 columns. The total surface area occupied by these tray columns is approximately 10 m² (40 columns × 0.25 m²/tray). Considering an additional 30 % allowance for access, air circulation, and structural needs, the total footprint per reactor is 13 m². Finally, the overall footprint required for 48 static bioreactors is 624 m² (48 × 13 m²). It should be noted that there is a great degree of flexibility in terms of actually implementing this type of design. A potential industrial plant could have different formulations, e.g. larger bioreactors with more columns and hence trays per bioreactor, potentially simplifying the design and reducing costs of auxiliary equipment. On the other hand, an alternative design could opt for more and smaller bioreactors

for better process control, lower danger of contaminating large volumes of feedstock and more flexibility in final product characteristics at the expense of higher auxiliary and personnel costs.

Table 3. Sizing data for TB-01/41 bioreactors.

Parameter	Value
Temperature	30 °C
Full operating cycle	8 d
Fermentation duration	7 d
Culture yield	5 g/L (dry base)
Medium thickness per m ²	5 cm
Active volume	10 m ³
Required active surface area	200 m ²
Tray area	0.25 m ²
Medium volume per tray	12.5 L
Trays/bioreactor (number of)	800
Final wet BNC thickness per tray	2.5 cm
Tray spacing	0.115 m
Chamber height	2.4 m
Trays/column	20
Number of Columns	40
Column footprint	10 m ²
Total reactor footprint	13 m ² (+30% over column area)
Total footprint (48 reactors)	624 m ²

To maintain the necessary oxygen concentration in the fermentation substrate as well as to ensure the optimum temperature conditions, each bioreactor is equipped with an autonomous heated air supply system. The air is introduced into the bioreactor through a duct and is evenly distributed above the trays, contributing both to oxygenation and thermal stability. The supply of heated air is achieved via a centrifugal fan, which draws air from the environment, heats it using electrical resistances up to 30 °C, and subsequently delivers it to the reactor. The system was designed based on the required air flow, which is 0.5 Vessel Volumes per Minute (VVM) per bioreactor, corresponding to 300 m³/h for the 10 m³ volume of culture medium. The characteristics of the fan are presented in Table 4.

Table 4. Bioreactor feed air fan characteristics.

Parameter	Value
Airflow	300 m ³ /h
Static Pressure	400 Pa
Fan Type	Centrifugal
Fan Power	0.165 kW
Fermentation Time	7 d (168 h)
Consumption per batch	27.72 kWh
Annual Consumption	55,440 kWh
Source	ebmpapst.com

Furthermore, to protect the culture from contamination, the incoming air passes through high-efficiency particulate air filters. These filters are made of glass fibers arranged in pleats, providing a large filtration surface. They offer a filtration efficiency of $\geq 99.97\%$ for particles with a diameter of $\geq 0.3\ \mu\text{m}$, according to various standards (e.g., ISO 29463). They are capable of retaining bacteria, dust particles, aerosols, and microorganisms, thus ensuring protection for both the culture and the surrounding environment (Soleha et al. 2024). The combination of air supply and filters guarantee stable and safe fermentation conditions during the BNC production process. Finally, for heating the air from ambient temperature (20 °C) to a fermentation temperature (30 °C), the energy required was calculated from the energy balances to be 0.975

kW per bioreactor. The total annual energy consumption for air heating, as also derived from the energy balances, is 327,600 kWh/y. Including the aeration system, the total energy consumption of the unit during the fermentation stage amounts to $55,440 + 327,600 = 383,040$ kWh/y.

3.4.2 Conveyor Dryer

Drying the BNC is a critical step in the production process. Removing water from BNC, via dewatering and drying, while retaining its nanoscale properties is a major challenge that needs to be overcome to achieve commercialization of BNC products. Indeed, reducing the water content of nanocellulose products is very much needed to reduce their transportation costs; it is also a requirement depending on the end-use applications. There are several different types of drying that can be employed apart from traditional oven drying such as freeze drying, supercritical CO₂ drying and spray drying. Both freeze drying and supercritical CO₂ drying avoid heating up the BNC and thus can avoid its hornification and loss of desirable properties (Andree et al., 2021). However, they are energy intensive and also need specialized equipment that cannot be easily scaled up for industrial purposes. Dewatering by applying pressure is a cheap and well known solution from the paper industry that has also been applied for reducing the water content of CNFs and CNCs that were suspended in water (Sinquefeld et al. 2020). However, this method has not been studied for BNC and may potentially be detrimental to the properties of BNC and the structural integrity of the produced films. More specifically, Andree et al. (2021) found that during drying or pressing at high temperature (100°C), intermolecular hydrogen bonds were formed that resulted in the interconnection of the individual fibres; this led to mechanical stiffening and a denser cellulose nano-fibre network. The water retention capacity of BNC could not be recovered by rehydration. The above were even more pronounced when uniaxial pressure was applied to remove water before drying. The upside of this is that the drying step can be leveraged to control the BNC properties and produce different BNC products (Andree et al., 2021).

In this technoeconomic study, a traditional drying process for the BNC was chosen, carried out in a continuous-operation conveyor dryer, designed for sheet-form materials with high moisture content. In these systems, the product is transported inside the dryer using conveyor belts moving at appropriate speed, while hot air is blown through or over the product layer (Sturgeon 1995). For the sizing of this system, it is necessary to calculate the required drying surface area and the length of the conveyor belt. It should be pointed out that there is a lack of robust data in the literature regarding the drying process of BNC. Several assumptions were made; these may need to be revisited in the future, once more concrete data are available. These details are presented in the supplementary material. The total required surface area of the conveyor dryer was found to be 123.5 m², split in two levels, 61.75 m² each and the energy consumption to achieve the desirable moisture content at the exit was calculated to be 8,996,400 kWh/y.

Finally, the design and sizing of the conveyor belt filters and the deionized water production system used in washing are presented in detail in the supplementary material along with their energy demands.

3.5 Equipment cost

For the estimation of the individual equipment cost of the plant, purchase-cost estimation formulas were used for each type of equipment, taken from literature sources related to the economics of plant design (Peters et al. 2004, 2008). Since most of these formulas give equipment costs in U.S. dollars, the following conversion factor was used: 1\$ = 0.8744 €. In addition, the CEPCI (Chemical Engineering Plant Cost Index) index was applied to estimate costs at the reference year 2024; its value was equal to 798.8.

3.5.1 Seed growth bioreactors

These bioreactors are standard aerated and agitated bioreactors, their technology is well known. For an estimation of the cost, data from Humbird et al. (2011) were used for seed reactor trains at various sizes; these costs refer to complete skids. The costs for both the 1,000 and 10,000 L bioreactors were estimated by employing the following equation obtained from Peters et al. (2004):

$$C_2 = C_1 (V_2/V_1)^n \quad (2)$$

where:

C_2 : cost of the new bioreactor

C_1 : known cost of the reference bioreactor

V_2 : new capacity (volume)

V_1 : known capacity

n : scaling exponent (typically 0.5–0.6 for reactors)

In this work, the known costs for 20 and 200 gallons bioreactors were used along with an exponent value of $n=0.6$.

3.5.2 Static tray bioreactors

The cost of static bioreactors was taken from the literature on BNC production using static trays, and amounts to 115,500\$ @2024 per unit (Behera et al. 2022). Thus, the total purchase cost for 48 bioreactors is 4.85 M €. It should be noted that this price also includes the aeration systems as well as the filters used in each reactor.

The costs and technical specifications of the conveyor belt filters, the conveyor belt dryer, the heat exchangers, the mixing tanks and the deionisation system are presented in detail in the supplementary material.

From the above individual equipment costs, the Fixed Capital Investment (FCI) was calculated; it includes all expenditures required for the construction and operation of the bacterial nanocellulose production plant, excluding operating costs. It is primarily based on the equipment purchase cost, which represents the core of the fixed capital. The FCI can be estimated from the purchase cost of equipment C_p as follows; $FCI=5 \cdot C_p$. Table 5 presents the purchase cost of all equipment to produce 100 tons per year of dry bacterial nanocellulose.

Table 5. Summary of equipment purchase cost for a 100 t/y dry BNC production plant.

Item	Characteristic size	Material	Purchase cost \$/unit	CEPCI	Total purchase cost (M €@2024)
M-101 (mixing tank)	21.20 m ³	SS304	164,746.5	240	0.209
M-102 (mixing tank)	1.25 m ³	SS304	34,735.4	240	0.044
<i>SFR-103/104 Seed reactors 1,000 L</i>	1.00 m ³	SS304	251,095.0	585.7	0.596
<i>SFR-105/106 Seed reactors 10,000 L</i>	10.00 m ³	SS304	339,386.0	585.7	0.807
TR-101/148 (bioreactors)	13.00 m ²	-	-	-	4.848
WSH-201/205 (NaOH belt conveyors)	20.00 m	-	21.0	357.6	0.105
WSH-206/210 (H ₂ O belt conveyors)	20.2. m	-	21.5	357.6	0.106

CDR-201 (Belt conveyor dryer)	62.3*2 = 124.60 m ²	-	641.7	381.7	1.174
E-101 (heat exchanger)	69.67 m ²	SS304	24,888.4	240	0.072
E-102 (heat exchanger)	2.20 m ²	SS304	5,093.8	240	0.015
E-103 (heat exchanger)	0.12 m ²	CS,SS	1.8	395.6	0.003
Holding Tube	L _{ht} = 60.00 m, d _{ht} 0.06m	SS316	72	390.4	0.129
P-101/102 (pumps)	2 hp	SS304	2*1,279.4	-	0.002
DIS (Deionised H ₂ O unit)	-	-	-	-	0.020
V-101 (glucose storage vessel)	182.4 m ³	CS	23,255	240	0.070
TOTAL EQUIPMENT PURCHASE COST (M €)					8.20
TOTAL FIXED CAPITAL COST (M €)					41.01

Figure 3 shows the equipment cost distribution, depicting clearly that the bioreactors are the main contributor.

3.6 Raw material cost

One of the main cost contributors are raw materials. The main raw materials used in this plant are those of the culture medium and the NaOH for washing BNC. Prices for their purchase were obtained from websites such as Alibaba.com and from various other sources for peptone (Cardoso et al. 2020). It should also be noted that glucose is available on the market as a 70 % solution. Since 200 kg/batch is required, the total quantity corresponds to $200/0.7 = 285.71$ kg/batch. With 2,000 batches per year, this results in an annual requirement of ~571.4 t/y of 70 % glucose solution, these data are presented in Table 6.

Table 6. Summary of raw material consumption data for a 100 t/y dry BNC plant.

Raw materials	Price (€/t)	Annual demand t/y	Annual cost (M €/y)	
Culture medium				
Glucose (70%)	450.0	571.4	0.26	(Dourado et al., 2016)
Peptone	6,100	100	0.61	(Cardoso et al., 2020)
Yeast extract	1,700	100	0.17	(Cardoso et al., 2020)
Na ₂ HPO ₄	2,000	54	0.11	(Cardoso et al., 2020)
Citric acid	1,200	23	0.03	(Latif et al., 2025)
Total medium production cost			1.18	
NaOH (98 %)	550	117.61	0.06	*
Total raw material cost (€M)		C_{RM} = 1.24		

As shown below, peptone represents around half of the total raw material cost, due to its high market price. Although this culture medium is considered very suitable for BNC production, it is relatively expensive compared to other non-conventional media. Moreover, it should be noted that the purchase price assumed for the glucose (450.0 €/t) corresponds to the high end of 1st generation sugars. The glucose cost is still a major cost contributor, corresponding at 21 % of the total raw material cost; this will increase given that the cost of 2nd generation sugars can be up to 3,000 €/t (Cheng et al. 2019).

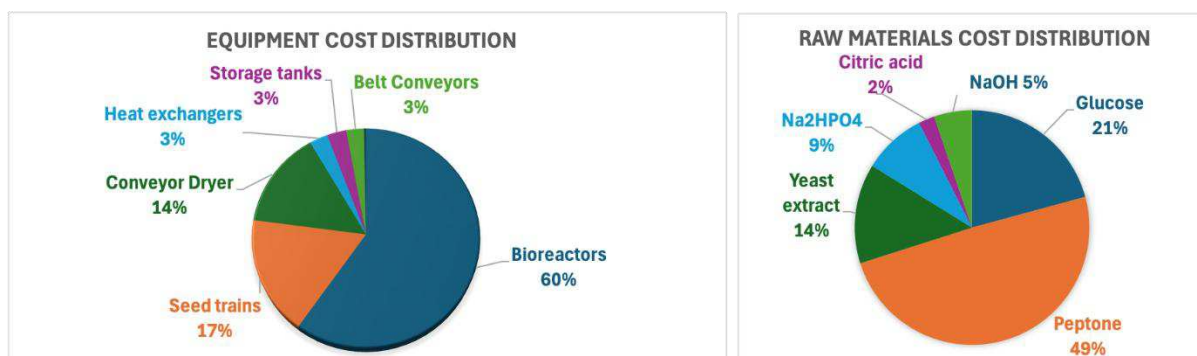


Figure 3. Distribution of raw material and equipment costs.

3.7 Utilities cost

In this plant, the utilities used are electricity, low-pressure steam, and water for the preparation of the culture medium and for the production of deionized water. These costs are classified as direct costs and form part of the total production cost. Total utility costs were estimated at 0.611 M €. The largest share is by far occupied by electricity consumption. This is because the plant primarily relies on the use of electric motors and electric resistances. However, it should be noted that since the required temperatures in the fermentation section are low, this type of direct electric heating could be replaced by much more efficient heat pumps, allowing for a significant cost reduction due to electricity consumption. This is also true for the drying stage of the process as heat pumps can heat air with a significantly reduced energy cost.

3.8 Waste treatment cost

The production process of bacterial nanocellulose is accompanied by the generation of significant amounts of liquid waste, mainly from the product washing stages (with NaOH solution and subsequently with water), as well as from fermentation residues. These wastes consist mostly of water but also contain small amounts of organic load, inorganic salts, and alkaline residues that must be treated before disposal. The wastes are considered non-toxic, and their treatment cost is estimated at 31.5 €/t, according to Perry's handbook. In the supplementary material, the quantities of waste as well as the annual cost for their treatment for 2,000 batches per year are presented. The total wastewater treatment cost was found to be CWT = 2.08 M €. Rodrigues et al. suggest that the production of BNC could be coupled with more advanced wastewater treatments that aim to recycle back a significant portion of the water, up to 45 % was recycled without affecting BNC yields; in addition methane was produced from the organic load of the wastewaters (Rodrigues et al. 2025). Given that the wastewater treatment cost is significant, it is clear that alternative strategies need to be considered to make BNC production more competitive.

3.9 Direct labor cost

Direct labor mainly includes both skilled and unskilled work. Estimating the personnel requirements of a chemical plant has proven to be quite complex, as it largely depends on factors such as know-how, degree of automation, and final product specifications. The method followed in this study to estimate the required workers per shift is based on Ulrich's method (ULRICH 2025). It should be noted that although the plant includes 48 bioreactors, the assumption is that 6 reactors are completing 6 batches per day and are the ones that require attention. The gross annual cost of the employees was assumed to be 21,860 €/y. Therefore, the total direct labor cost was found to be CL = 0.79 M €/y.

3.10 Total production cost

The fixed capital cost (FCI) was found to be 41.01 M € as presented in Table 6. The total annual cost of raw materials (CRM) amounts to 1.24 M €. The annual cost of utilities (CUT) is 0.61 M € and finally, the cost of waste treatment (CWT) as well as the direct labor cost (CL) amount to 2.08 M € and 0.79 M €, respectively. Thus, the total product cost is

$$TPC = 1.22(1.24 + 0.61 + 2.08) + 2.66 * 0.79 + 0.195 * 41.01$$

$$TPC = 14.89 \text{ M €/year}$$

Next follows the determination of the total cost per kilogram of bacterial nanocellulose produced, as well as the cost per batch of the plant. The plant's target has been set at 100 tons of dry product per year. This includes an additional water content (15 %), resulting in a final capacity of $100/0.85 = 117.65 \text{ t/y}$ of BNC with 15 % moisture. Furthermore, the plant can carry out a total of 2,000 batches per year using 48 bioreactors. Thus, the cost per kilogram of BNC is calculated as:

$$\text{Unit production cost} \left(\frac{\text{€}}{\text{kg}} \right) = \frac{TPC}{\text{Capacity}} = \frac{14.89 \frac{\text{M €}}{\text{y}}}{117.65 \frac{\text{t}}{\text{y}}} = 126.56 \frac{\text{€}}{\text{kg}}$$

$$\text{Cost per batch} \left(\frac{\text{€}}{\text{batch}} \right) = \frac{TPC}{2,000 \frac{\text{batch}}{\text{y}}} = 7,445.0 \frac{\text{€}}{\text{batch}}$$

The above costs refer to obtaining the final product with 15 % moisture after the drying stage.

3.11 Economic analysis results: cost breakdown, sensitivity analysis

For the financial evaluation of the investment, a cash flow analysis was carried out based on annual revenues, expenses, and capital flows. The net cash flows were discounted at a Minimum Acceptable Rate of Return (MARR) of 10 % to calculate the Net Present Value (NPV) and assess the viability of the investment. Additionally, the MACRS method was applied for equipment depreciation over 7 years, with a residual value of 3 %. Working capital was also considered, which is released at the end of the plant's useful life together with the residual value. Table 7 presents the parameters used for the calculation of cash flows.

Table 7. Parameters for cash flows calculation from the construction of a BNC plant.

Construction time (years)	3
Plant useful time (years)	30
Working capital	5% of fixed capital
Residual value	3%
Equity financing	50%
Loan	Repayment in 10 years at 8% interest
Distribution of fixed capital 1st year / 2nd year	8%/ 62% / 30%
Equipment depreciation	7 year-MACRS
Income tax	35%
Cost of capital or MARR	10%
Production level in first year	100% of nominal capacity

Subsequently, two scenarios will be examined for the calculation of the Net Present Value. In the first scenario BNC with 15 wt. % moisture is produced while in the second one BNC gel with 99 wt. % water content is sold without any drying taking place. Since no accurate selling price exists for such a large-scale production of BNC, the selling price of BNC will be determined so that the investment achieves a payback period (PBP) of 8 years. In the second

scenario, (99 % water content) the selling price according to the literature amounts to approximately ~21.9 €/kg (Dourado et al., 2016).

3.11.1 Scenario A – Payback period of 8 years

As shown above, capital expenditures are distributed as 8 % of the FCI (3.28 M €) in the first year (year -2), 62 % (24.61 M €) in the second year and 30 % (13.12 M€) in the third year (year 0). 50 % of the fixed capital is covered by equity, while 50 % is financed by a bank loan with a 10-year repayment period and an interest rate of 8 %. It should also be noted that, since the plant operates at a loss in the first years, there is a tax refund.

The results obtained by setting PBP = 8 years gave a selling price of 202.9 €/kg, which corresponds to the sale of 117.65 t/y of BNC with 15 % moisture, leading to annual revenues of 23.86 M €. After calculating the net cash flows, the Net Present Value (NPV) was found to be 21.5 M €. Subsequently, the diagram of cumulative present value is presented (Figure 4), illustrating how the accumulated, discounted net cash flow evolves over the useful lifetime of the plant.

According to the graph, a positive NPV is observed after the 8th year, i.e., at the point in time when the defined PBP is achieved. The continuation of operation up to 30 years provides additional return for this plan, further increasing the NPV.

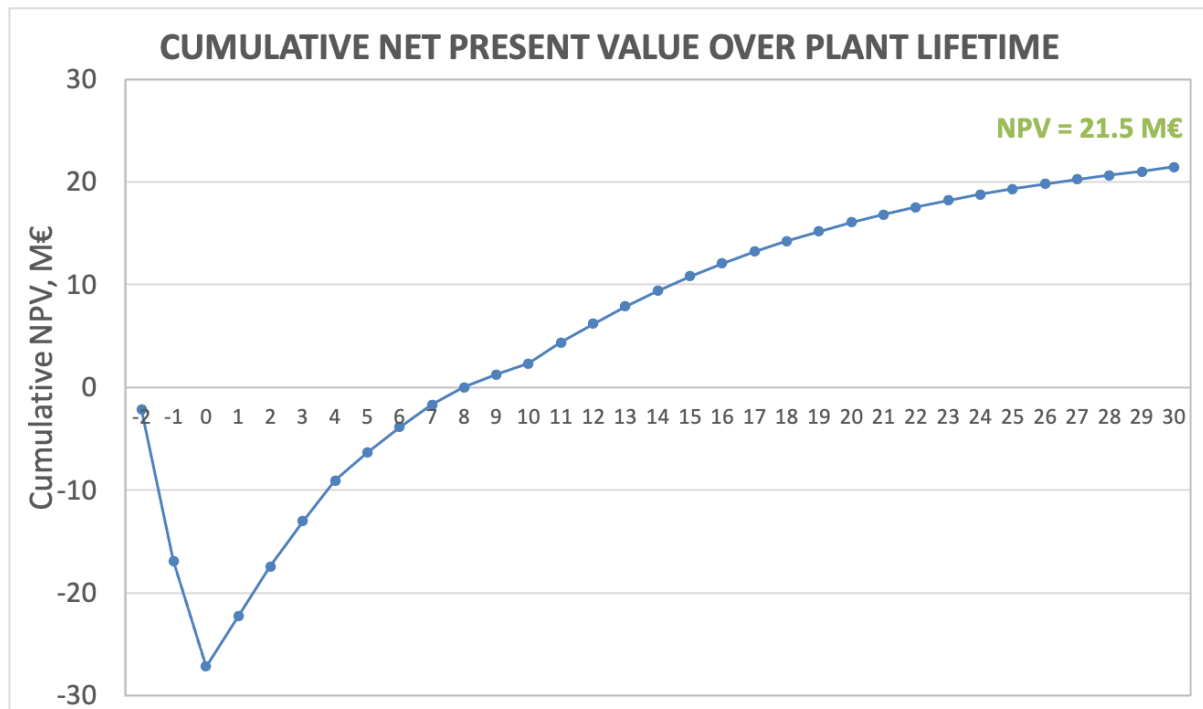


Figure 4. Accumulation of net present value over the years for Scenario A (15 wt. % moisture content).

3.11.2 Scenario B – Sale of BNC-gel (99 % water content)

In this scenario, the investment plan is evaluated for selling bacterial nanocellulose in hydrogel form. The drying stage is omitted, so the product is sold directly after neutralization with deionized water. This BNC form targets mainly skincare markets, e.g., facial masks. It should also be noted that, with the target set at 100 tons of dry product, the total annual quantity at 99 % moisture is 10,000 t/y of wet BNC.

The PBP was once again set at 8 years. The result was a positive NPV equal to 18.4 €M, figure 5 presents the diagram of cumulative net present value. The selling price of BNC with 99 % moisture was calculated at 2.07 €/kg, generating annual revenues of 20.74 M €. Compared to

the price of ~21.9 €/kg of wet biomass calculated by Dourado et al. (2016) we notice an order of magnitude of difference. This difference can be attributed to several factors. Firstly, there is a significant difference in the production scale, in this work the plant capacity is set at 100 tons per year of dry BNC or approximately 10,000 tons of wet BNC, while in the work of Dourado et al. the production capacity is 504 tons of wet BNC annually. In addition, there is a significant difference in the assumed bioreactor cost. Dourado et al. assume a cost of 500,000 US\$ (2016 prices) for a clean room with a capacity of 12,340.29 L. in this work a similar capacity bioreactor (10,000 L) is assumed to cost 115,500\$ @2024 per unit according to Behera et al. (2022). This highlights even more the importance of scaling up the technology in pilot scale and subsequently in a first of its kind plant to gain insight into actual equipment costs and ways to minimize them.

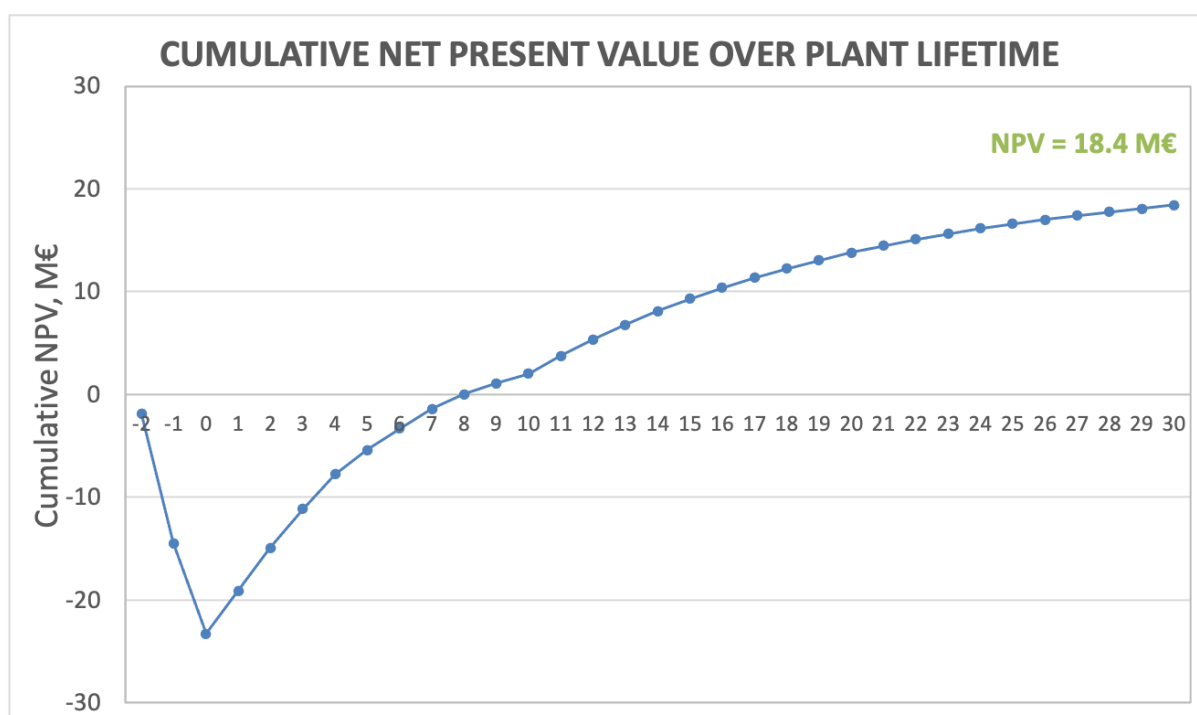


Figure 5. Accumulation of net present value over the years for Scenario B (no drying).

Projected on a dry basis, 0 wt. % moisture, scenario A results in a price of 238.7 €/kg of dry BNC and scenario B results in a price of 207.4 €/kg of dry BNC. The price difference is attributed to the reduced FCI and operating costs due to the removal of the dryer section of the plant. However, it should be noted that in scenario B, higher transportation costs per kg of dry BNC should be expected.

3.11.3 Sensitivity analysis

A sensitivity analysis is carried out to determine which of the following parameters has the greatest influence on the NPV. The price of bacterial nanocellulose (BNC) is kept constant and equal to the value calculated in the previous scenarios. Initially, an analysis is performed considering parameter variations within a $\pm 10\%$ range from their baseline values, and subsequently, a detailed tornado diagram is provided showing how NPV changes under variations from -10% to $+10\%$. The parameters selected for the analysis are the fixed capital investment (FCI), the price of peptone and glucose as raw materials, the cost of waste treatment CWT, and the cost of electricity.

The variation of the NPV for the $\pm 10\%$ range of the selected parameters is presented below (Figure 6). From this diagram, it becomes evident that the variation in fixed capital cost has a

very pronounced effect on the NPV. Specifically, a -10 % change in FCI results in an +40.0 % change in NPV. Conversely, the smallest impact on NPV is observed with the price of glucose, where a +10 % increase leads to a negative change of approximately -1.1 % in NPV. The same analysis was conducted for scenario B where no drying took place. In this case the FCI is reduced since no dryer is purchased and installed and there is also a significant reduction in electricity consumption. Still FCI is the parameter that affects predominantly the NPV. The effect of electricity cost is even less pronounced in this case as it is now minimized.

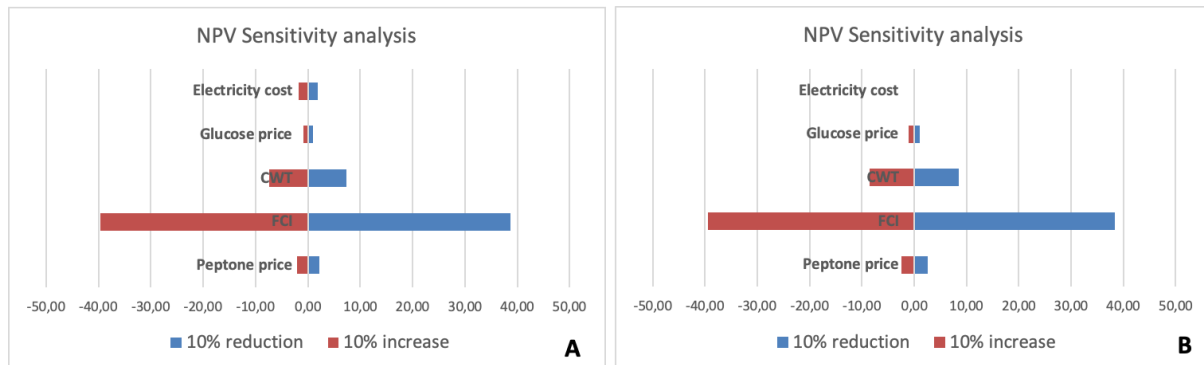


Figure 6. Effect of ± 10 % variation of parameters on NPV a) for scenario A (15 wt. % moisture content), b) for scenario B (no drying). FCI – Fixed Capital Investment, CWT – Wastewater Treatment Cost

As a next step to the analysis, a variation of the selected parameters up to ± 20 % was performed, and in each case the NPV was calculated. These data are presented in tables in the supplementary material. From the above analysis, it is clear that the FCI is the parameter that determines whether an investment in BNC production is viable or not. A significant reduction in FCI is needed to achieve financial viability and bringing down the selling prices of BNC.

To highlight further the significance of the equipment cost's contribution to the economics of a BNC industrial plant, the case where glucose has a procurement price of 1,350 € per ton is presented. This price is 3 times higher compared to the base case scenario of 450 € per ton that was previously considered. Assuming a procurement price of 1,350 € per ton for glucose results in a CRM of 1.75 M € annually. To maintain the same PBP of 8 years the selling price of BNC needs to be increased from 202.9 €/kg to 208.1 €/kg for scenario A. This is an increase of 5.2 €/kg or 2.5 %, a very small increase compared to the 200% increase in the price of glucose. The NPV in this case marginally decreases from 21.5 M € to 21.44 M €. As stated above, a -10 % change in FCI results in an +40.0 % change in NPV. The bioreactors cost is by far the main cost contributor that strongly affects FCI. To better highlight this, a scenario is examined where the bioreactors' cost is halved, that is the cost of the bioreactors is reduced from 4.848 M € to 2.424 M € and the total cost of equipment is reduced to 5.78 M € that corresponds to an FCI of 28.88 M €. To maintain the same PBP of 8 years, the selling price of dry BNC is reduced to 165.6 €/kg, a decrease of 37.9 €/kg or 18.4%. Should the selling price of dry BNC remain at 202.9 €/kg, the PBP is reduced to around 3.3 years and the NPV at the end of the 30 years that was considered as the plant life time is almost doubled to 42.06 M €.

This scenario considers a reduction in cost only for the bioreactors, given the maturity of the technology used in the other process steps. However, a scale up of the production capacity, use of alternative, cheaper drying equipment and a reduction in the cost of the seed reactors as their scale increases can also lead to significant cost gains represented as a reduction in the selling price of BNC.

To achieve these reductions in equipment and hence production costs, genetic engineering and innovative reactor solutions need to be developed. Genetic engineering of *Komagataeibacter*

strains and novel bioreactor designs offer promising strategies to accelerate bacterial nanocellulose (BNC) production, potentially cutting fermentation times from 7–14 days to 3–5 days while reducing costs by 30–50% through higher yields and lower energy inputs. Genetic manipulation of BNC-producing strains and in situ modifications of the culturing conditions can lead to BNC with enhanced yield, productivity and properties (Moradi et al. 2021). In addition, new genetic tools enable biosynthesis of patterned cellulose, functionalization of the cellulose surface with proteins, and tunable control over cellulose production, allowing the engineering of new cellulose-based biomaterials with added value (Florea et al. 2016). Moreover, novel bioreactor schemes allow for maximization of productivity. Rotary disc bioreactors have been found to significantly reduce scale up cost while achieving 13.0 g/L dry yield of BNC in just 5 days (Jagtap and Dastager, 2024). Such advancements are critical for the industrialization of BNC production. Once this scale of equipment cost reduction is achieved, other parameters such as peptone, sugars and electricity prices along with waste water treatment will have a stronger effect and will also need to be further evaluated to optimize the process.

4. Conclusions

Bacterial nanocellulose (BNC) has superior physical properties such as improved mechanical strength, water holding capacity, and barrier characteristics. These properties along with the fact that it can be grown on scaffolds to form desirable shapes give it unique advantages for its use in high added value applications, e.g. biomedical scaffolds, wound dressings, cosmetic masks, food coatings and biodegradable packaging. Technoeconomic analyses consistently identify feedstock cost (glucose or alternative carbon sources), media components (peptone, yeast extract), and energy demands (drying, sterilization) as primary factors influencing production cost and profitability. In this work two different scenarios were evaluated. In one case the end product was a nanocellulose with 15 wt. % moisture; this was achieved with drying the BNC hydrogel with the help of a conveyor dryer. A selling price of 202.9 €/kg of final product resulted in a PBP of 8 years and an NPV of 21.5 M € at the end of the 30-year lifetime of the plant. In the second scenario, the BNC hydrogel, containing 99 wt. % water, was sold as it was produced without additional drying. To achieve a PBP of 8 years, a selling price of 2.07 €/kg was needed, resulting in an NPV of 18.4 M € for the same plant lifetime. It is more likely that a commercial plant will have an integrated drying section to produce different products of varying moisture content. Overall, the main cost contributor was found to be the capital costs and more specifically the bioreactors section with the tray bioreactors and the seed trains contributing 60 % and 17 % of the total capital cost; combined they accounted for more than 3 quarters of the total capital cost. For the technology to move forward and to become a sustainable and realistic solution, it is imperative that the bioreactors' cost is significantly reduced. There are several ways to achieve this. Economies of scale can help cut down significantly the contribution of the equipment cost in the final product price. Scaling up bioreactor volumes by a factor of 10 results in only doubling or tripling of the equipment cost. Novel reactor configurations and genetic engineering can reduce fermentation time, typically now between 7-10 days, achieving great savings. A higher degree of automation can also reduce both the time the bioreactors remain inactive and the labor costs. Minimising down time in these types of processes is also a critical factor, therefore the seed trains and the bioreactors must have capacities that ensure that downtime is close to zero. Moreover, research should focus on efficient dewatering and drying of the BNC to significantly reduce its water content without altering its properties. It is still unclear how drying or cheap dewatering methods, such as applying pressure, affect BNC.

Selling the BNC hydrogel is an option that eliminates the cost of drying, however it comes with higher transportation costs and it limits the usage cases of BNC. Using more efficient technologies for drying, such as heat pumps, can also result in a significant reduction in electricity costs. As the above costs fall, the sugars' cost contribution will become more prevalent; at this point the sugars' cost contribution is low.

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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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Literature

- Abol-Fotouh D, Hassan MA, Shokry H, et al (2020) Bacterial nanocellulose from agro-industrial wastes: low-cost and enhanced production by *Komagataeibacter saccharivorans* MD1. *Sci. Rep.* 10:3491. <https://doi.org/10.1038/s41598-020-60315-9>
- Andree V, Niopek D, Müller C, et al (2021a) Influence of drying methods on the physical properties of bacterial nanocellulose. *Mater. Res. Express* 8:025402. <https://doi.org/10.1088/2053-1591/abe016>
- Asimakopoulou G, Karnaouri A, Staikos S, et al (2021) Production of omega-3 fatty acids from the microalga *cryptocodinium cohnii* by utilizing both pentose and hexose sugars from agricultural residues. *Fermentation* 7:. <https://doi.org/10.3390/fermentation7040219>
- Bagherniya M, Babaeipour V, Soleimani A (2021) Optimization of Bacterial Nano-Cellulose Production in Bench-Scale Rotating Biological Contact Bioreactor by Response Surface Methodology. *Iran. J. Chem. and Chem. Eng.* 40:407–416. <https://doi.org/10.30492/ijcce.2020.38040>
- Barja F (2021) Bacterial nanocellulose production and biomedical applications. *J. Biomed. Res.* 35:310–317. <https://doi.org/10.7555/JBR.35.20210036>
- Behera B, Laavanya D, Balasubramanian P (2022) Techno-economic feasibility assessment of bacterial cellulose biofilm production during the Kombucha fermentation process. *Bioresour. Technol.* 346:126659. <https://doi.org/10.1016/j.biortech.2021.126659>
- Blair MJ, Mabee WE (2021) Techno-economic and market analysis of two emerging forest biorefining technologies. *Biofuels, Bioproducts and Biorefining* 15:1301–1317. <https://doi.org/10.1002/bbb.2218>
- Brugnoli M, Carvalho JPF, Arena MP, et al (2025) Co-cultivation of *Komagataeibacter sp.* and *Lactocaseibacillus sp.* strains to produce bacterial nanocellulose-hyaluronic acid nanocomposite membranes for skin wound healing applications. *Int. J. Biol. Macromol.* 299:140208. <https://doi.org/10.1016/j.ijbiomac.2025.140208>
- Cardoso VM, Campani G, Santos MP, et al (2020) Cost analysis based on bioreactor cultivation conditions: Production of a soluble recombinant protein using *Escherichia coli* BL21(DE3). *Biotechnol. Rep.* 26:e00441. <https://doi.org/10.1016/j.btre.2020.e00441>
- Chen G, Chen L, Wang W, et al (2019) Improved bacterial nanocellulose production from glucose without the loss of quality by evaluating thirteen agitator configurations at low speed. *Microb. Biotechnol.* 12:1387–1402. <https://doi.org/10.1111/1751-7915.13477>
- Chen X, Yuan F, Zhang H, et al (2016) Recent approaches and future prospects of bacterial cellulose-based electroconductive materials. *J. Mater. Sci.* 51:5573–5588. <https://doi.org/10.1007/s10853-016-9899-2>

971 Cheng M-H, Huang H, Dien BS, Singh V (2019) The costs of sugar production from different
 972 feedstocks and processing technologies. *Biofuels Bioprod. Bioref.* 13:723–739.
 973 <https://doi.org/10.1002/bbb.1976>

974 de Araújo e Silva R, Santa Brígida AI, de Freitas Rosa M, et al (2020) An approach for
 975 implementing ecodesign at early research stage: A case study of bacterial cellulose
 976 production. *J. Clean. Prod.* 269:122245. <https://doi.org/10.1016/j.jclepro.2020.122245>

977 Dheskali E, Michailidi K, de Castro AM, et al (2017) Optimal design of upstream processes
 978 in biotransformation technologies. *Bioresour. Technol.* 224:509–514.
 979 <https://doi.org/10.1016/j.biortech.2016.10.084>

980 Dourado F, Fontão A, Leal M, et al (2016) Process Modeling and Techno-Economic
 981 Evaluation of an Industrial Bacterial NanoCellulose Fermentation Process. In:
 982 *Bacterial Nanocellulose*. Elsevier, pp 199–214.

983 Dute S, Bijwe M, Pawar D (2025) Design Modification of Tray Dryer to Increase Efficiency.
 984 *Int. J. Advanced Res. Sci., Com. Technol.* 267–277.
 985 <https://doi.org/10.48175/IJARSCT-23239>

986 Florea M, Hagemann H, Santosa G, et al (2016) Engineering control of bacterial cellulose
 987 production using a genetic toolkit and a new cellulose-producing strain. *Proc. Natl.*
 988 *Acad. Sci. U.S.A.* 113:E3431–E3440. <https://doi.org/10.1073/pnas.1522985113>

989 Folmann Lima N, Maciel GM, De Andrade Arruda Fernandes I, Windson Isidoro Haminiuk
 990 C (2023) Optimising the Production Process of Bacterial Nanocellulose: Impact on
 991 Growth and Bioactive Compounds. *Food Technol. Biotechnol. (Online)* 61:494–504.
 992 <https://doi.org/10.17113/ftb.61.04.23.8182>

993 Forte A, Dourado F, Mota A, et al (2021a) Life cycle assessment of bacterial cellulose
 994 production. *Int. J. Life Cycle Assess* 26:864–878. [https://doi.org/10.1007/s11367-021-](https://doi.org/10.1007/s11367-021-01904-2)
 995 [01904-2](https://doi.org/10.1007/s11367-021-01904-2)

996 Girard V-D, Chaussé J, Vermette P (2024) Bacterial cellulose: A comprehensive review. *J.*
 997 *Appl. Polym. Sci.* 141:e55163. <https://doi.org/10.1002/app.55163>

998 Gromovkykh TI, Sadykova VS, Lutcenko SV, et al (2017) Bacterial cellulose synthesized by
 999 *Gluconacetobacter hansenii* for medical applications. *Appl. Biochem. Microbiol.*
 1000 53:60–67. <https://doi.org/10.1134/S0003683817010094>

1001 Hu M, Lv X, Wang Y, et al (2024) Guideline for the extraction of nanocellulose from
 1002 lignocellulosic feedstocks. *Food Biomacromolecules* 1:9–17.
 1003 <https://doi.org/10.1002/fob2.12011>

1004 Humagain S (2018) Growth of bacteria and the bacterial growth curve. In: *Online Science*
 1005 *Notes*. [https://onlinesciencenotes.com/growth-of-bacteria-and-the-bacterial-growth-](https://onlinesciencenotes.com/growth-of-bacteria-and-the-bacterial-growth-curve/)
 1006 [curve/](https://onlinesciencenotes.com/growth-of-bacteria-and-the-bacterial-growth-curve/). Accessed 3 Feb 2026

1007 Humbird D, Davis R, Tao L, et al (2011) Process Design and Economics for Biochemical
 1008 Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and
 1009 Enzymatic Hydrolysis of Corn Stover (No. NREL/TP-5100-47764, 1013269).
 1010 <https://doi.org/10.2172/1013269>

1011 Jacek P, Dourado F, Gama M, Bielecki S (2019) Molecular aspects of bacterial nanocellulose
1012 biosynthesis. *Microb. Biotechnol.* 12:633–649. [https://doi.org/10.1111/1751-](https://doi.org/10.1111/1751-7915.13386)
1013 7915.13386

1014 Jagtap A, Dastager SG (2024a) Bacterial nanocellulose: A versatile biopolymer production
1015 using a cost-effective wooden disc based rotary reactor. *Biopolymers* 115:e23577.
1016 <https://doi.org/10.1002/bip.23577>

1017 Jirathampinyo S, Chumchoochart W, Tinoi J (2023) Integrated Biobased Processes for
1018 Nanocellulose Preparation from Rice Straw Cellulose. *Processes* 11:1006.
1019 <https://doi.org/10.3390/pr11041006>

1020 Jonas R, Farah LF (1998) Production and application of microbial cellulose. *Polym. Degrad.*
1021 *Stab.* 59:101–106. [https://doi.org/10.1016/S0141-3910\(97\)00197-3](https://doi.org/10.1016/S0141-3910(97)00197-3)

1022 Kalogiannis KG, Karnaouri A, Michailof C, et al (2020) OxiOrganosolv: A novel acid free
1023 oxidative organosolv fractionation for lignocellulose fine sugar streams. *Bioresour.*
1024 *Technol.* 313:123599. <https://doi.org/10.1016/j.biortech.2020.123599>

1025 Kargupta W, Stevenson T, Sharman S, et al (2023) Sustainable production of nanocellulose:
1026 Technoeconomic assessment, energy savings and scalability. *J. Clean. Prod.*
1027 425:138748. <https://doi.org/10.1016/j.jclepro.2023.138748>

1028 Katsimpouras C, Dedes G, Bistis P, et al (2018) Acetone/water oxidation of corn stover for
1029 the production of bioethanol and prebiotic oligosaccharides. *Bioresour. Technol.*
1030 270:208–215. <https://doi.org/10.1016/j.biortech.2018.09.018>

1031 Katsimpouras C, Kalogiannis KG, Kalogianni A, et al (2017) Production of high
1032 concentrated cellulosic ethanol by acetone/water oxidized pretreated beech wood.
1033 *Biotechnology for Biofuels* 10:. <https://doi.org/10.1186/s13068-017-0737-9>

1034 Luo H, Cha R, Li J, et al (2019) Advances in tissue engineering of nanocellulose-based
1035 scaffolds: A review. *Carbohydr. Polym.* 224:115144.
1036 <https://doi.org/10.1016/j.carbpol.2019.115144>

1037 Makharita RR, El-Ahmady El-Naggar N, Baghdadi AM, Hamouda RA (2025) Sustainable
1038 production of bacterial nanocellulose from date fruit waste using *Bacillus haynesii* for
1039 waste valorisation and crystal violet dye removal. *Sci. Rep.* 15:25133.
1040 <https://doi.org/10.1038/s41598-025-04711-z>

1041 Melani L, Gunawan GB, Wicaksono RAS, Pratama GM (2025) Optimization of Bacterial
1042 Nanocellulose Production from Sweet Potato Waste via Response Surface
1043 Methodology. *J Korea TAPPI* 57:41–55.
1044 <https://doi.org/10.7584/JKTAPPI.2025.12.57.6.41>

1045 Moniri M, Boroumand Moghaddam A, Azizi S, et al (2017) Production and Status of
1046 Bacterial Cellulose in Biomedical Engineering. *Nanomaterials* 7:257.
1047 <https://doi.org/10.3390/nano7090257>

1048 Moradi M, Jacek P, Farhangfar A, et al (2021) The role of genetic manipulation and in situ
1049 modifications on production of bacterial nanocellulose: A review. *Int. J. Biol.*
1050 *Macromol.* 183:635–650. <https://doi.org/10.1016/j.ijbiomac.2021.04.173>

1051 Ong X-R, Chen AX, Li N, et al (2023) Nanocellulose: Recent Advances Toward Biomedical
1052 Applications. *Small Sci.* 3:2200076. <https://doi.org/10.1002/smsc.202200076>

1053 Perry's Chemical Engineers' Handbook, 8th ed., 2008. McGraw-Hill, New York, NY, USA.
1054

1055 Peters, M.S., Timmerhaus, K.D., West, R.E., West, R.E., 2004. Plant design and economics
1056 for chemical engineers, 5th ed, McGraw-Hill chemical engineering series. McGraw-
1057 Hill, New York, NY, USA.

1058 Phan P-D, Nguyen AP-H, Do TVV, Dai H-N Optimized production of bacterial
1059 nanocellulose by *Komagataeibacter Xylinus* HBCM-B0092 and preliminary
1060 application with sugarcane bagasse. *Vietnam J. Chem.* n/a:
1061 <https://doi.org/10.1002/vjch.70023>

1062 Putranto AW, Suhartini S, Wibisono Y, et al (2025) Life cycle assessment of deep eutectic
1063 solvent employment for sustainable nanocellulose production from biomass: a
1064 systematic review. *Green Chem. Lett. Rev.* 18:2507283.
1065 <https://doi.org/10.1080/17518253.2025.2507283>

1066 R R, Philip E, Thomas D, et al (2021) Bacterial nanocellulose: engineering, production, and
1067 applications. *Bioengineered* 12:11463–11483.
1068 <https://doi.org/10.1080/21655979.2021.2009753>

1069 Reiniati I, Hrymak AN, Margaritis A (2017) Kinetics of cell growth and crystalline
1070 nanocellulose production by *Komagataeibacter xylinus*. *Biochemical Engineering*
1071 *Journal* 127:21–31. <https://doi.org/10.1016/j.bej.2017.07.007>

1072 Rodrigues AC, Martins D, Duarte MS, et al (2025) Optimizing bacterial nanocellulose
1073 production from eucalyptus bark: A circular approach to wastewater management and
1074 resource recovery. *J. Environ. Chem. Eng.* 13:115442.
1075 <https://doi.org/10.1016/j.jece.2025.115442>

1076 Saleh AK, El-Gendi H, Soliman NA, et al (2022) Bioprocess development for bacterial
1077 cellulose biosynthesis by novel *Lactiplantibacillus plantarum* isolate along with
1078 characterization and antimicrobial assessment of fabricated membrane. *Sci. Rep.*
1079 12:2181. <https://doi.org/10.1038/s41598-022-06117-7>

1080 Schramm M, Hestrin S (1954) Factors affecting Production of Cellulose at the Air/ Liquid
1081 Interface of a Culture of *Acetobacter xylinum*. *Microbiology* 11:123–129.
1082 <https://doi.org/10.1099/00221287-11-1-123>

1083 Shavyrkina NA, Budaeva VV, Skiba EA, et al (2021) Scale-Up of Biosynthesis Process of
1084 Bacterial Nanocellulose. *Polymers* 13:. <https://doi.org/10.3390/polym13121920>

1085 Sinquefield S, Ciesielski PN, Li K, et al (2020) Nanocellulose Dewatering and Drying:
1086 Current State and Future Perspectives. *ACS Sus. Chem. Eng.* 8:9601–9615.
1087 <https://doi.org/10.1021/acssuschemeng.0c01797>

1088 Skočaj M (2019) Bacterial nanocellulose in papermaking. *Cellulose* 26:6477–6488.
1089 <https://doi.org/10.1007/s10570-019-02566-y>

1090 Soleha TU, Oktafany, Ayu PR, Nafisah A (2024) The effectiveness of using HEPA filters in
 1091 reducing the number of airborne bacteria in the operating room area. AIP Conf. Proc.
 1092 2970:050026. <https://doi.org/10.1063/5.0209846>

1093 Sreedharan M, Vijayamma R, Liyaskina E, et al (2024) Nanocellulose-Based Hybrid
 1094 Scaffolds for Skin and Bone Tissue Engineering: A 10-Year Overview.
 1095 Biomacromolecules 25:2136–2155. <https://doi.org/10.1021/acs.biomac.3c00975>

1096 Sturgeon, L.F., 1995. Conveyor Dryers, in: Handbook of Industrial Drying. CRC Press, Boca
 1097 Raton, Florida, USA.

1098 Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A., 2008. Analysis, Synthesis and
 1099 Design of Chemical Processes. Pearson Education, Upper Saddle River, NJ, USA.

1100 Ulrich, K., 2025. Product Design and Development, 8th ed. McGraw-Hill Education, New
 1101 York, NY, USA.

1102 Wang X, Tang J, Huang J, Hui M (2020) Production and characterization of bacterial
 1103 cellulose membranes with hyaluronic acid and silk sericin. Col. Surf. B: Biointerfaces
 1104 195:111273. <https://doi.org/10.1016/j.colsurfb.2020.111273>

1105 Watanabe K, Tabuchi M, Morinaga Y, Yoshinaga F (1998) Structural Features and Properties
 1106 of Bacterial Cellulose Produced in Agitated Culture. Cellulose 5:187–200.
 1107 <https://doi.org/10.1023/A:1009272904582>

1108 Wong KJ, Leiu YX, Hoo DY, et al (2025) Life cycle assessment and techno-economic
 1109 analysis of nanocellulose synthesis via chlorine-free biomass pretreatments. Process
 1110 Saf. Environ. Prot. 203:107912. <https://doi.org/10.1016/j.psep.2025.107912>

1111 Zeng M, Laromaine A, Roig A (2014) Bacterial cellulose films: influence of bacterial strain
 1112 and drying route on film properties. Cellulose 21:4455–4469.
 1113 <https://doi.org/10.1007/s10570-014-0408-y>

1114 Zhou Z, Li Y, Zhou W (2021) The Progress of Nanocellulose in Types and Preparation
 1115 Methods. J Phys: Conf. Ser. 2021:012042. [https://doi.org/10.1088/1742-](https://doi.org/10.1088/1742-6596/2021/1/012042)
 1116 6596/2021/1/012042

1117 Zou X, Wu G, Stagge S, et al (2017) Comparison of tolerance of four bacterial nanocellulose-
 1118 producing strains to lignocellulose-derived inhibitors. Microb. Cell. Fact. 16:229.
 1119 <https://doi.org/10.1186/s12934-017-0846-y>

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