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ORIGINAL ARTICLE

From marine invaders to advanced materials: A techno-economic blueprint for commercial-scale cellulose nanocrystals from tunicate biomass

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Abstract

This study aimed to assess the technical feasibility and economic viability of cellulose nanocrystals produced from a marine animal, i.e., tunicate. An industrial-scale process simulation model was developed with a 50 tonne/day production capacity of tunicate-based cellulose nanocrystals, at 1% solid. The system boundary included preprocessing and pretreatment of raw tunicate, acid hydrolysis, filtration, and concentration. The minimum selling price of tunicate-based cellulose nanocrystals (1% solids) in the baseline scenario was estimated to be $1.16/kg, and it could be reduced to $0.77/kg by improving the process design parameters in alternative scenarios. Increasing the production scale was identified as an alternative option to further reduce the production costs and minimum selling price of tunicate-based cellulose nanocrystals. The outcomes of this research would help establish the performance targets needed to reach the viability of cellulose nanocrystals production from tunicate at the commercial scale.

Keywords Tunicate · Cellulose nanocrystal · Process model · Technical feasibility · Minimum selling price

1 Introduction

Cellulose is the most abundant natural polymer on Earth, with an estimated annual global production of 1.5 trillion tons [1]. It can be derived from a variety of sources, including plants, algae, fungi, bacteria, and marine animals such as tunicates. Although tunicates contribute a relatively small portion of this biomass, their contribution, as estimated to exceed one billion tons annually within the top 100 m of the ocean [2], is ecologically and industrially significant.

Traditionally, cellulose has found applications in the pulp, paper, and textile industries. However, recent advancements have enabled its transformation into high-value products, especially in the form of cellulosic nanomaterials (CNMs)

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[3]. CNMs are gaining traction as sustainable materials due to their renewability, biodegradability, biocompatibility, and versatile surface chemistry [4–6]. Two primary types of CNMs, i.e., cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs), are distinguished by their morphology and production methods. CNCs are rod-like particles typically produced via acid hydrolysis, measuring 3–50 nm in width and 50 − 2,000 nm in length, with aspect ratios ranging from 2 to 200 [7]. CNFs, produced through mechanical processes, are longer fibrillar structures ranging from 4 to 100 nm in width and over 1,000 nm in length, and have an aspect ratio of 10–100 [3].

CNCs derived from tunicates exhibit significantly higher aspect ratios (148 ± 147) than those from wood (23 ± 12), as well as superior mechanical properties and higher purity of cellulose Iβ crystals [8]. These attributes make tunicate-based CNCs (T-CNC) a promising alternative or supplement to wood-based CNCs. Tunicates, while abundant and a valuable source of high-quality CNCs, pose a major threat to aquaculture. As invasive filter-feeding organisms, they compete with mussels, clams, and scallops, compromising the sustainability and productivity of mussel farming operations. For instance, in Canada, mussel farms spend approximately 15% of their operational costs on tunicate removal [8]. These marine biomass residues, often considered waste, represent a valuable and underutilized feedstock for CNC production, potentially transforming a costly liability into a profitable opportunity [9, 10].

Despite the high potential of CNCs, commercial-scale production remains limited. Current CNC manufacturing is almost exclusively based on wood pulp, with only a few pilot facilities operating globally, primarily in North America, Europe, and Japan [3]. The nanocellulose market is projected to grow at a CAGR (Compound Annual Growth Rate) of 23.7%, reaching $3.4 billion by 2032 [11].

However, production cost remains a key barrier. De Assis et al. showed that the cost of wood-based CNCs (W-CNCs) ($/tonne of CNC dry) varies between $3,860 and $4,248 using an acid hydrolysis pathway and wood pulp feedstock. Acid hydrolysis uses a large volume of sulfuric acid, however, the implementation of acid recovery technology increases the overall cost, as acid recovery requires a large capital investment, which surpasses the benefits of recovering and recycling acid. Co-locating CNC plants with pulp mills can help reduce costs, primarily by lowering feedstock expenses [12]. Wood pulp was the main source for the production of W-CNCs, incurring more than 40% of the total manufacturing cost [12]. Thus, finding alternative and cheap sources (feedstocks) can reduce the overall cost of CNCs. Other major cost components were capital and energy usage. The production of CNC using organic acids such as citric acid can be environmentally superior but more costly compared to production using sulfuric acid because the cost of citric acid is not only very high, but it is also less effective to break the cellulose fibers, requiring additional costly operations such as ultrasonication [12, 13]. Bondancia et al. estimated the minimum selling price (MSP) of around $17,000/dry tonne of CNC using citric acid hydrolysis and eucalyptus kraft cellulose pulp [13], which was about four times higher than those reported in the previous study [12]. The higher cost of CNC preproduction in the later study [13], compared to [12], was due to smaller plant capacity and higher cost of inputs, especially citric acid.

While several techno-economic analyses (TEAs) have been conducted for W-CNCs [12, 14–17], no such studies exist for T-CNCs. Given their superior properties and the growing problem of tunicate infestations in aquaculture, there is a clear need to assess the feasibility of scaling up T-CNC production. The objective of this study is to develop a process simulation model for commercial-scale production of T-CNC and to conduct a financial analysis to evaluate its economic viability. This research aims to not only fill a critical knowledge gap but also provide a potential pathway for value generation from aquaculture waste, thereby supporting the economic sustainability of the mussel farming industry.

2 Materials and methods

2.1 Process modeling

The production capacity of the T-CNC facility was considered to be 50 tonne per day. The production capacity estimate is based on guidance from Tunistrong Technologies, which processed 12–14 tonne of tunicates per day last year in their pilot plant. According to their data, mussel farming in Prince Edward Island can generate 5–15 tonne of tunicates per acre as bycatch, with approximately 5,000 acres of aquaculture leases available in the region. Furthermore, the tunicates removed are naturally replaced by fully grown individuals within approximately two months, due to their rapid growth rate. The commercial-scale process model was developed based on previously reported lab-scale data [8], which was supplemented by pilot-scale production trials conducted by Tunistrong Technologies Inc. The system boundaries for this analysis included all major unit operations required for CNC production from tunicates (Fig. 1), as described in detail in the following sections. The process model was constructed using SuperPro Designer v10 [18]. Mass balances were established by quantifying input and output flow rates for all process streams across the defined system. Process parameters, including temperature, pressure, reaction efficiency, and residence time, were defined based on the reported

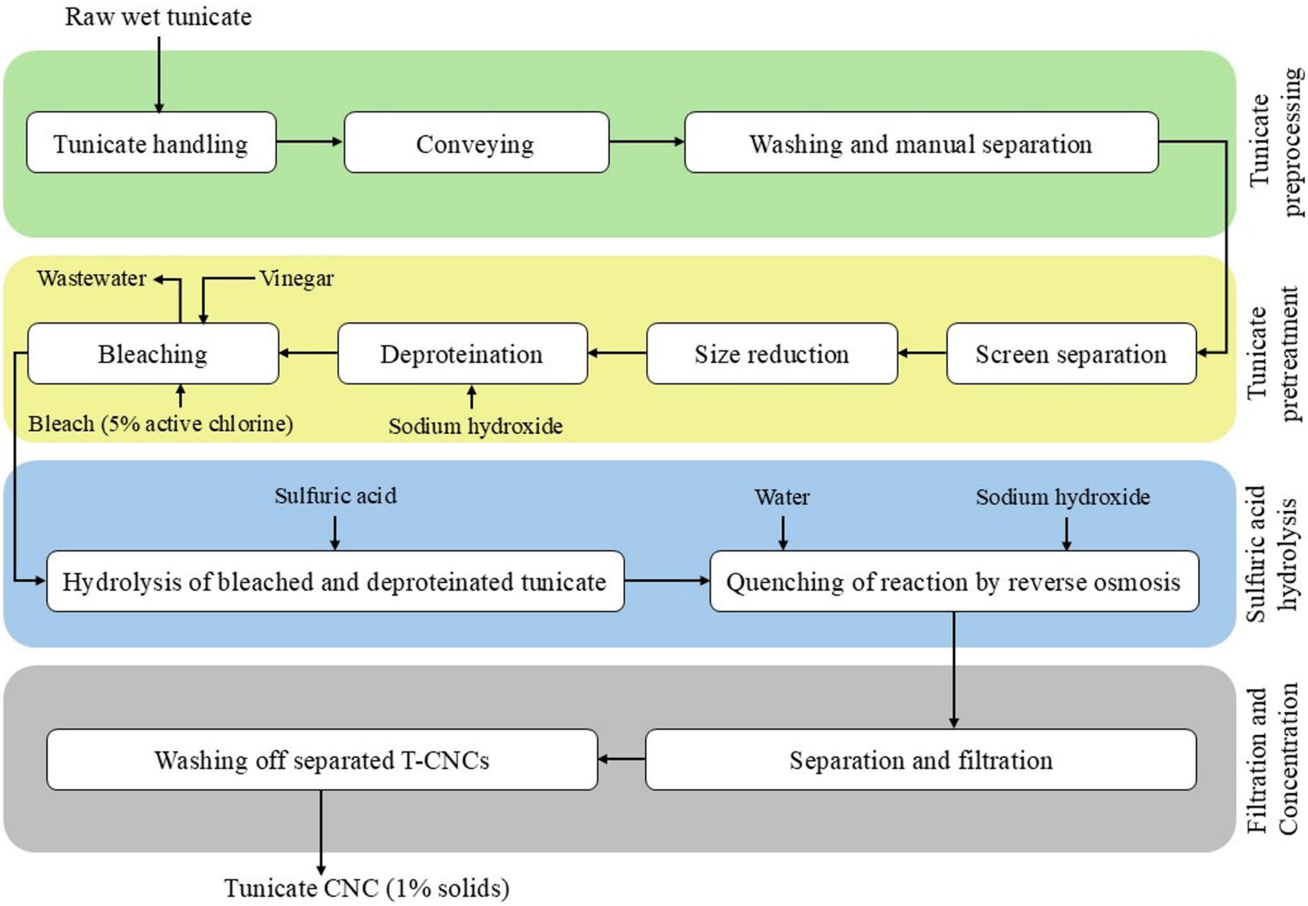


Fig. 1 Process flow diagram of cellulose nanocrystals production from raw tunicate

literature values and experimental observations, as outlined in the following sections. Built-in process models and default correlations within SuperPro Designer were used to estimate equipment sizing and determine the number of required processing units for each operation.

2.2 System description

The system includes all major operations required to convert tunicates into CNCs, excluding cultivation and harvesting. Since tunicates are collected as bycatch from mussel farming, their cultivation and harvesting costs are assumed to be zero. Only transportation costs are included in the tunicate feedstock cost. The system boundaries covered four main stages: tunicate preprocessing, pretreatment, acid hydrolysis, and filtration and concentration, as illustrated in Fig. 1. Tunicate preprocessing consisted of handling and cleaning steps to prepare the marine biomass for downstream processing. The pretreatment stage included tunicate tissue extraction and deproteination to isolate the cellulose-rich fraction. This was followed by acid hydrolysis and neutralization, which facilitated the breakdown of cellulose into nanoscale crystalline structures. The resulting CNC suspension was then subjected to ultrafiltration to achieve the final product. Detailed descriptions of each unit operation and the associated process parameters are provided in the subsequent sections.

2.2.1 Tunicate preprocessing

The T-CNC production process begins with the handling and cleaning of raw tunicate biomass. The raw tunicate consists of approximately 5% cellulose, 30% protein, 5% salt, 45% water, and 15% debris. Initial separation of tunicates from non-target materials is conducted manually using labor. The collected tunicates are then washed with water in a mechanical washing unit to remove surface contaminants. Following washing, the wet tunicates are passed through a roller system designed to mechanically disrupt the outer tunic layer. The processed material is then transferred to a circulation barrel, where gentle agitation facilitates the separation of the tunic from internal organs. This mixture is poured onto a screen separator to isolate solids, after which the tunic and organs are manually separated. The cleaned tunic fraction is further processed using a mechanical fibrillator to initiate physical breakdown of the fibrous structure. The resulting wet, fibrillated tunic is collected and forwarded to the pretreatment stage for further processing.

2.2.2 Tunicate pretreatment – deproteination

The fibrillated tunicate is subjected to a chemical pretreatment process to remove proteins and non-cellulosic components. Sodium hydroxide (NaOH) and water are added to the wet tunicate biomass, and the mixture is heated to 65 °C and maintained for 12 h in a batch reactor to facilitate alkaline deproteination. Additional water is added, and the mixture is again heated to 65 °C for 12 h. The treated slurry is then subjected to hot filtration using a centrifuge to separate NaOH-rich solution from the solid tunic material. Although the NaOH solution is currently reused in some applications (e.g., soap production), no reuse or valorization was considered for this study. The solid fraction is washed and filtered through two sequential washing steps with fresh water to remove remaining chemicals. The resulting deproteinated tunicate material is collected and directed to the bleaching stage.

2.2.3 Tunicate pretreatment – bleaching

The deproteinated tunicate material is initially mixed with concentrated sulfuric acid (98% H_2SO_4), water, household bleach (5% active chlorine), and vinegar (5% acetic acid - CH_3COOH). The mixture is heated to 65 °C and maintained for 12 h to promote partial hydrolysis and oxidative bleaching. Following the initial bleaching stage, three additional bleaching charges, each consisting of household bleach, are added consecutively at 1 h intervals. After the final bleaching charge, the mixture is hot-filtered and the solid tunic material from the bleaching solution are separated using the centrifuge. The resulting solid fraction is further washed twice with water. The washed, deproteinated, and bleached tunic is then subjected to acid hydrolysis for CNC extraction.

2.2.4 Sulfuric acid hydrolysis

For this step, 1 kg of wet tunicate cellulose (10 wt% cellulose content) is partially dried through evaporation to achieve a concentration of 20 wt% cellulose. The partially dried material is then mixed with 5.5 kg of aqueous sulfuric acid (81 wt% H_2SO_4). The reaction mixture is maintained at 45 °C and continuously stirred for 2 h to allow for selective hydrolysis of amorphous cellulose regions. The reaction is terminated by quenching the mixture with 200 L of reverse osmosis (RO) water. The resulting suspension, containing dispersed CNCs, is forwarded to the filtration and concentration stage for purification and drying.

2.2.5 Filtration and concentration

Following quenching, the acidic solution is then neutralized by gradually adding RO water containing NaOH. The resulting neutralized mixture remains highly saline due to dissolved reaction byproducts. The suspension is left undisturbed for 12 h to allow the CNC aggregates to settle by gravity. After the settling period, the supernatant containing excess salts and residual acids is decanted, and the remaining aggregated CNC is transferred to a tangential flow filtration (TFF) system. In the TFF system, the CNC suspension is washed repeatedly with RO water to remove remaining salts and soluble impurities. The T-CNC is then concentrated in the TFF system to achieve a final concentration of approximately 1 wt% T-CNC. This final product is then ready for drying or downstream applications, depending on the intended use.

2.2.6 Process improvement scenarios

This study evaluated the impact of selected process improvement strategies on the technical feasibility and production cost of T-CNC manufacturing. Four distinct scenarios were defined and analyzed to assess potential benefits from equipment upgrades and process optimization.

Scenario 1 (S1) *Baseline scenario, which represents the reference configuration, incorporating all unit operations as described in the system overview (Fig. 1), including manual washing and baseline operating conditions for bleaching, quenching, and hydrolysis.*

Scenario 2 (S2) *Identical to S1, but with improved tunicate washing and separation efficiency. This is achieved through the introduction of dedicated mechanical equipment designed specifically for biomass washing and solid-liquid separation, replacing labor-intensive manual operations.*

Scenario 3 (S3) *Builds upon S2 with optimization of key operational parameters in the bleaching, quenching, and acid hydrolysis steps, as follows.*

- Bleaching: operating conditions are modified from 45 °C for 12 h to 89 °C for 1.5 h.
- Quenching: temperature increased from 65 °C to 89 °C, and residence time reduced from 60 to 7.5 min.
- Acid hydrolysis: temperature increased from 45 °C to 53 °C, and duration reduced from 2 to 1 h.

Scenario 4 (S4): Builds upon S3 with further process efficiency improvements. Specifically, the use of water in the filtration stage is reduced by 50%, resulting in lower operating costs. However, this reduction in washing volume also leads to a lower degree of final product purification.

2.3 Economic analysis

Techno-economic analysis was performed based on 2024 cost data. The assumed construction and startup periods were 18 months and 6 months, respectively. The operational lifetime of the facility was considered to be 20 years. Equipment purchase costs were estimated based on required capacities using an exponential scaling approach, as recommended in the literature [19]. Cost adjustments were applied to account for both process scale and inflation to reflect 2024 pricing (Table S1). Equipment sizing, material flows, and utility requirements were obtained from the SuperPro Designer process model, which also served as the basis for estimating total capital investment across all scenarios (Table S2). Equipment installation costs were estimated by applying appropriate installation factors taken from established references [18, 19]. These values were used to estimate the capital costs of the plant establishment. An overview of the integrated process modeling and economic analysis framework is provided in Fig. S1.

Annual operating cost was estimated by accounting for expenditures associated with raw materials, labor, consumables, utilities, facility-dependent costs, and laboratory and quality control activities. Unit costs for all major material inputs are summarized in Table S3. Membrane filtration systems were considered in the process design, and the membrane cost was assumed to be $400/m^2$. Utility costs were based on the three main types: standard power ($69.5/MWh), low-pressure steam ($12/tonne), and high-pressure steam ($20/tonne). Facility-dependent costs included expenses related to equipment maintenance, depreciation, insurance, taxes, and other general overheads [18]. Labor requirements were estimated based on the operational needs of each process section. A base labor rate of $20/h was used, as reported by [20]. Total labor cost was calculated using the following equation [18]:

$$Labor\ Cost = Base\ Rate \times (1 + B + S + Su + A) \times Labor\ Use \tag{1}$$

Where B represents benefits (0.40), S is supplies (0.10), Su is supervision (0.20), and A is administration (0.60) [18]. The economic performance of each scenario was evaluated using key financial indicators, including internal rate of return (IRR), net present value (NPV), and minimum selling price (MSP). In addition, a sensitivity analysis was conducted to assess the influence of production capacity on the overall economic feasibility of T-CNC production. Significant cost reductions were also achieved through reduced RO water consumption, which led to lower capital and utility demands. These findings identify critical opportunities for improving the economic viability of T-CNC production, including optimized chemical use, enhanced washing and filtration efficiency, and reduced process water needs.

3 Results and discussion

3.1 Material and energy utilization for the production of 1 wt% CNC solution

The material and energy requirements for producing a 1 wt% CNC suspension were evaluated for each scenario at a production capacity of 50 tonne/day. In S1, which represents the baseline process, daily production of 1% CNC required 8.02 tonne of household bleach (5% active chlorine), 6.40 tonne of sulfuric acid, 6.48 tonne of sodium hydroxide, 3.98 tonne of vinegar (5% acetic acid), and 99.74 tonne of wet tunicate biomass. Water consumption in S1 was substantial, totaling 1,187.83 tonne/day due to extensive washing and filtration operations. S2, which incorporates improved washing equipment, significantly reduced chemical and water usage. Daily requirements included 2.52 tonne of bleach, 5.14 tonne of sulfuric acid, 5.12 tonne of sodium hydroxide, 1.25 tonne of vinegar, and 718.74 tonne of water, while the tunicate biomass requirement remained unchanged at 99.74 tonne. In S3, where bleaching, quenching, and hydrolysis parameters were optimized, material consumption remained similar to S2. However, improved reaction efficiency and residence times resulted in reduced energy demand. S4 featured a 50% reduction in water use during the filtration stage, leading to the lowest water consumption among all scenarios at 469.41 tonne/day.

Utility demands also varied across scenarios. Annual electricity consumption was highest in S1, totaling 3,117 MWh, followed by S2 at 1,704 MWh, whereas S3 and S4 each required 1,701 MWh annually. Steam consumption was likewise highest in S1, with 3,845 tonne of low-pressure steam and 1,623 tonne of high-pressure steam. S2 consumed 1,117 tonne of low-pressure and 586 tonne of high-pressure steam, while S3 and S4 each required 841 tonne of steam and 2,126 tonne of high-pressure steam. The elevated utility demands in S1 were primarily attributed to the less efficient pretreatment process, which involved extended reaction times and higher water and energy requirements. Process improvements in S2-S4 led to notable reductions in both material consumption and energy intensity.

3.2 Economic analysis

3.2.1 Capital investment

The estimated total capital investments for S1 through S4 were \$21.66 million, \$16.47 million, \$16.16 million, and \$13.26 million, respectively. The baseline scenario (S1) exhibited the highest capital cost due to its higher water and chemical demands, longer processing times, and manual operations, all of which contribute to larger equipment sizing and greater utility needs. In S2, the introduction of dedicated equipment for tunicate washing reduced capital investment by approximately 24% relative to S1. S3, which featured optimized reaction conditions, further reduced capital investment to 25% below that of S1. While the overall production rate remained unchanged across scenarios, reductions in process residence times could enable more process cycles per day, thereby increasing throughput and enhancing profitability. S4 demonstrated the lowest capital investment, representing a 39% reduction compared to S1. This reduction was primarily due to decreased water consumption, which allowed for smaller equipment sizing in the filtration and concentration units. Across all scenarios, the filtration and concentration section accounted for the largest share of total capital investment, contributing 46.81% (S1), 58.47% (S2), 59.57% (S3), and 50.79% (S4). The ultrafiltration system was the single most capital-intensive component, comprising 22%, 29%, 30%, and 36% of total capital investment in S1 through S4, respectively. This highlights the critical importance of filtration system design and optimization in the economics of T-CNC production. A detailed breakdown of capital investment by process area is presented in Table 1. Improvements in washing efficiency (S2) and reaction conditions (S3) led to moderate reductions in these areas, while the significant water reduction in S4 resulted in the lowest equipment and construction costs. Installation, piping, and auxiliary facilities also declined progressively from S1 to S4 due to smaller equipment requirements. Contingency, startup, and working capital costs followed similar trends, highlighting the broad impact of process optimization on capital investment.

3.2.2 Operating cost and profitability factors

The annual operating costs for S1, S2, S3 and S4 were estimated at \$17.99 million, \$12.75 million, \$12.72 million and \$12.04 million, respectively (Fig. 2). Raw materials were the dominant cost driver, contributing 45.24% to 54.18% of total operating costs, with S1 exhibiting the highest share due to its greater consumption of chemicals and water. S1 required 68.57% more bleach, 19.62% more sulfuric acid, 21.10% more sodium hydroxide, 68.57% more vinegar, and up to 60.48% more water compared to the improved scenarios (S2-S4). Fig. S2 visually emphasizes the substantial material intensity of S1 relative to other configurations. The sharp reduction in bleach, acid, and vinegar costs in S2–S4 highlights the effectiveness of process improvements, especially in washing, quenching, and filtration in minimizing chemical demand. A detailed summary of the economic analysis for all scenarios is provided in Table 2.

3.2.3 Minimum selling price and sensitivity analysis

For the four scenarios, the MSP of 1 wt% T-CNC suspension was estimated to be \$1.16/kg (S1), \$0.82/kg (S2), \$0.82/kg (S3), and \$0.77/kg (S4). When normalized on

Table 1 Breakdown of the total capital investment for 50 tonne/day T-CNC production plant under four process scenarios (S1-S4)

Description	S1	S2	S3	S4
Equipment Purchase Cost	\$3,142,000	\$2,419,000	\$2,371,000	\$1,928,000
Installation	\$1,523,000	\$1,121,000	\$1,101,000	\$884,000
Process Piping	\$1,100,000	\$847,000	\$830,000	\$675,000
Instrumentation	\$1,257,000	\$968,000	\$949,000	\$771,000
Insulation	\$94,000	\$73,000	\$71,000	\$58,000
Electrical	\$314,000	\$242,000	\$237,000	\$193,000
Buildings	\$1,414,000	\$1,089,000	\$1,067,000	\$867,000
Yard Improvement	\$471,000	\$363,000	\$356,000	\$289,000
Auxiliary Facilities	\$1,257,000	\$968,000	\$949,000	\$771,000
Engineering	\$2,643,000	\$2,022,000	\$1,983,000	\$1,609,000
Construction	\$3,700,000	\$2,831,000	\$2,776,000	\$2,252,000
Contractor's Fee	\$846,000	\$647,000	\$634,000	\$515,000
Contingency	\$1,691,000	\$1,294,000	\$1,269,000	\$1,030,000
Working Capital	\$1,239,000	\$840,000	\$843,000	\$828,000
Startup Cost	\$973,000	\$744,000	\$730,000	\$592,000
Total capital investment	\$21,664,000	\$16,468,000	\$16,166,000	\$13,262,000

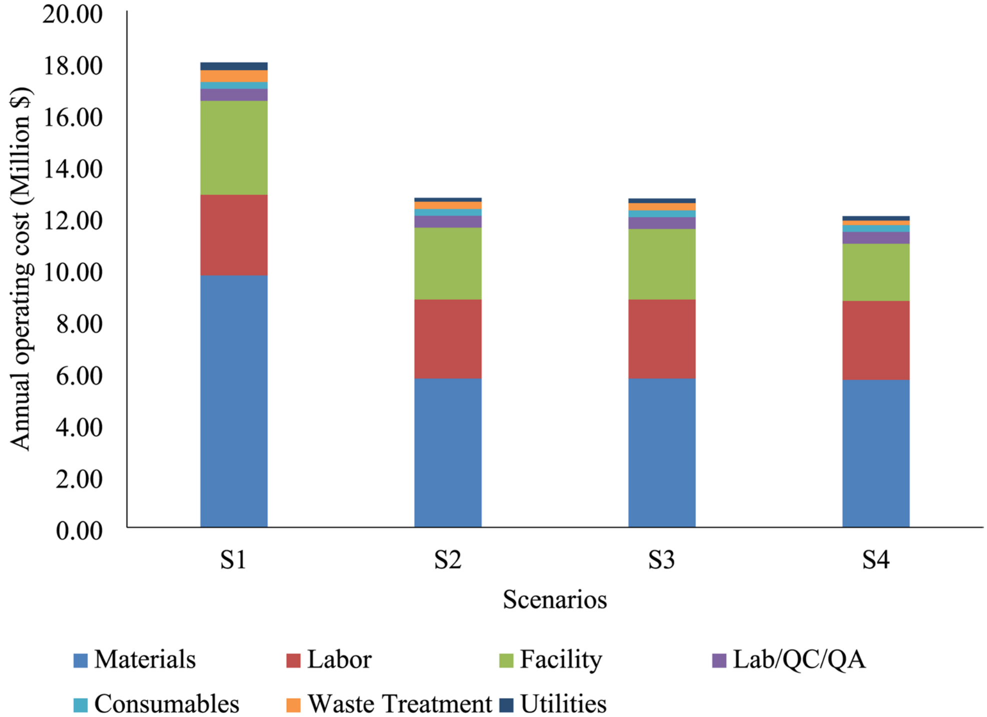


Fig. 2 Breakdown of annual operating cost of T-CNC production for different scenarios

Table 2 Summary of economic analysis of T-CNC production for different scenarios

Description	S1	S2	S3	S4	Units
Capital Investment	21,664,000	16,468,000	16,166,000	13,262,000	$
Operating Cost	17,993,000	12,745,000	12,721,000	12,044,000	$/yr
Revenues	19,470,000	14,025,000	14,025,000	13,196,000	$/yr
Cost Basis Annual Rate	16,500,093	16,499,938	16,499,800	16,494,771	kg MP/yr
Net Unit Production Cost	1.09	0.77	0.77	0.73	$/kg MP
Unit Production Revenue	1.18	0.85	0.85	0.80	$/kg MP
Gross Margin	7.58	9.12	9.29	8.73	%
Return On Investment	13.64	14.41	14.62	15.00	%
Payback Time	7.33	6.94	6.84	6.67	years
IRR (After Taxes)	9.98	10.36	10.53	10.56	%
NPV (at 7.0% Interest)	6,973,000	6,161,000	6,382,000	5,428,000	$

*MP- Main Product

a dry CNC basis, the MSP corresponds to approximately $116/kg, $82/kg, $82/kg, and $77/kg of dry CNC for S1-S4, respectively. The lowest MSP in S4 is attributed to reduced capital investment and operating costs resulting from optimized water use and process intensification. Previous studies have assessed the economic viability of CNC production from various feedstocks and processing routes [13, 17, 21, 22]. Rajendran et al. investigated the economic feasibility of dry W-CNC production from wood pulp using the acid hydrolysis method and reported an MSP of $4.89/kg [17]. Rosales-Calderon et al. examined the economic feasibility of W-CNC production from kraft pulp using both acid and enzymatic hydrolysis methods, reporting MSPs of $10/kg for acid hydrolysis and $65.74/kg for enzymatic hydrolysis [22]. Bondancia et al. [13, 21] also reported higher costs for CNC production using organic acids and small-scale systems. It is important to note that most published MSP values are reported for dry CNC products, whereas this study evaluates the MSP of a 1 wt% CNC suspension. For comparison, the MSP of T-CNC was also normalized to a dry basis based on the solids content of the suspension. The normalized dry-basis MSP of T-CNC appears higher due to the low CNC concentration in the suspension. In addition, direct economic comparisons with literature values remain challenging and misleading due to variations in system boundaries, feedstock types, processing technologies, and product specifications. Producing dry CNC requires an additional drying step, which increases both capital investment and operating costs, thereby directly affecting the MSP of dry CNC.

A sensitivity analysis was performed to evaluate the impact of production capacity on MSP. Results showed that increasing production capacity leads to economies of scale, significantly reducing MSP, particularly under the optimized scenarios (S3 and S4). This suggests that process improvements, when implemented at larger scales, can further enhance the economic competitiveness of T-CNC production. A sensitivity analysis in this study included an economic analysis of different production capacities from 0.5 to 100 tonne/day to evaluate its impact on the MSP of T-CNC. The capital investment and operating cost of different capacities are shown in Fig. S3 and S4. In S1, the MSP decreased from \$24.89 to \$1.04/kg; in S2, it decreased from \$23.06 to \$0.71/kg; in S3 it decreased from \$23.04 to \$0.71/kg; and in S4 it decreased from \$23.03 to \$0.64/kg (Fig. 3). Increasing production capacity raises capital investment and operating costs, which in turn enhances the production rate and lowers the MSP of T-CNC. The NPV was also estimated based on different plant capacities (Fig. 4). An increase in production capacity enhances overall production output and profitability, leading to a higher NPV. The results of sensitivity analysis also suggest that process improvements, when implemented at larger scales, can further enhance the economic competitiveness of T-CNC production.

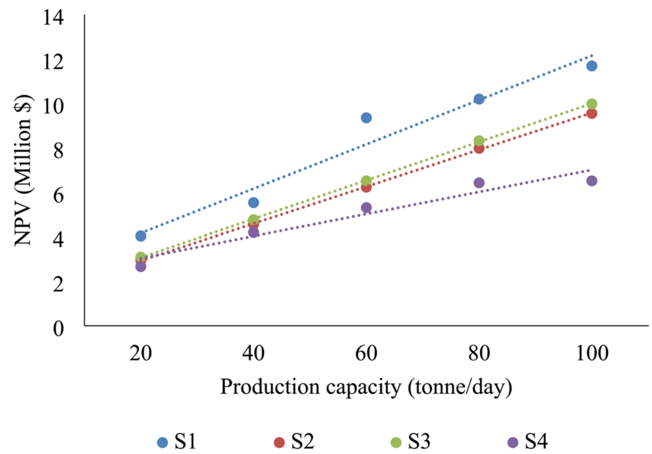
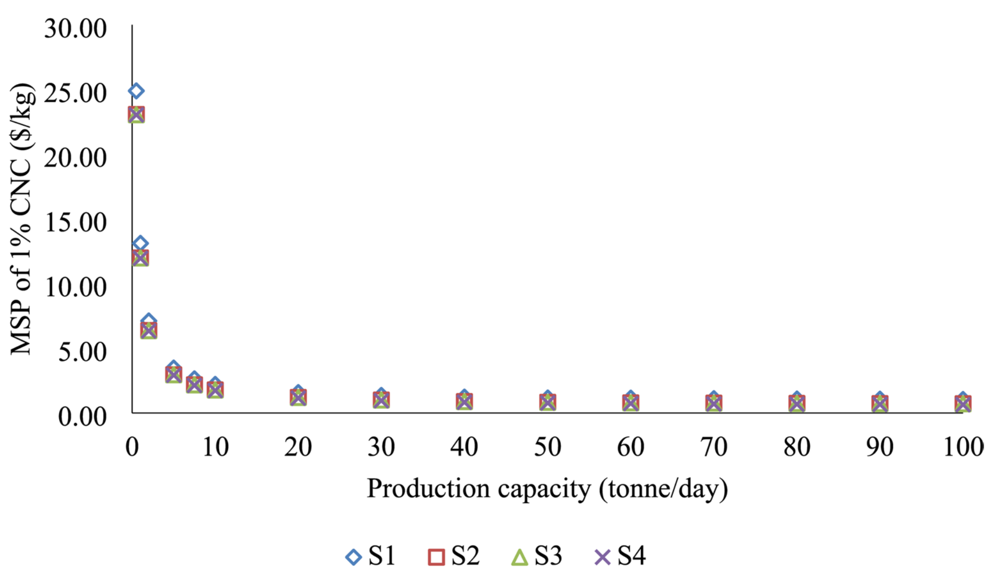


Fig. 4 Net present value analysis of T-CNC production at various capacities (tonne)

3.3 Limitations and future studies

This study presents a comprehensive TEA of large-scale T-CNC production, scaled up from laboratory and pilot-scale data. The analysis focused on the production of a 1 wt% CNC suspension, which is relevant for many industrial applications but differs from the dry CNC form commonly evaluated in previous studies. Additionally, a detailed tunicate collection and handling process model was not included in this analysis and should be addressed in future studies to provide a more complete assessment of the production system. Future work should explore the production of T-CNC at varying concentrations, including dry powder forms, to assess how concentration affects the downstream process, transportation logistics, and market value. Additionally, investigating alternative processing pathways such as enzymatic hydrolysis, greener acid systems, or integrated biorefinery configurations could further improve process efficiency and reduce costs. This study lays the foundational framework for future research on T-CNC production, identifying key economic barriers to commercialization and supporting the development of more sustainable and competitive nanomaterial production platforms.

Fig. 3 Minimum selling price of T-CNC based on different production capacities



4 Conclusion

This work delivers the first commercial-scale techno-economic assessment of producing CNC from tunicate biomass. The MSP for 1% CNC was estimated at $1.16/kg in the baseline scenario and reduced to $0.77/kg under the optimized process configuration. Results showed that raw material costs, particularly for chemicals, are major contributors to operating expenses, underscoring the importance of process improvements to reduce MSP. When normalized on a dry T-CNC basis, the MSP appears higher than that reported dry W-CNC products due to the low solids content of the suspension. Future studies incorporating drying processes to produce dry T-CNC would allow a more direct comparison with commercial products and provide a more realistic estimation of the MSP of dry T-CNC.

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Authors' contributions Seyed Hashem Mousavi-Avval: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Visualization, Validation, Writing - Original Draft, Writing - Review & Editing. Naveenkumar Rajendran: Formal analysis, Investigation, Visualization, Validation, Writing - Original Draft, Writing - Review & Editing. Matthew J. Dunlop: Formal analysis, Investigation, Data Curation, Validation, Writing - Review & Editing. Kamalakanta Sahoo: Conceptualization, Formal analysis, Investigation, Validation, Writing - Review & Editing. Troy Runge: Formal analysis, Investigation, Resources, Validation, Supervision, Project administration, Funding acquisition, Writing - Review & Editing. Richard Bergman: Formal analysis, Investigation, Resources, Validation, Supervision, Project administration, Funding acquisition, Writing - Review & Editing.

Data availability The models that support the findings of this study are available from the corresponding author, upon reasonable request for non-commercial use.

Declarations

Competing interests There are no conflicts to declare.

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