

Techno-Economic Comparison of Conventional and Heated Water-Assisted Alginate Extraction from *Sargassum crassifolium* Using Process Simulation

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Abstract

Alginate is a valuable marine-derived polysaccharide widely used in food, pharmaceutical, and biomedical applications, with brown seaweed serving as an important renewable source. This study evaluated the industrial feasibility of alginate extraction from *Sargassum crassifolium* using process simulation and techno-economic analysis in SuperPro Designer. Two process configurations were compared: a baseline control process (BCP) and a modified heated process (MHP) incorporating heated water-assisted extraction through additional pump and heater units. The simulation was based on a batch operation of 7,920 h per year and employed literature-derived composition and yield assumptions for Indonesian *S. crassifolium* biomass. Process units were modeled using stoichiometric reactors, splitters, filtration, drying, and material handling operations to represent pretreatment, extraction, purification, and sodium alginate formation. Utility costs were estimated using Indonesian industrial prices for electricity, water, steam, and chilled water. The added parameters improved batch performance by reducing recipe batch time from 16.33 h to 9.17 h and increasing annual batch count from 2,108 to 2,877. Although the MHP plant required higher capital investment and utility consumption, it achieved better economic performance than the control BCP case, as indicated by lower unit production cost (USD 5.90/kg versus USD 6.06/kg), higher return on investment (26.50% versus 23.25%), shorter payback time (3.77 years versus 4.30 years), and a positive net present value of approximately USD 17,000 at an 18.95% discount rate. Overall, the heated water-assisted configuration of MHP was found to be the more economically favorable option, although the margin of viability remained narrow and waste management remains an important consideration.

Introduction

Alginate is a naturally occurring anionic polysaccharide extracted primarily from brown seaweeds and produced by some bacteria. It is composed of linear chains of β -D-mannuronic acid (M) and α -L-guluronic acid (G) residues linked through (1 $\rightarrow$ 4) glycosidic bonds, arranged in homopolymeric M- and G-blocks as well as heterogeneous MG sequences [1]. The M/G ratio and block distribution vary according to species, season, and environmental conditions, and these structural differences strongly determine the physicochemical behavior of the polymer [1, 2]. In general, gels M-rich alginates yield softer and more elastic networks, whereas, G-rich alginates form stiffer and stronger [3, 4]. Because of this tunable gelation behavior, alginate has become one of the most widely used marine-derived biopolymers in food, pharmaceutical, biomedical, and industrial applications. Commercial alginate is usually supplied as sodium alginate, with molecular weights commonly in the 10^5 – 10^6 Da range, although lower molecular-weight fractions are also used for specialized applications [2].

Alginate is valued for its strong water retention, biocompatibility, and ability to undergo ionotropic gelation in the presence of divalent cations, especially Ca^{2+} , through the well-known egg-box mechanism [6, 7]. Industrial extraction generally begins with dried brown seaweed, in which native $\text{Ca}^{2+}/\text{Mg}^{2+}$ alginate salts are converted into soluble sodium alginate by alkaline treatment, followed by filtration, precipitation, purification, and drying [2]. The resulting polymer can be converted into different ionic

forms and further modified to adjust solubility, degradation behavior, and mechanical properties. For this reason, alginate is commonly used in edible films, thickening agents, wound dressings, cell encapsulation, drug delivery systems, and tissue engineering scaffolds [6–8]. It is also considered safe for human use and is widely recognized in food and biomedical regulations [4, 10].

Among the natural sources of alginate, brown macroalgae of the genus *Sargassum* are especially important. *Sargassum crassifolium* is a tropical brown macroalga widely reported from Indonesian coastal waters. In current taxonomic treatments, many records under *S. crassifolium* are placed within the *Sargassum aquifolium* complex, but the older name remains common in Indonesian literature. This species has been recorded or utilized from several Indonesian regions, including Banten, Gresik, Kepulauan Seribu, and Lombok, indicating that it is broadly distributed along shallow reef flats and island coastlines [12–15]. Morphologically, *S. crassifolium* is characterized by a tough brown thallus with a differentiated holdfast, stipe, lateral branches, flattened leaf-like blades, vesicles for buoyancy, and seasonal receptacles. Its size is variable and depends on local habitat conditions, with thalli ranging from several tens of centimeters to more than 1 m in favorable environments [15].

In Indonesia, *S. crassifolium* was a major research focus; with efforts on the extraction and characterization of alginate from this species, given its potential for biomaterials, food formulations, and tissue-engineering scaffolds [11]. Indonesian studies have also explored its use in capsule-shell films and other seaweed-based materials, reflecting growing interest in replacing less efficient animal-derived or synthetic polymers with renewable marine resources [12]. In addition, *S. crassifolium* has shown promise in agriculture and environmental remediation, including use as a bio stimulant and as a source of bioactive compounds relevant to fertilizer development and heavy-metal biosorption [9]. These applications suggest that *S. crassifolium* is not merely a coastal seaweed resource, but a promising raw material for value-added bioproducts in Indonesia's emerging blue economy.

According to Bojorges, et.al. (2023) [16] the extraction of sodium alginate from brown seaweeds (Phaeophyceae) conventionally follows a systematic six-step sequential process involving biomass pre-treatment, acid treatment, alkaline extraction, precipitation, bleaching, and dehydration. The initial pre-treatment phase focuses on eliminating impurities and undesirable matrix components from the harvested algal biomass. This is typically followed by an acid wash stage—using dilute mineral acids—to protonate the native insoluble alginate salts (primarily calcium, magnesium, and sodium matrices found within the seaweed cell walls) into insoluble alginic acid.

The core of the solubilization process occurs during the subsequent alkaline extraction stage, where the isolated alginic acid is treated with alkaline solutions, most commonly sodium carbonate. This reaction converts the water-insoluble structural polymer into highly soluble sodium alginate, allowing it to be separated from the residual cellular debris through filtration or centrifugation. Once the clear sodium alginate aqueous phase is recovered, the biopolymer is recovered from the solution via chemical precipitation, which can be achieved either directly by converting it back into an insoluble state to isolate the target fraction.

The whole process had been observed to be positively impacted by an increase in temperature on the reaction required for form ionic-alginate compounds. The temperature increase was concurred to push the reactions necessary to form desired alginates to yield higher, in turn hastened reactions in conditions where feed substrate was the limitation factor.

Methodology

Process simulation and techno-economic evaluation used SuperPro Designer (SPD) from Intelligen, Inc., a bioprocess and industrial manufacturing platform. It models, balances mass and energy, sizes equipment, schedules, and assesses cost for batch and continuous systems. Process units from the library were selected and configured for alginate production. Equipment capacities, operating conditions, and sequencing were set to fit the scaled plant and reflect both control and heated-water-assisted processes.

This study used a SuperPro Designer version with SchedulePro, an integrated module that optimizes batch operations by identifying production bottlenecks, resource conflicts, idle time, and cycle limits. By analyzing process dependencies and equipment use, the tool suggests batch staggering, overlapping, or different schedules to boost throughput and efficiency. This is useful for batch alginate extraction, where unit sequences are constrained for a 5.5 tons ton of raw *S.crassifolium* input processing capacity.

SuperPro Designer is a deterministic simulation tool driven by user-set structure, parameters, and material data. It has a large internal database of chemicals, utilities, and processing materials. Proprietary or custom materials can be added with the Substances and Mixtures feature. For this study, this allowed modeling feedstock, alginate streams, and custom formulations not in the default library. SuperPro Designer provides engineering and economic results, including material and energy balances, equipment sizes, utility use, labor, and batch cycle data. Scheduling outputs include Gantt charts for visualizing tasks, occupancy, cleaning, and overlaps. These tools reveal underused equipment and process issues, aiding improvements to the extraction scenarios.

The platform features a built-in techno-economic analysis framework. It supports reviewing different extraction setups. Capital costs (CAPEX) are estimated from equipment, piping, buildings, and infrastructure. Operating costs (OPEX) cover raw materials, labor, consumables, waste, maintenance, and utilities. Economic performance also depends on user-defined assumptions such as debt-to-equity ratio, tax rates, depreciation method, project lifetime, repayment schedules, and interest rates. Using these inputs, SuperPro Designer estimates profitability indicators—unit production cost, annual revenue, margin, net present value, and payback, enabling comparison of extraction methods.

A key feature is classifying waste, emissions, and by-products by stream rather than component, for detailed environmental tracking and sustainability analyses. SuperPro Designer can export simulation data to Excel (.xls) for further processing or sensitivity tests. The platform thus provides operational and environmental data, which are essential for assessing alternative alginate extraction methods. Overall, SuperPro Designer was chosen for this study because it combines process modeling (simulating and

analyzing production pathways), production scheduling (planning batch operation timing), and economic evaluation (estimating costs, profits, and feasibility) into one platform. This makes it especially appropriate for assessing whether alginate extraction and downstream processing (post-extraction steps) are industrially feasible.

Variables defining

The variables in this case are defined by the two different streams of input, which contains additional pump and heater unit that produces heated solvent streams. The first one would be the water stream used in the second washer, representing base water extraction method used to prime *S.crassioflum* sludge for extraction. Then followed suit by the sodium carbonate solvent extraction where the solution would be heated to assist with the main alginate extraction.

The properties for alginates inputted by the author as the software used was mostly based on some literature reviews; this is partially due to the uncertain nature of alginates' properties produced from *S.crassifolium* seaweed in mass scale factories. The simulation assumes a single fixed scenario where extracted alginates quality or physical properties is constant.

As for the *S.crassifolium* seaweed utilized in the simulations, the author used the information provided by Mushollaeni, W (2011) [17] where the seaweed utilized was *Sargassum Crassifolium* from the coral coast of Gunung Kidul Yogyakarta from Java Island, Indonesia. This information represents a more optimistic view of the cultivated *Sargassum* seaweeds in Indonesia detailed in Table 1, at least in terms of yield and ash content. The biomass came from SuperPro™ simulations default library and will act as a placeholder for a biomass-based by-product. Ash will act as the lowest form of non-processable chemical waste that has to be disposed of.

Table 1
Seaweed chemical
composition breakdowns

Components	Ratio
Alginates	34.0%
Ash	32.59%
Biomass	31.98%
Water	1.43%

Components definitions in the factory

Alginates within the factory was defined with a fixed molar mass for simulation purposes based on a database [18]. Then the calcium alginate and calcium carbonate followed suit using alginates as the

base backbone then added their respective metals to the molar mass. Details of the chemical components used in the simulation can be seen in Table 2

Table 2
Components definitions within the library

Components	Definitions	Details
Alginates	Defined by user	[C ₁₂ H ₁₆ O ₁₂], molar mass of 352.25 g mol ⁻¹
Calcium Alginate	Defined by user	[C ₁₂ H ₁₄ CaO ₁₂] molar mass of 390.31 g mol ⁻¹
Calcium Carbonate	SuperPro Database	[Ca ₂ CO ₃] Molar mass 100.087 g mol ⁻¹
Sodium Carbonate	SuperPro Database	[Na ₂ CO ₃] Molar mass 105.989
Sodium Bicarbonate	SuperPro Database	[NaHCO ₃] Molar mass 84.007
Seaweed	Defined by user	combination of alginates, ash, biomass and water
Cellulose	SuperPro Database	Molar mass of 200 g mol ⁻¹
Ash	SuperPro Database	Pure waste product
Water	SuperPro Database	Molar mass of 18.02 g mol ⁻¹
Proteins	SuperPro Database	[CH _{1.8} O _{0.5} N _{0.2}]
Air	SuperPro Database	76.72% Nitrogen and 23.29% Oxygen
Fat	SuperPro Database	Defined as, molar mass of 147.60 g mol ⁻¹
Carbohydrates	SuperPro Database	[C ₆ H ₁₂ O ₆]
Biomass	SuperPro Database	[CH _{1.8} O _{0.5} N _{0.2}]
Sodium Alginate	Defined by user	[Na ₂ CO ₃] Molar mass 198.105 g mol ⁻¹
Potassium Hydroxide	SuperPro Database	[KOH], Molar mass 56.106 g mol ⁻¹
Hydrochloric Acid	SuperPro Database	[HCl], Molar mass 36.461 g mol ⁻¹

Unit processes required in the factory

The unit processes implemented in the factory model followed the standard unit operation library provided by the SuperPro Simulator software. Unit labeling adhered to the default automated identification system embedded within the software environment; while the final product configuration may differ in labeling, the functional roles of each unit operation remained consistent. The SuperPro unit

library was considered sufficient for representing the technical feasibility of the required unit processes, whereas scheduling and economic parameters were adjusted to reflect contemporary operational capabilities.

Two simulation flow structures were defined within the process model: a control simulation flow and a variable simulation flow. The control simulation flow represented baseline operating conditions and was used to establish process continuity and mass balance stability. In contrast, the variable simulation flow incorporated additional dynamic unit operations, specifically heaters and pumps (utilized in MHP), to support the heated solvent extraction process. These units enabled controlled adjustment of temperature and flow rate parameters, allowing evaluation of their influence on extraction performance and overall process behavior.

A detailed list of all unit processes, along with their respective roles within both simulation flows, is provided in Table 3.

Table 3
Units required within the factory

Unit type	Unit label	Function in process
Transport truck	P-2	Introduction of seaweed
Washer (bulk)	WSH-101	Partial removal of ash
Grinder	GR-101	Size reduction
Mixer	MX-101	Mix with water
Washer (bulk)	WSH-102	Partial removal of ash
Pump (variable)	PM-101	Heated water formation
Electric heater (variable)	EH-101	Supercritical water formation
Pump (variable)	PM-102	Heated water formation
Electric heater (variable)	EH-102	Heated water formation
Microfiltration	MF-101	Biomass Removal
Stoichiometric reactor – sodium alginate	R-101	Soluble Sodium alginate
Component splitter	CSP-101	Salt by product removal
Stoichiometric Reactor- Calcium alginate	R-102	Intermediary calcium alginate formation
Temporary storage vessel	R-103	Calcium chloride removal
Final sodium alginate tank	R-104	Final product formation, sodium alginate
Tray drying	TDR-101	Water removal
Belt conveyor	BC-101	Short range transport
Long term transport	P-12	Long range transport

Units and equipment sizing

Equipment sizing within the factory model was performed using user-specified, design-calculated dimensions rather than fully customized, throughput-optimized sizing. This approach was deliberately adopted to maintain consistency with standard techno-economic analysis practices, where representative equipment sizes are commonly employed when reliable cost correlations for bespoke chemical process equipment are unavailable or highly uncertain. By applying standardized sizing assumptions, the simulation preserves internal comparability across unit operations while avoiding over-interpretation of cost precision.

Table 4 summarizes the unit operations included in the simulation, along with their construction materials and nominal processing capacities. The model does not incorporate staggered operation or standby units, as the analysis focuses on steady-state process performance rather than operational redundancy or availability optimization. Figure 1 acts as the visualization of the factory simulation as presented in the software

Table 4
Units sizing within the factory

Name	Type	No. of Units	Size (capacity per unit)	Construction Material
WSH-101	Washer (bulk flow)	1	16500 kg h	CS
GR-101	Grinder	1	3922.64 kg h	CS
MX-101	Mixer	1	18563.53 kg h	SS316
WSH-102	Washer (bulk flow)	5	16707.17 kg h	CS
PM-101	Water pump	1	11.97 kWh	SS316
EH-101	Electric heater	15	84.5 kWh	SS316
PM-102	Water pump	1	31.61 kWh	SS316
EH-102	Electric heater	2	100.62 kWh	SS316
MF-101	Microfiltration	3	375.647 sqm	SS316
R-101	Reactor vessel	1	24252.29 kg	SS316
CSP-101	Splitter	1	130296.38 kg	CS
R-102	Reactor vessel	1	6785.43 kg	SS316
R-103	Reactor vessel	1	13653.34 kg	SS316
R-104	Reactor vessel	1	15348.45 kg	SS316
TDR-101	Tray dryer	7	95.65 sqm	SS316
BC-101	Belt conveyor	1	2106.24 kg h	CS

Costs of Utilities within the factory

The costs of electricity and water shall be simulated using Indonesian early 2026 costs. Which was USD 0.056/kWh for electricity and USD 0.4/ MT for water.

Power demands of the factory

The overall power demand of the factory was primarily driven by the electricity consumed by the installed unit processes. Given that most operations were electrically actuated, power requirements were modeled in watts. In this study, however, power consumption was treated as a resulting performance metric rather than a predefined input parameter, as the primary analytical focus was placed on process modifications and the introduction of additional unit operations that altered the factory configuration.

Heating steam was incorporated mainly as an economic consideration, and direct power costs associated with steam generation were not explicitly evaluated. Most of the process-unit equipment was assumed to be procured from third-party suppliers and subsequently assembled onsite. Table 5 summarizes the equipment required for the factory, including baseline power demand values and the corresponding reference sources used for estimation.

Process parameters

Process parameters were defined to closely represent the operating conditions governing each unit operation within the simulated process flow. Individual modules were parameterized according to their position in the sequence, ensuring alignment between material throughput, compositional changes, and stage-specific functional roles, consistent with established modular simulation practices [10]. This modular structure enabled consistent tracking of process evolution while preserving flexibility in adjusting operating conditions where required.

Temperature and pressure were treated as the principal control variables and were applied uniformly across all modules, reflecting their dominant influence on material behavior and process stability in process modeling studies [20]. The system was modeled under atmospheric conditions, as no vacuum environments were involved in the actual operation. Accordingly, air was represented as a composite gas mixture sourced from the simulation library, following common assumptions in industrial-scale simulations

Additional parameters, including material flow rates and residence times, were selected within practical industrial ranges to balance physical realism with numerical robustness). Automated unit labeling was integrated into the simulation framework, allowing unambiguous identification of process streams and facilitating systematic analysis of intermediate and final outputs, as recommended in prior simulation-based process analyses. The complete set of operating parameters and boundary conditions employed in the simulation is summarized in Table 3.

Table 5
Unit parameters within the factory

Operations	Unit label	Temp (°C)	Pressure	Conditions
Transport truck	P-2	n/a	n/a	Assumed to be a singular unit
Washer (bulk)	WSH-101	25	n/a	80% ash removal
Grinder	GR-101	n/a	1.013 bar	Assumed no dissipation of heat
Mixer	MX-101	n/a	1.013 bar	Water mixing
Washer (bulk)	WSH-102	62.5	n/a	More ash removal
Pump(variable)	PM-101	n/a	10 bar	Variable unit
Electric heater(variable)	EH-101	120	n/a	Variable unit
Pump (variable)	PM-102	n/a	15 bar	Variable unit
Electric heater(variable)	EH-102	100	n/a	Variable unit
Microfiltration	MF-101	25	Atmospheric	Assume 90% recovery
Stoichiometric reactor – sodium alginate	R-101	25	Atmospheric	Assume 90% reaction efficiency
Component splitter	CSP-101	25	Atmospheric	
Stoichiometric reactor- calcium alginate	R-102	25	Atmospheric	
Temporary storage vessel	R-103	25	Atmospheric	
Final sodium alginate tank	R-104	25	Atmospheric	
Tray drying	TDR-101	70	7.931 bar	
Belt conveyor	BC-101	n/a	n/a	Assumed to be singular unit
Long-term transport	P-12	n/a	n/a	Assumed to be singular unit

Determination of Discount Rate for Net Present Value (NPV) Analysis

The discount rate applied in the Net Present Value (NPV) assessment was estimated using the widely accepted framework for determining the required rate of return on equity investments under market risk conditions. CAPM relates the expected return of an investment to the time value of money and its exposure to systematic risk, thereby providing an appropriate rate for discounting projected future cash flows to present value. The model is expressed as:

$$R_e = R_f + \beta (E(R_m) - R_f)$$

where:

- R_e ; required return on equity (used herein as the discount rate)
- R_f ; risk-free rate
- β ; beta coefficient representing systematic risk relative to the market
- $E(R_m) - R_f$; equity risk premium (ERP), i.e., the expected excess market return over the risk-free rate

For this study, the risk-free rate was proxied by the yield on Indonesian government bonds and taken as 6.72% [21]. The equity risk premium for Indonesia was reported as 6.87%, with an additional country risk premium of 2.54% [22]. To reflect the elevated market uncertainty associated with a niche seaweed-processing venture relative to the broader agricultural sector, a beta value of 1.30 was adopted, slightly above the reported agricultural industry beta of 1.20 [23].

Substituting these values into the CAPM equation gives:

$$R_e = 6.72 + 1.30(6.87 + 2.54)$$

$$R_e = 18.95 \%$$

Accordingly, a discount rate of approximately 18.95% was applied in the NPV analysis. This rate reflects both Indonesia's macroeconomic risk environment and the higher systematic risk associated with commercialization of a specialized seaweed-based processing enterprise.

Mode of Operations

The plant simulation was carried out under a batch-system framework with an annual operating time of 7,920h [24]. Ahmed et al. (2022) indicated that 330 operating days would be adequate for a lean manufacturing simulation [19]. This operating schedule was deliberately chosen to also allow for intermittent shutdowns associated with system upgrades and routine equipment maintenance.

The Flowchart Presentation

The flowcharts will be split into 3 as presented in Fig. 2. The processes will share a pretreatment and a post treatment with the split occurring in the alginate extraction and formation processes.

Results and Discussions

Factory Summary Flowcharts

The plans generate a single revenue flow and seven waste flows. The revenue flow was the product of alginates and the wastes were split into ash, biomass and unused reactants. With ash deemed to be the most problematic due to its much lower economic value. The Simulation can be summarized using multiple flowcharts. With Fig. 2 acting as the factory summary whilst Figs. 3 and 4 showing the difference that occurred within the process schematics from the additional units introduced into the system.

The pre-treatment in this simulation case starts with transportation of dried seaweeds. The raw *S.crassifolium* will be washed to remove some of the debris in the form of ash. Then the size of the seaweed will be reduced by grinding it down before mixing it with water to form sludge. The grinding was expected to increase the surface area that will aid in maximalizing the contact between seaweed sludge substrate and the multiple extraction solvents that will occur throughout the rest of the processing. Then acid will be introduced in the form of hydrochloric acid solution to pull out alginate, in literature this is supposedly insoluble alginic acid.

The main alginate extraction steps in the simulations are where the control BCP version as summarized in Fig. 4 and the modified heated water assisted MHP version as summarized in Fig. 5 of the factories start to diverge. The heated water will be supplied with a separate pump and heater; this choice was to properly split the energy and water inputs into the system. In both scenarios there were a washer and a microfiltration unit. The washer starts removing alginate from the substrate using hot water and then the microfiltration separates the raw alginate from the water.

The first by-product in the form of insoluble sodium alginate was formed using the sodium actor vessel. Inside the vessel the first sodium carbonate introduction happened. It will be followed by the component splitter where most of the spare reactants will be removed before moving on to the second washer on the alginate formation phase.

Finally, after the extraction process, the product formation processing began as detailed in Fig. 6. The product formation starts with introduction of calcium chloride into a vessel. The calcium chloride will form calcium alginate as a byproduct. Then there will be an acid washing to remove unwanted reactants. The calcium alginates will then react with sodium carbonate for form final product in this case being sodium alginate in aqueous form. The sodium alginate later dried into solid form using tray drying aided with steam to heat up the fluids faster.

The final product will be packaged using a belt conveyor for short range transport and long-range transport using sea cargo. Sea cargo in this case shall be simulated economically.

Energy and utilities

The energy and utilities demand by the factory can be split by standard power to denote electricity along with Steam and chiller water as heat exchanging agents. The energy and heat exchanging agents demand of the modified factory was significantly higher than the control factory. The increased demands of the modified factory for more power and heat exchanging agents will drove up the operating costs of the factory. The direct heating in the MHP system more than doubled the demand for electricity in the form of Standard energy. Details of the heating energy demand is within the appendix tables.

Table 6
Utilities demand of each factory

Baseline control process (BCP)					
Utility	Unit cost (\$)	Annual amount	Ref. units	Annual cost (\$)	%
¹ Std Power	0.056	1941449	kwh	108721	0.65
² Steam	12	73836	MT	886036	97.46
Chilled water	0.4	40282	MT	16113	1.89
Total				1010870	100
Modified heated process (MHP)					
Utility	Unit Cost (\$)	Annual Amount	Ref. Units	Annual Cost (\$)	%
¹ Std power	0.056	4620024	kwh	258721	1.35
² Steam	12	62778	MT	753341	73.53
Chilled water	0.4	623842	MT	249537	25.12
Total				1261599	100
¹ Std Power- Electricity					
² The steam charge of 12 USD/ Tons reflects the thermal energy delivered to the process. Steam provides a high heat-transfer coefficient through condensation, precise temperature control, and reliable heat delivery.					

Economic assessments

Since both factories are technically feasible; the economic assessments will be the main differentiating method to decide which one of the two scenarios should be chosen. In this case the economic assessments should start with a batch time and annual batch cycle. Here it is shown that the batch time

differs significantly, with the modified process showing a much better time by a 7 hours difference per batch and one hour per batch cycling.

The difference in each batch and batch cycling affects directly the number of annual batches that can be conducted with a fixed 7920 hours per annum as inputted by the author. As detailed in Table 7 the annual batch amount of the modified factory was outnumbering the control factory by 769 batches per annum. The difference of batch time also indirectly affects the annual number of products as a factory's output. It is worth noting though that rounding up of batch numbers was observed as half batches and decimals are not applicable in calculating batches.

Table 7
Annual batch cycles summary

Factors	Modified	Control	Units
Annual operating time	7920		h
Unit production reference rate	6059647.62	4439950.36	kg MP/yr
Batch size	2106.24		kg MP
Recipe batch time	9.17	16.33	h
Recipe cycle time	2.75	3.75	h
Number of Batches per Year	2877	2108	-

The Economic Assessment Summary

The economic assessment in this case is the feasibility range of the two factories. The first aspect that should be observed was the total capital investment, where the modified factory demands more capital investments along with more operating costs. The capital costs were driven by the added units within the factory. The added materials and energy required by the modified factory as summarized by Table 5 driven up the operating costs.

Both factory scenarios operated on a user inputted revenue stream of USD 6585 per tons of final products introduced into the market to assume similar qualities as determined by market agreement. Using that fixed parameter, the margin of the MHP factory is still noticeably higher than the control factory simulation. Table 8 broke down several variables that determined feasibility of each factory. The MHP process factory simulated a higher capital investment. MHP scenario also demands a higher cost for operating a factory; partially caused by a spike in utility as detailed in Table 6. But MHP has a lower production cost of USD 5.90/kg against BCP's USD 6.06 and a faster payback period of 3.77 years compared to the 4.3 years of the control factory

Return on investment (ROI) is a financial metric used to evaluate the efficiency or profitability of an investment by comparing the gains obtained relative to the cost incurred. It is commonly expressed as a percentage and calculated by dividing the net benefit of the investment by the total investment cost,

thereby enabling comparison between different projects or expenditures. Again, it demonstrates that the modified factory is more profitable than the control factor as it was about 3.7% higher. This is also backed up by the payback time where the modified factory returns its capital in a much faster rate than the control factory.

The internal rate of return (IRR) is a financial indicator used to estimate the profitability of an investment or project by identifying the discount rate at which the net present value (NPV) of future cash flows becomes zero. A higher IRR generally indicates a more attractive investment, as it reflects a greater expected rate of return relative to the project's cost and risk. While Net present value (NPV) is a financial evaluation method used to determine the profitability of an investment by calculating the difference between the present value of expected future cash inflows and the present value of cash outflows over a specified period. A positive NPV indicates that the project is expected to generate value and exceed the required rate of return, whereas a negative NPV suggests that the investment may not be financially viable.

Consequently, IRR and NPV are closely related, as the IRR represents the specific discount rate at which a project neither gains nor loses value in present-value terms, while projects with an IRR higher than the required rate of return generally produce a positive NPV and are considered financially attractive. Both the BCP and MHP factory runs on a country weighed and modified 18.95% interest risk rate adjusted for Indonesia in early 2026. The IRR of the control BCP factory is lower than the NPV, thus concluding an insolvency of the factory. Meanwhile the Modified MHP factory has a closer number on both aspects, barely breaking even numerically at barely USD 17000.

Table 8
Economic profitability summary of the two factories

Factors	Control	Modified	units
Total capital investment	9082000	13567000	\$
Capital Investment Charged to This Project	9082000	13567000	\$
Operating cost	26922000	35747000	\$/yr
Revenues	29259000	39933000	\$/yr
Cost basis annual rate	4439950	6059648	kg MP/yr
Unit production cost	6.06	5.90	\$/kg MP
Net unit production cost	6.06	5.90	\$/kg MP
Unit production revenue	6.59	6.59	\$/kg MP
Gross margin	7.99	10.48	%
Return on Investment	23.25	26.50	%
Payback time	4.30	3.77	years
Irr (after taxes)	15.39	18.98	%
NPV (at 18.9% Interest)	-1282000	17000	\$

Conclusions

This study demonstrated that both the BCP and MHP alginate extraction processes from *Sargassum crassifolium* are technically feasible within the SuperPro Designer simulation framework. However, the MHP configuration incorporating heated water-assisted extraction performed better from an economic standpoint, despite requiring higher capital investment and greater utility consumption. The improved batch efficiency of the MHP process, reflected in its shorter recipe batch time and higher annual batch count, had a direct positive impact on plant productivity and overall economic performance. As a result, the MHP factory achieved a lower unit production cost, higher return on investment, shorter payback period, and a positive net present value, whereas the control process remained economically less attractive under the same operating assumptions.

The results suggest that process intensification through the addition of heating and pumping units can improve the industrial viability of alginate production from *S. crassifolium*. Nevertheless, the economic advantage of the modified process is relatively narrow, indicating that the project remains sensitive to assumptions regarding utility prices, biomass composition, product yield, and market revenue. Small changes in operating costs or product value could significantly alter the profitability outcome. Therefore, while the heated water-assisted MHP process is preferable in this simulation, its superiority should be interpreted as conditional rather than absolute.

Several limitations should also be acknowledged. First, the simulation was based on a simplified and fixed representation of alginate composition, yield, and product quality, whereas real seaweed processing is affected by variability in raw material properties, seasonal composition, and extraction efficiency. Second, the model did not fully capture product degradation, molecular-weight distribution, or quality differences that may arise during processing and drying. Third, waste management was not optimized in detail, even though ash and other residue streams may impose additional treatment, handling, and disposal costs at industrial scale. Ash remains a major concern because it is both abundant and potentially burdensome from an environmental and economic perspective.

Overall, this study indicates that heated water-assisted extraction offers a promising route for improving the techno-economic performance of alginate production from Indonesian *Sargassum* biomass. However, further work is needed to validate the process under experimental conditions, refine the assumptions used in simulation, and evaluate downstream opportunities for waste valorization. Future studies should also examine sensitivity to feedstock composition, utility prices, extraction temperature, and product recovery efficiency to better define the robustness of the process and its potential for real industrial deployment.

Declarations

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.

Competing Interests

The authors declare no competing economic interests.

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Author Contribution

R.N Conceptualizes the research. F.S did the experiment and wrote most of the paper including figures and tables, J.M, K.O and A.I are additional reviewers.

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Figures

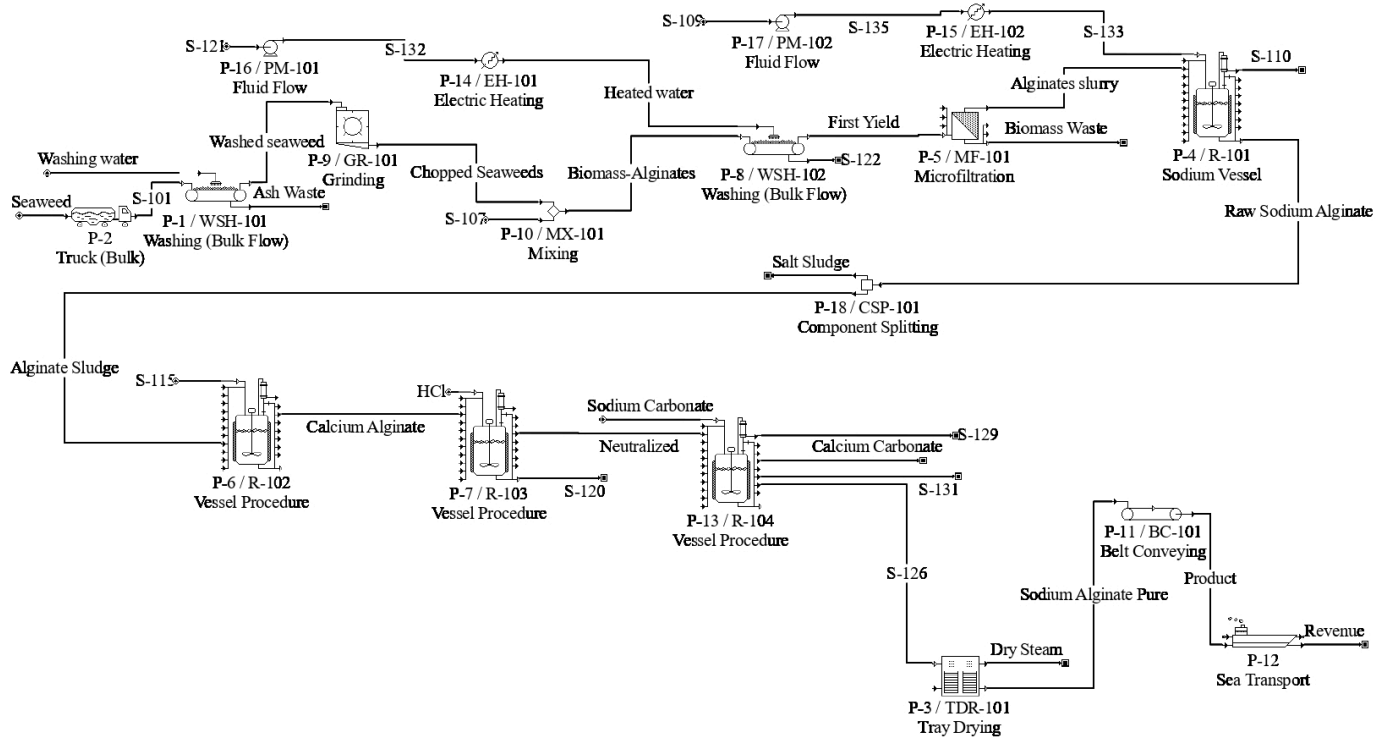


Figure 1

Software generated schematics, based on Modified Heated Process (MHP) simulation

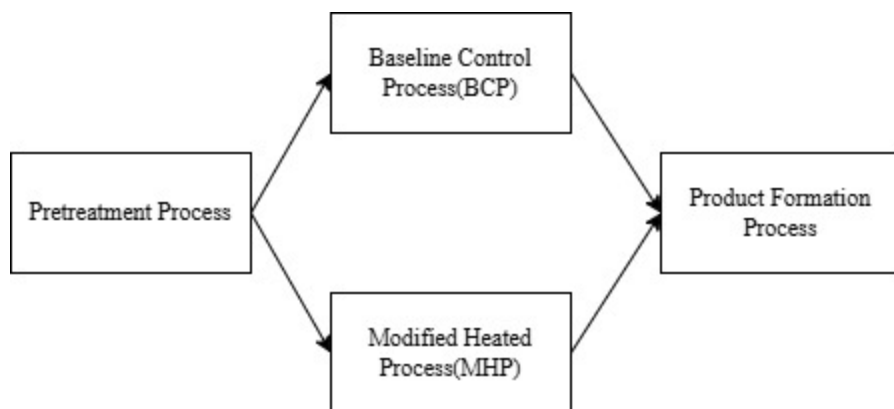


Figure 2

Flowchart with Baseline Control Process (BCP) and Modified Heated Process (MHP)

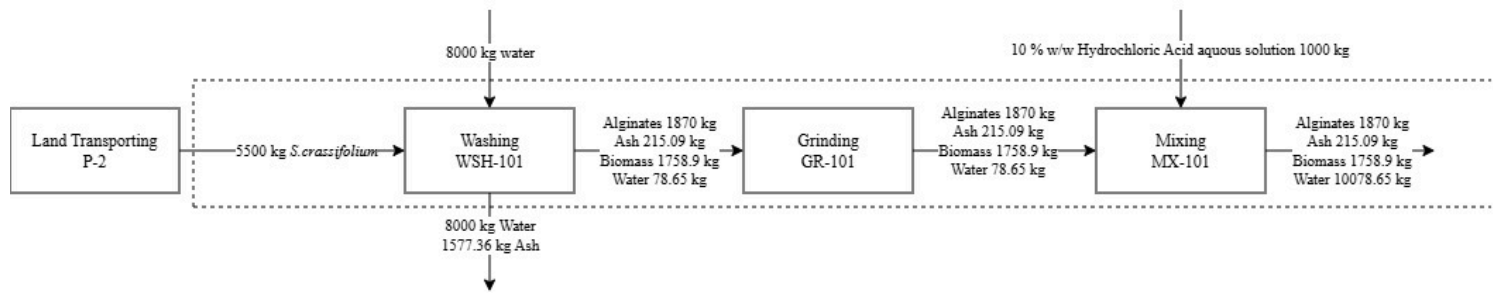


Figure 3

Pretreatment process for raw material preparati

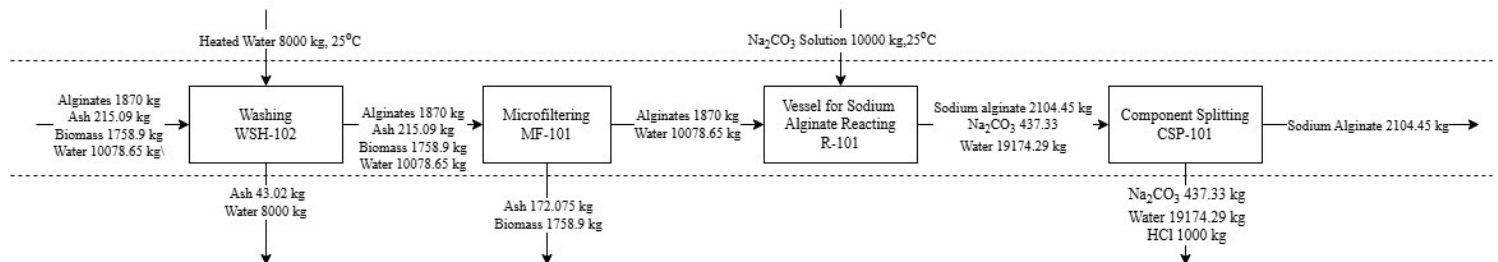


Figure 4

Baseline Control Process (BCP) for alginate production

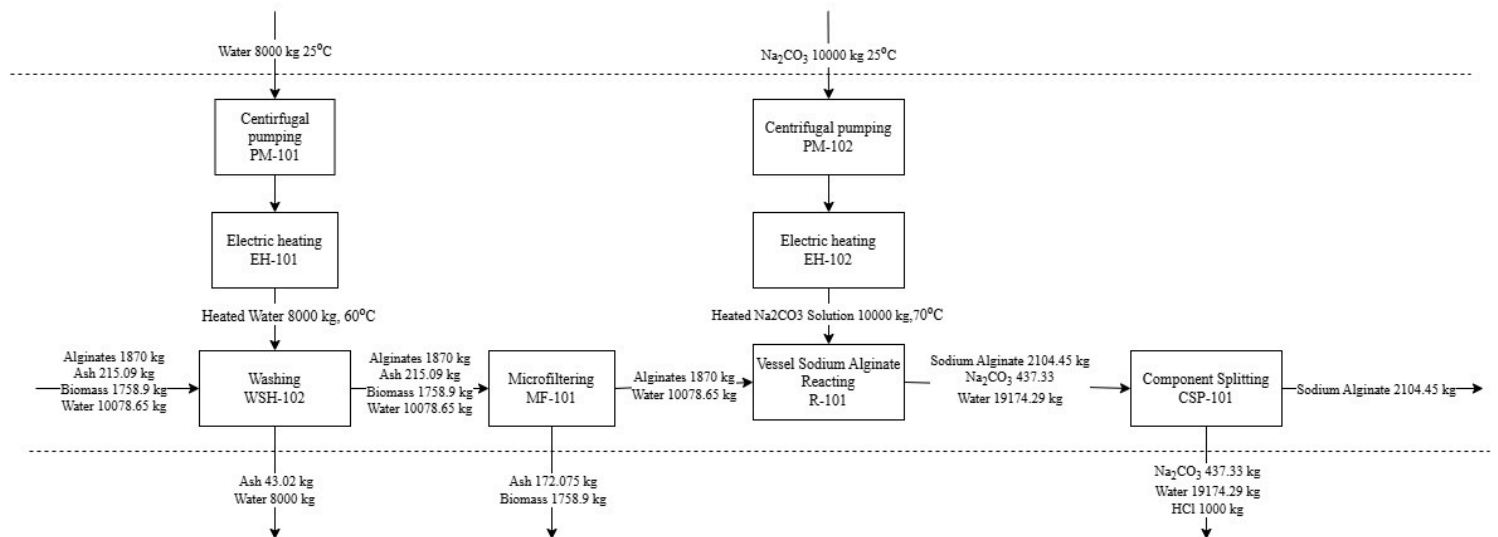


Figure 5

Modified Heating Process (MHP) for alginate production

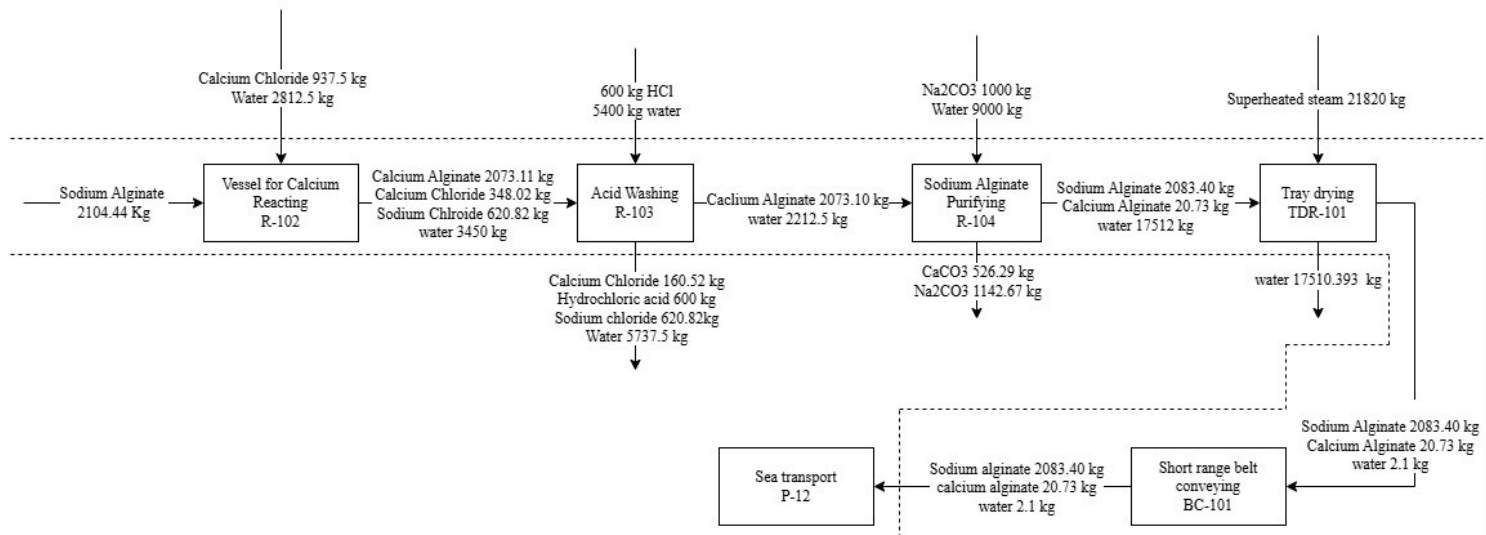


Figure 6

Product formation process

Supplementary Files

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