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Techno-Economical Assessment of Kappaphycus alvarezii Carrageenan Extraction Plant

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Abstract

Kappaphycus alvarezii carrageenan extraction was optimized using a software-based process simulation. The study focused on the Indonesian seaweed industry, utilizing the advanced modeling capabilities of "SuperPro™". The simulation involved comprehensive analysis of the extraction process, from dried seaweed transport to final carrageenan production. Furthermore, an economic sensitivity analysis was conducted, incorporating the seaweed production cost as a critical parameter. This analysis provides valuable insights into the financial viability of *Kappaphycus alvarezii* carrageenan extraction by considering the variations in the input costs, market prices, and other economic factors. The data show that a factory producing *Kappaphycus alvarezii* carrageenan is both technically and economically feasible within a 10-year lifespan. The plant processes 11.5 MT of raw *Kappaphycus* seaweed per batch, amounting to an annual input of 44.045 MT raw materials, and an annual output of 3.14 MTs of carrageenan, totaling the processing of 13,074 MTs of *Kappaphycus alvarezii* carrageenan annually with a payback period of around 8 year and a return on investment of 11.33%. The results provide information for stakeholders, including seaweed farmers, processors, and policymakers, about the potential financial benefits and challenges associated with scaling-up *Kappaphycus alvarezii* carrageenan extraction in Indonesia.

1 INTRODUCTION

Indonesia, a prominent archipelagic nation, has successfully cultivated diverse seaweed varieties (Sultana et al., 2023), securing its position as the world's second-largest producer of annual fresh seaweed tonnage, trailing behind China (World Bank, 2023). The harvested seaweeds are primarily exported in their raw state to more developed nations, with limited domestic consumption, primarily within the pharmaceutical sector. The processing of seaweeds to enhance their pharmaceutical value has focused on the extraction of fine chemicals, driven by extensive research into the medicinal and nutritional benefits of seaweeds.

One such chemical that has received extensive scrutiny and has been extracted for pharmaceutical applications is *Kappaphycus alvarezii* carrageenan. The substance is characterized as a linear sulfated polysaccharide. Carrageenan is both flavorless and colorless (Guo et al., 2022). Most types of carrageenans exhibit gel-forming properties at different temperatures, except for λ-carrageenan, which maintains a predominantly rigid structure (Running et al., 2012). Carrageenan is commercially extracted from red algae of varying molecular masses, and is used in capsules, tablet coagulants, and dairy emulsifiers (Bongaerts et al., 1999).

Indonesia has several red seaweeds that yield carrageenan, which are currently being mass-cultivated across numerous significant islands. *Kappaphycus alvarezii*, formerly known as *Euchema cottonii*, stands out among these species (Guo et al., 2022). Despite not being indigenous to the Indonesian archipelago (Ask & Batibasaga, Aisake & Zertuche, Jose & San, 2003), *Kappaphycus alvarezii* has successfully adapted to local Indonesian coasts, becoming an invasive species. The primary yield of this seaweed is κ-carrageenan, which justifies its reclassification. Thriving in coastal areas of warmer oceans, *Kappaphycus alvarezii* can be effectively cultivated using rope anchoring (Rama et al., 2018).

To initiate the industrial-scale production of carrageenan from *Kappaphycus alvarezii*, establishing a pilot-scale production plant is imperative. Considering the inevitable cost-implications, establishing a production plant requires comprehensive calculations. This underscores the significance of employing factory simulation software, which facilitates multiple calculations and minimizes potential errors that may contribute to escalating capital costs (Casavant & Côté, 2004). This study aims to conceptualize a carrageenan extraction plant for treating *Kappaphycus alvarezii*, with the simulation yielding a feasible scheme from both the engineering and economic perspectives. Envisaging industrial-scale production of red-seaweed carrageenan, this initiative is expected to add value to fresh seaweed cultivated in Indonesia, thereby contributing to the advancement of the blue industrial revolution through the novel exploration of marine resources.

2 METHODOLOGY

The simulation was preformed using SuperPro™ as a Software Process Designer (SPD). The tools were obtained from parts of the software library and sized accordingly.

2.1 SuperPro™ Simulation Software

SuperPro™, a commercially distributed software from Intelligen Inc., is a bioprocess-oriented production simulation software. This software contains multiple simulated chemical process units and additional supply chain-oriented units. The software version utilized in this assessment is equipped with SchedulePro™, which is available under the SuperPro™ suite, and is integrated within the system.

SchedulePro™ is a scheduling software that identifies bottlenecks and provides solutions or overlaps batches to maximize the time efficiency.

SuperPro™, in general, works passively off the user's input within the process and the material parameters. The materials in SuperPro™ are mostly provided through the built-in library; however, if required in a specific case, users can input their own materials through the 'substance and mixtures' menu. The software can perform a general economic assessment, technical assessment, and provide a Gantt chart that visually represents the batch schedule in a production plant. SuperPro™ can also be integrated with Microsoft Excel to generate ". xls" reports that have broader appeal for investors and engineers alike.

The economic aspects of SuperPro™ are also passively influenced by manual input of the material costs, unit costs, labor, consumables, and utilities. Debt and repayment can also be managed through the investment ratio, taxes, and factory lifetime, which users can input into the software. Revenue, waste, and emissions can be classified per stream rather than per material.

2.2 Mode of Operation

The plant simulation was conducted within the framework of a batch system characterized by an annual operational time of 7920 h (Ahmed et al., 2022). Ahmed et al. suggested that 330 d was sufficient for a lean manufacturing simulation. This intentional selection of the operating time was also predicated based on the need to accommodate the intermittent downtimes necessitated by system upgrades or routine equipment maintenance.

2.3 Definition of Components in the Simulation

Table 1 lists the components used in the simulations. The components were collected in the SuperPro™ built-in database; in this case, several additional components were inputted into the library due to default collection limitations.

Table 1
Components and Definition of the Simulation

Components	Definition	Details
Carrageenan	Defined by the user	Molar mass of 193 kg/mol
Seaweed	Mixture of Proteins	Fats, Ash, Cellulose, Biomass and Carrageenan
Cellulose	SuperPro™ database, chemical formula	
Ash	SuperPro™ database	Molar mass of 200 g/mol
Water	SuperPro™ database	Molar mass of 18.02 g/mol
Air	SuperPro™ database	76.72% Nitrogen, 23.29% Oxygen
Potassium Chloride	SuperPro™ database	Molar mass of 74.54 g/mol
Potassium Oxide	SuperPro™ database	Molar mass of 56.11 g/mol
Proteins	SuperPro™ database	Defined as $CH_{1.8}O_{0.5}N_{0.2}$, Molar mass of 147.60 g/mol
Fat	SuperPro™ database	Defined as $CH_{1.8}O_{0.5}N_{0.2}$, Molar mass of 147.60 g/mol
Carbohydrate	SuperPro™ database	$C_6H_{12}O_6$
Biomass	SuperPro™ database	Defined as $CH_{1.8}O_{0.5}N_{0.2}$

2.4 Chemical Modelling of Simulated Seaweed

The input material for this factory, namely. *Kappaphycus* seaweed, has multiple compositions, which were programmed by customizing the SuperPro™ library and are summarized in Table 2. The baseline ratios were obtained through a literature review and wet-chemical information from the University of Riau, and were rounded to two decimal places (Diharmi et al., 2020).

Table 2
Carrageenan Stock Mixture Modelling

(Source, Diharmi, et.al, 2020)

Ingredient	%
Ash	12.35
Proteins	3.67
Fats	0.26
Carrageenan	30.77
Biomass	3.84
Water	49.20
Total	100.00

2.5 Carrageenan Modelling

Carrageenan as a substrate does not possess any fixed properties; the researcher utilized information provided by the University of Riau to define the baseline properties for Carrageenan modeling. The molar mass and ash content were particularly variable; thus, a number from the literature review was used (Younes et al., 2018).

2.6 Unit Processes Involved in the Plant

The unit processes performed herein followed the unit library provided by the SuperPro™ simulator software. Labeling followed the default automated unit labeling system built into the software; the final product may differ in labeling, but the overall functions typically remain the same. The SuperPro™ library was deemed sufficient for unit process simulations in terms of technical feasibility, whereas the scheduling and economic parameters had to be modified according to more modern capabilities. The details of the unit processes are listed in Table 3.

Table 3
Classification of Units Utilized in the Production Plant

Unit type	Unit Label	Function in the process
Transport truck	P-10	Transport of raw feed to the factory site
Cold water washer 1	WSH-101	Partial removal of ash
Extractor	MSX-101	Removes carrageenan from raw feed with strong acid
Cold water washer 2	WSH-102	Partially washes the acid from carrageenan slurry
Batch vessel 1	V-101	Sedimentation site
Plate and frame filter 1	PFF-101	Filters out sludge from water
Batch vessel 2	V-102	Neutralization using a strong base
Tray drying 1	TDR-101	Dries the Carrageenan
Grinder	GR-101	Produces powder form of Carrageenan
Plate and frame Filter 2	PFF-102	Removed by-product from water
Tray drying 2	TDR-102	Dries the by-product

2.7 Equipment Sizing

User-inputted, design-calculated sizing was applied to the equipment operating within the factory, instead of a more customized throughput-calculated sizing, because of the lack of available information regarding the prices of customized chemical process equipment. Table 4 shows a brief breakdown of the units required in the simulation, construction materials, and simulated capacity. The simulation did not use staggered or standby units.

Table 4
Unit Processes Utilized in the Plant

Name	Type	No. of Units	Size (Capacity)	Material of Construction
WSH-101	Washer (Bulk Flow)	6	4,000 kg/h	CS
MSX-101	Mixer-Settler Extractor	2	3,509 L/h	SS316
WSH-102	Washer (Bulk Flow)	4	3,886 kg/h	CS
V-101	Blending Tank	1	27,870 L	SS316
PFF-101	Plate & Frame Filter	1	402 m^2	SS316
V-102	Blending Tank	1	6,256 L	SS316
TDR-101	Tray Dryer	1	236 m^2	SS316
GR-101	Grinder	1	3,413 kg/h	CS
PFF-102	Plate & Frame Filter	1	88 m^2	SS316
TDR-102	Tray Dryer	1	322 m^2	SS316

2.8 Power Demands of the Factory

Dominated by the electricity consumed by the unit processes established within the factory, the power demands were modeled in watts owing to the electrically driven nature of most processes. Note that the superheated steam was primarily modeled as an economic factor, and power costs were not considered. Most of the process-unit equipment were purchased from a third party and assembled onsite. Table 5 presents a summary of the equipment required in the factory, with the baseline power demand and a reference for the power demand.

Table 5
Power Demands Per Unit of Process

Unit label	Power Demand	Reference
WSH-101	13.5 kWh	Henan Ocean Machinery Equipment Co., Ltd., 2024.
MSX-101	15.0 kWh	Wenzhou Chinz Machinery Co., Ltd., 2024
WSH-102	13.5 kWh	Henan Ocean Machinery Equipment Co., Ltd., 2024
V-101	11.0 kWh	Henan Xingyang Mining Machinery Manufactory, 2024.
PFF-101	7.50 kWh	Woking Environmental Technology Co., Ltd., 2024.
V-102	4.00 kWh	Weishu Machinery Technology (Shanghai) Co., Ltd., 2024.
TDR-101	35.0 kWh	Shandong Qike Machinery Equipment Co., Ltd., 2024.
GR-101	15.0 kWh	Harun et al., 2019.
PFF-102	7.50 kWh	Woking Environmental Technology Co., Ltd., 2024.
TDR-102	35.0 kWh	Shandong Qike Machinery Equipment Co., Ltd., 2024).

2.9 Process Parameters

Each discrete module within the simulation framework is tailored to align with the specific throughput and compositional characteristics of each sequential phase within the batch input stream (Arias et al., 2022). The implemented software facilitates automated labeling of

individual units by incorporating inherent numerical identifiers. Temperature and pressure emerged as the predominant variables that were uniformly employed across all modules (Araque et al., 2020). Notably, the operation environment in the factory did not entail a vacuum, and for simulation purposes, atmospheric air was modeled as a composite mixture within the simulation library. Details of these processes are listed in Table 6.

Table 6
Process Parameters and Conditions

Operations	Unit label	Temp. (ºC)	Pressure	Conditions
Truck	P-10	n/a	n/a	Assumed to be a singular unit
Seaweed washing	WSH-101	25	Atmospheric	75% ash removal
Main extraction	MSX-101	80	Atmospheric	Strong base extraction using KOH
Carrageenan washing	WSH-102	25	Atmospheric	Ash and KOH removal from the substrate
Sedimentation	V-101	25	Atmospheric	Added water
Carrageenan filtration	PFF-101	25	Atmospheric	Assumed LOD of 10% and 8 cm cake thickness
Neutralization	V-102	37	Atmospheric	Strong acid KCl to counter the strong base
Carrageenan drying	TDR-101	70	Atmospheric	Water removal
Product grinding	GR-101	25	Atmospheric	Assumed no dissipation to heat
By product filtration	PFF-102	25	Atmospheric	Assumed LOD 30% and 8 cm Cake thickness
By product drying	TDR-102	70	Atmospheric	Water removal

2.10 Contents of the Flow

The constituent elements of plant apparatus encompass the conveyance of raw materials and intermediate substances in diverse forms. Nevertheless, owing to the influence of the environmental parameters inherent to operational processes and discernible effects on the physical attributes of specific components, coupled with considerations of equipment sizing and constraints, a degree of anticipated incongruity in the volumetric content of the flow became evident. The expectations regarding what should be found in a particular flow for the entire simulation are listed in Table 7.

Table 7
Process Flow Contents and Their Functions

Flow label	Expected contents	Flow purpose
Supplier's stash	Raw Seaweed	Starts the whole process
Fresh chopped seaweed	Raw seaweed	Main Process flow, feed for the washer
First ash removal	Ash and water	Waste classification
Wash water 1	Water	Washer input flow
KOH Mix	Potassium hydroxide and water	Additional Process flow, Extraction Solvent
Washed seaweed	Seaweed components and water with reduced ash	Main process flow, feed for the extractor
Seaweed sludge	Ash, Biomass, Carrageenan, Proteins, Water, KOH	Recently extracted seaweeds.
Wash Water 2	Water	
Second ash removal	Ash and water	Waste classification
Washed sludge	Ash, Biomass, Carrageenan, Proteins, Water	Feed for sedimentation tank
KCl Mix	Potassium Chloride and water	Additional Process flow: Neutralize the basic sludge
S-114	Air and Biomass	
Sediments	Carrageenan, Proteins, water	
Filter Cake 1	Proteins and Water	Waste product of filtration
Filtered product	Carrageenan, proteins, water	
KCl Input	KCl-water mix	Neutralizing solution
S-117	Air and water	Neutralizing vessel exhaust
Wash water 3	Water	Aiding in sedimentation
Raw Carrageenan	Solid Carrageenan, water, and proteins	Carrageenan sludge, feed for the tray drying
Crude Carrageenan	Solid Carrageenan and protein	
Carrageenan powder	Solid Carrageenan and protein	Final product for the market, the main revenue flow
Filter cake 2	Ash, Biomass, Fats, KOH Sediments, Proteins, and water	Waste product of filtration
S-124	Biomass, Carrageenan, Fats, KOH, Proteins, water	Filtered product feed for by-product tray drying.
S-126	water	Removed water vapor
Dried By-Product	Biomass, fats, protein, carbohydrates, Cellulose	By-product, secondary revenue flow

2.11 Plant Consumables

Plant consumables encompass a category of material inputs that influence processes by modulating the environmental parameters, distinct from active involvement in operational processes. This classification arises from the capacity of the plant consumables to directly influence the operational costs, warranting amalgamation with such costs during a rigorous economic assessment. The consumables for the plant are recorded in Table 8 with suitable quantitative units, preferably SI units, along with the respective functions.

Table 8
Consumables Required by the Plant

Consumables	Main dimension	Unit of measurement	Function	Source
Superheated steam	weight	MTs	Heat exchanger agent	SuperPro™ library
Cooling water	weight	m^3	Heat exchanger agent	SuperPro™ Library
Electricity	Energy	KW/h	Unit process consumption	SuperPro™ Library

3 RESULTS

3.1 Factory Schematics

The plant generates two revenue flows and eight waste flows. The revenue flows were split into carrageenan powder as the primary revenue flow and a mixture of waste products that could be used as premium fertilizer as the secondary revenue flow. The wastes comprised ash, fats, used acids, and base- and tray-dried exhaust waste outputs, with ash being deemed the most troublesome because of its low potential value.

Figure 1 provides an overview of the process simulation as generated by SuperPro™ 10.3. The simulation contained a washer, grinder, reactor, three filtration units, centrifuge, three distillation towers, four heat exchanger units, and one freeze-drying unit. The flowchart presented in Fig. 2 summarizes the process and its demands. The flowchart includes details of the power demands and step-by-step breakdown of the process flow.

3.2 Time Constraints of the Factory

3.2.1 Plant Operational Scheduling

The deviation from the conventional calendrical standards of 365 or 360 days within an operational timeframe of 7,920 h per annum was implemented as a deliberate measure to accurately capture and account for instances of maintenance and upgrade-related downtime. This approach acknowledges the inherent complexities in large-scale production lines, wherein interruptions to regular operations necessitate more comprehensive accounting for time to achieve a deeper understanding of the system's functioning. Table 9 lists the recipe cycle times between batches. The factory operated a batch process model instead of a continuous process (Goršek & Glavič, 1997).

Table 9
Factory's Batch Scheduling

Scheduling item	
Annual operating time	7,918.43 h
Recipe batch time	5.17 h
Recipe cycle time	2.07 h
Number of batches per year	3,830 cycles

3.2.2 Plant Batch Scheduling

Batch operation of a plant involves the orchestration of multiple interdependent processes within the operational framework. Notably, these processes are sequentially linked, wherein the output of a given process serves as the input for the successive processes. Additionally, specific processes operate concurrently, imparting a semi-continuous character to the overall processing regimen as the output seamlessly transitions into subsequent processing units (Tan et al., 2019).

Most processes delineated in the Gantt chart were configured within the parameters stipulated by the software, as illustrated in Fig. 3. Notably, several processes were assigned a time-span of 1 h to align with the conventional duration of a standard 8 h workday. Accordingly, the graphical representation in Fig. 3 is demarcated into 8 h cycles. As a departure from the default flow or process set, which adhered to throughput-based computation, the pull-in and transfer-in processes within the factory were deliberately set to

durations of less than 1 h. This adjustment was aimed at aligning with the principal process while accounting for scaling considerations and enhancing the overall representational fidelity of the simulation.

After considering the manner in which a single batch can be executed in a factory, multiple batches must be considered in parallel. In this case, a new batch can be started when the current batch is halfway to completion. Figure 4 shows how such overlapping processes can be conducted within the same plant. This arrangement allows more batches to be run within 24 h, thus increasing profitability and productivity (Joseph & B, 2021).

The material balance report can be broken down into a summary and stream details. The summary, as presented in Table 10, was split into three columns, and consisted of the materials, annual demands, and batch demands.

Table 10
Batch and Annual Material Consumptions for the Factory

Material	MT/yr	MT/batch
KClMix	7,660	2.0
KOH mix	15,320	4.0
Seaweed	44,045	11.5
Water	103,410	27.0
Total	170,435	44.5

The water input was derived passively through a composite methodology involving manual adjustment of the per-unit input, as well as the computed demand of specific unit processes beyond the researcher's immediate purview. The main aim of the factory simulation was to process the seaweed supply using the amount of seaweed that was first determined by the researcher. Potassium hydroxide, potassium chloride, and water were used to fulfill the processing demands of raw seaweed input. This calculation was extended to encompass nuanced process demands, including those of a more esoteric nature, such as the requirement for a thermal jacket with fluid convection.

3.3 Revenue and Cost Classifications

The revenue flow was split into two major components: the main stream of revenue consisted mostly of *Kappaphycus alvarezii* carrageenan, and the by-product comprised multiple biodegradable components. The Capital costs are split into various elements, such as the establishment price, labor costs, and unit purchases (Al-Sharrah & Marafı, 2023). The pie chart in Fig. 5 shows that the raw materials are the primary contributors to the operating cost. R&D will be conducted chiefly through university collaborations with external funding; thus, the costs in this chart will be lowered by default.

Waste disposal has a low contribution to the cost, consisting solely of the costs of disposing ash and biomass. The energy costs of waste disposal are divided into utility and unit costs with depreciation. Land-based truck transportation is the main mode of transportation.

3.4 Materials and Energy

The generated income comprised *Kappaphycus alvarezii* carrageenan output as the main product and the secondary biomass-dominated by-product. The calculated yield for these substances was heavily influenced by the composition of the fresh seaweed, which is the primary feedstock of this factory, assuming that the composition would not change in the long run. The factory produces approximately 3,143 kg of carrageenan powder from 11,000 kg of fresh seaweed.

The main contributor to the energy consumption is the electricity required to power process units within the factory. Some additional energy consumption in the model is expected in the transport phase using long-haul trucks that run primarily on diesel fuel. However, the software opted to treat the input fuel consumption directly as an economic burden instead of passively as fuel consumption.

This factory has a built-in waste treatment process for separating low-value ash waste from biomass and biodegradable waste with potential economic value. Although built-in waste treatment processes within factories can contribute to a more independently run

factory because the presence of any third-party waste treatment service is rendered unnecessary, the upfront capital required to establish this process is much higher and may be a prelude to higher debt or required investments.

The factory had two plate and frame filter units. Although this filter is commonplace and deemed necessary by the author, the carrageenan found in the simulated results of the first filtration should be neglected. Carrageenan is the main product; thus, neglecting carrageenan within the by-product load may reduce both the yield and profitability.

3.5 Assessment of the Predicted Final Product

The final marketable product of this factory is solid carrageenan in powdered form. The final product contained less than 0.1% impurities, which complies with the FAO standards for carrageenan purity. The calculation showed that the ash was completely removed through multiple separation processes in the plant simulation. Ash within the simulation was considered as a monolith instead of the commonplace dual classification of acid-soluble and acid-insoluble wastes.

A minor hurdle in harnessing the final product is the loss of carrageenan due to bulk filtering. Bulk filtering was deemed an appropriate choice for economic reasons; however, from the technical perspective, the carrageenan lost by filtering can cause a loss of potential revenue.

3.6 Economic Breakdown

The intent is for the factory to process and transport freshly harvested seaweed instead of establishing an in-house cultivation unit or seaweed farm. This significantly increases the cost required to run the factory, with raw material procurement dominating the cost. The utilities mainly consist of the electricity needed to run the unit processes, whereas ash removal increases the waste-treatment cost.

The factory payment system was evaluated through a meticulous cash flow analysis with a protracted 20-year payment horizon. Notably, in typical scenarios, a factory commences operations with an initial phase of nonprofitability, gradually transitioning to capital returns after a minimum of 10 year. The economic framework of the analysis predicts a flat tax rate of 6%. The factory profitability was measured by examining two crucial financial metrics: the internal rate of return (IRR) and net present value (NPV).

The IRR represents the discount rate at which a project's NPV attains equilibrium, reaching zero (Zenkovich et al., 2021). Concurrently, the NPV is defined as the sum of all forthcoming cash flows, encompassing both positive and negative flows, throughout the lifespan of an investment and is meticulously discounted to the present value (Naim et al., 2007). This analytical framework ensures a rigorous and comprehensive assessment of the factory payment system, thereby enhancing the investigation's scholarly rigor and depth.

The costs of energy and water in the plant were modeled after the national electricity and water prices set by the Indonesian Government, which means that the costs were somewhat subsidized. The classification of this plant fell under ‘Industri skala besar’ (large-scale industries), which warrants a reduced purchase price for both water and energy. Table 11 shows the potential payback time and gross margins of the factory, as generated by SuperPro™ software.

Table 11
Basic Economic Breakdown of the Factory

Total Capital Investment	**1,914,000**	**$**
Capital Investment Charged to This Project	1,914,000	$
Operating Cost	6,950,000	$/year
Revenues	7,109,000	$/year
Gross Margin	2.23	%
Return on Investment (ROI)	11.35	%
Payback Time	8.81	years
IRR (After Taxes)	7.11	%
NPV (at 7.0% Interest)	19,000	$

3.7 Sensitivity Analysis

Figure 6 presents a sensitivity analysis for determining which of the many market factors has the strongest impact on the factory's profitability (represented by the NPV) in the long run. The authors considered three significant factors: the price of the sold product, price of seaweed as factory feed, and cost of labor (Fig. 6). The factory was most strongly affected by fluctuations in the carrageenan market selling price, with labor costs affecting it the least. The three graphs meet at the equilibrium point close to 0%, where the prices of these components will cause the factory to barely break-even, even when covering the operations.

4 Conclusions

The analysis shows that the upscaling of a *Kappaphycus alvarezii* carrageenan extraction factory is technically and economically feasible within a 10-year payback period, assuming the products can find considerable demand on the market. Certain considerations must be made regarding the waste treatment and secondary product manufacturing. In the present study, there were no clear prospects for secondary products that could properly supplement the income provided by *Kappaphycus alvarezii* carrageenan. The waste products within the simulation contained a significant amount of ash, which is considered nonbiodegradable and may inflict both economic and environmental burdens on the factory, regardless of the ash classification.

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, A.D provides the wet lab information and aided with building a database. F.S does 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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References

1. Sultana, F., Wahab, M. A., Nahiduzzaman, M., Mohiuddin, M., Iqbal, M. Z., Shakil, A., Mamun, A.-A., Khan, M. S., Wong, L., & Asaduzzaman, M. (2023). A Review of seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment. Aquaculture and Fisheries, 8(5), 463–480. Retrieved 23rd of June 2024, from: https://doi.org/10.1016/j.aaf.2022.09.001.
2. World Bank (2023). Global Seaweed: New and Emerging Markets Report, 2023. Retrieved 23rd of June 2024, from: https://doi.org/10.1596/40187
3. Guo, Z., Wei, Y., Zhang, Y., Xu, Y., Zheng, L., Zhu, B., & Yao, Z. (2022). Carrageenan oligosaccharides: A comprehensive review of preparation, isolation, purification, structure, biological activities and applications. *Algal Research*, *p. 61*, 102593. Retrieved 3rd of July 2024, from: https://doi.org/10.1016/j.algal.2021.102593
4. Running, C. A., Falshaw, R., & Janaswamy, S. (2012). Trivalent iron-induced gelation in Lambda-Carrageenan. Carbohydrate Polymers, 87(4), 2735–2739. Retrieved 21st of may 2024, from: https://doi.org/10.1016/j.carbpol.2011.11.018

5. Bongaerts, K., Reynaers, H., Zanetti, F., & Paoletti, S. (1999). On the molar mass of κ-carrageenan in the course of conformational transition from the disordered to the fundamental ordered form. Macromolecules, 32(3), 675–682. Retrieved 11th of March 2024, from: https://doi.org/10.1021/ma981203z
6. Guo, Z., Wei, Y., Zhang, Y., Xu, Y., Zheng, L., Zhu, B., & Yao, Z. (2022). Carrageenan oligosaccharides: A comprehensive review of preparation, isolation, purification, structure, biological activities and applications. Algal Research, 61, 102593. Retrieved 15th of March 2024, from: https://doi.org/10.1016/j.algal.2021.102593
7. Ask, E. I., Batibasaga, A., Zertuche-Gonzalez, J. A., & De San, M. (2003). Three decades of Kappaphycus alvarezii (Rhodophyta) introduction to non-endemic locations. In Proc Int Seaweed. Symp (Vol. 17, pp. 49–57). Retrieved 15th of March 2024, from: https://www.researchgate.net/publication/283970777_Three_decades_of_Kappaphycus_alvarezii_Rhodophyta_introduction_to_non-endemic_locations
8. Rama, R., Ode Muhammad Aslan, L., Iba, W., Nurdin, A. R., Armin, A., & Yusnaeni, Y. (2018). Seaweed cultivation of micropropagated seaweed (kappaphycus alvarezii) in Bungin permai coastal waters, Tinanggea Sub-district, South Konawe Regency, South East Sulawesi. IOP Conference Series: Earth and Environmental Science, 175, 012219. Retrieved 16th of March 2024, from: https://doi.org/10.1088/1755-1315/175/1/012219
9. Casavant, T. E., & Côté, R. P. (2004). Using chemical process simulation to design industrial ecosystems. *Journal of Cleaner Production*, *12*(8–10), 901–908. Retrieved 16th of March 2024, from: https://doi.org/10.1016/j.jclepro.2004.02.034
10. Ahmed, A., Olsen, J., & Page, J. (2022). Integration of six sigma and simulations in real production factory to improve performance – A case study analysis. International Journal of Lean Six Sigma, 14(2), 451–482. Retrieved 17th of March 2024, from: https://doi.org/10.1108/ijlss-06-2021-0104
11. Diharmi, A., Rusnawati, & Irasari, N. (2020). The characteristics of Carrageenan Eucheuma cottonii were collected from the coast of Tanjung Medang Village and Jaga Island, Riau. *IOP Conference Series: Earth and Environmental Science*, *404*(1), 012049. Retrieved 25th of February 2024, from: https://doi.org/10.1088/1755-1315/404/1/012049
12. Younes, M., Aggett, P., Aguilar, F., Crebelli, R., Filipič, M., Frutos, M. J., Galtier,P., Gott, D., Gundert-Remy, U., Kuhnle, G. G., Lambré, C., Leblanc, J., Lillegaard,I. T., Moldeus, P., Mortensen, A., Oskarsson, A., Stankovic, I., Waalkens-Berendsen,I., Woutersen, R. A., … Dusemund, B. (2018). Re-evaluation of Carrageenan (E 407)and processed Eucheuma Seaweed (E 407A) as food additives. EFSA Journal, 16(4). Retrieved 28th of March 2024, from: https://doi.org/10.2903/j.efsa.2018.5238
13. Henan Ocean Machinery Equipment Co., Ltd. (2024, January 30). Industrial carrot potato and vegetable washer fruit vegetable washing machine Henan Ocean Machinery Equipment Co., Ltd. Alibaba. Retrieved 19th of June 2024, from: https://www.alibaba.com/product-detail/Industrial-Carrot-Potato-And-Vegetable-Washer_1600437946484.html?spm=a2700.7735675.0.0.21017URU7URUHw&s=p
14. Wenzhou Chinz Machinery Co., L. (2024). TQ-Z series multifunctional extracting Tank/ herbal extractor/extraction tank. Alibaba. Retrieved 19th of June 2024, from: https://www.alibaba.com/product-detail/TQ-Z-series-multifunctional-extracting-Tank_903197414.html?spm=a2700.7724857.0.0.662d4634ZyY7OW
15. Henan Xingyang Mining Machinery Manufactory. (2024). Factory Price Sedimentation Tank NZS-3 Sludge Mining Thickener For Sale. Alibaba. Retrieved 19th of June 2024, from: https://www.alibaba.com/product-detail/Factory-Price-Sedimentation-Tank-NZS-3_60805722687.html?spm=a2700.7724857.0.0.58cb5025c825PO
16. Woking Environmental Technology Co., Ltd. (2024). high pressure industry plate and frame Filter Press Machine stone mud dehydrator. Alibaba. Retrieved 19th of June 2024, from: https://www.alibaba.com/product-detail/Frame-Filter-Press-Sludge-High-Pressure_1600145193509.html?spm=a2700.7724857.0.0.6d694e3f3NDxKA&s=p
17. Weishu Machinery Technology (Shanghai) Co., L. (2024, February 8). 300-5000l Liquid Mixing Tank Agitator Heated Mixing Container Stainless Steel Mixing Tank. Alibaba. Retrieved 19th of June 2024, from: https://www.alibaba.com/product-detail/300-5000l-Liquid-Mixing-Tank-Agitator_1600802698807.html?spm=a2700.7724857.0.0.637864c2YiFid1
18. Shandong Qike Machinery Equipment Co., Ltd. (2024). Commercial Food Dryer. Alibaba. Retrieved 19th of June 2024, from: https://www.alibaba.com/product-detail/Commercial-Food-Dryer-Fruit-Dryer-Machine_1600982447955.html?spm=a2700.7724857.0.0.17a5405294LV8i&s=p
19. Harun, N., Othman, N. A., Zaki, N. A., Mat Rasul, N. A., Samah, R. A., & Hashim, H. (2019). Simulation of anaerobic digestion for biogas production from food waste using SuperPro Designer. *Materials Today: Proceedings*, *19*, 1315–1320. Retrieved 7th of July 2024, from: https://doi.org/10.1016/j.matpr.2019.11.143
20. Arias, A., Barreiro, D., Feijoo, G., & Moreira, M. T. (2022). Waste Biorefinery towards a sustainable biotechnological production of pediocin: Synergy Between Process Simulation and Environmental Assessment. *Environmental Technology & Innovation*, *26*,

102306. Retrieved 9th of July 2024, from: https://doi.org/10.1016/j.eti.2022.102306

21. Araque, J., Niño, L., & Gelves, G. (2020). Industrial scale bioprocess simulation for Ganoderma lucidum production using SuperPro designer. Journal of Physics: Conference Series, 1655(1), 012077. Retrieved 25th of June 2024, from: https://doi.org/10.1088/1742-6596/1655/1/012077
22. Goršek, A., & Glavič, P. (1997). Design of batch versus continuous processes. *Chemical Engineering Research and Design*, *75*(7), 718–723. Retrieved 24th of July 2024, from: https://doi.org/10.1205/026387697524218
23. Tan, J., Yee Foo, D. C., Kumaresan, S., & Abdul Aziz, R. (2019). Evaluation of Debottlenecking strategies for a liquid medicine production utilizing batch process simulation. International Conference of Computational Methods in Sciences and Engineering 2004 (ICCMSE 2004), 666–670. Retrieved 5th of June 2024, from: https://doi.org/10.1201/9780429081385-163
24. Joseph, S., & B, R. (2021). Modelling and optimization of bioplastic production using SuperPro designer. SSRN Electronic Journal. Retrieved 5th of June 2024, from: https://doi.org/10.2139/ssrn.4019994
25. Al-Sharrah, G., & Marafi, M. (2023). Process simulation and techno-economic evaluation of recovery of metals and alumina from spent hydroprocessing catalysts using leaching with EDTA. Journal of Engineering Research. Retrieved 25th of August 2024, from: https://doi.org/10.1016/j.jer.2023.10.019
26. Rama, R., Ode Muhammad Aslan, L., Iba, W., Nurdin, A. R., Armin, A., & Yusnaeni, Y. (2018). Seaweed cultivation of micro propagated seaweed (kappaphycus alvarezii) in Bungin Permai coastal waters, Tinanggea Sub-district, South Konawe Regency, South East Sulawesi. IOP Conference Series: Earth and Environmental Science, 175, 012219. Retrieved 5th of August 2024, from: https://doi.org/10.1088/1755-1315/175/1/012219
27. Zenkovich, M. V., Drevs, Y. G., Inozemtseva, V. S., & Shevchenko, N. A. (2021). Industrial Plants Investment Projects Efficiency Estimation based on simulation and Artificial Intelligence Methods. *Procedia Computer Science*, *190*, 852–862. Retrieved 11th of august 2024, from: https://doi.org/10.1016/j.procs.2021.06.107
28. Naim, M. M., Wikner, J., & Grubbström, R. W. (2007). A net present value assessment of make-to-order and make-to-stock manufacturing systems. Omega, 35(5), 524–532. Retrieved 11th of august 2024, from: https://doi.org/10.1016/j.omega.2005.09.006

Figures

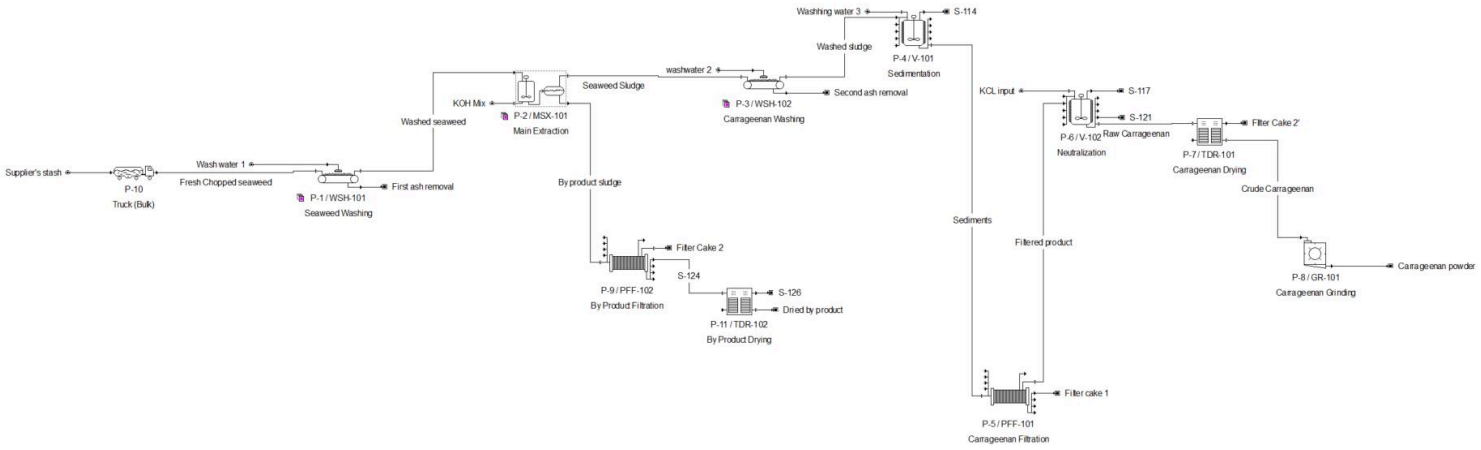


Figure 1

Factory Schematic as Visualized by SuperPro™

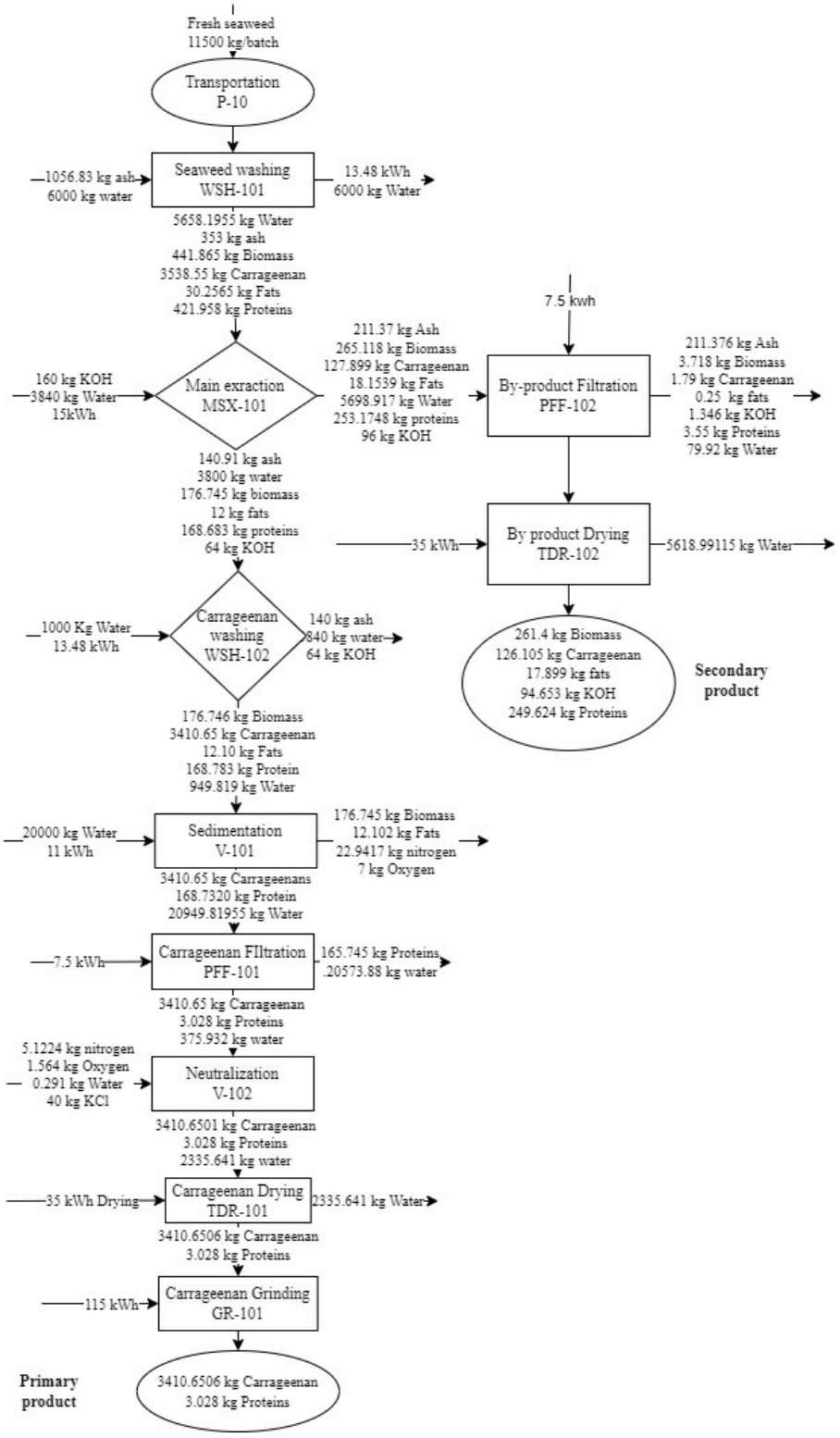


Figure 2

Simplified Process Flowchart of Energy and Material

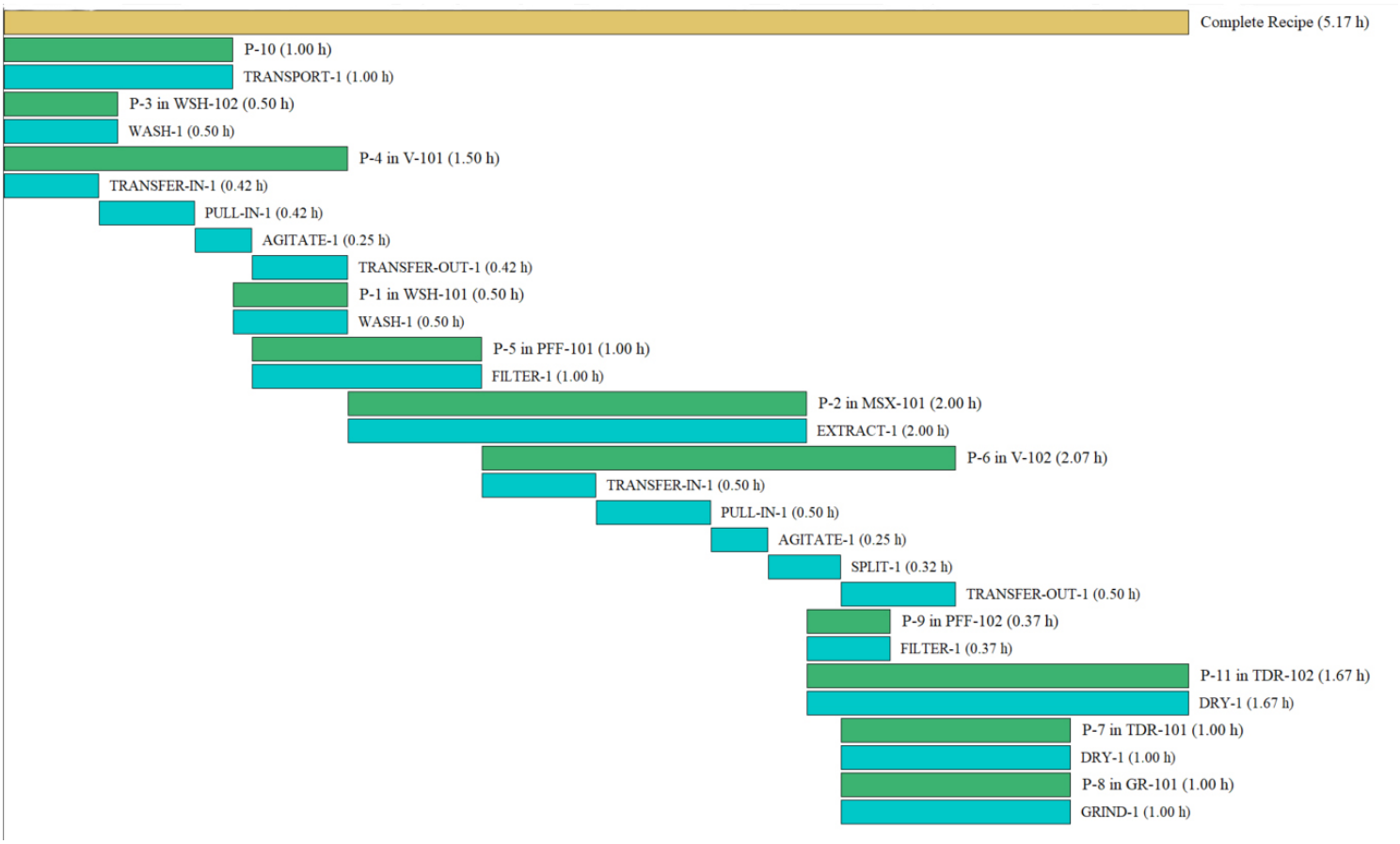


Figure 3

Gantt Chart for a Single Batch

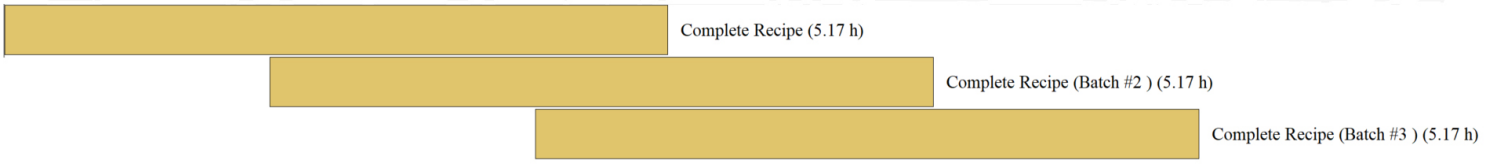


Figure 4

Gantt Chart for Multiple Batches

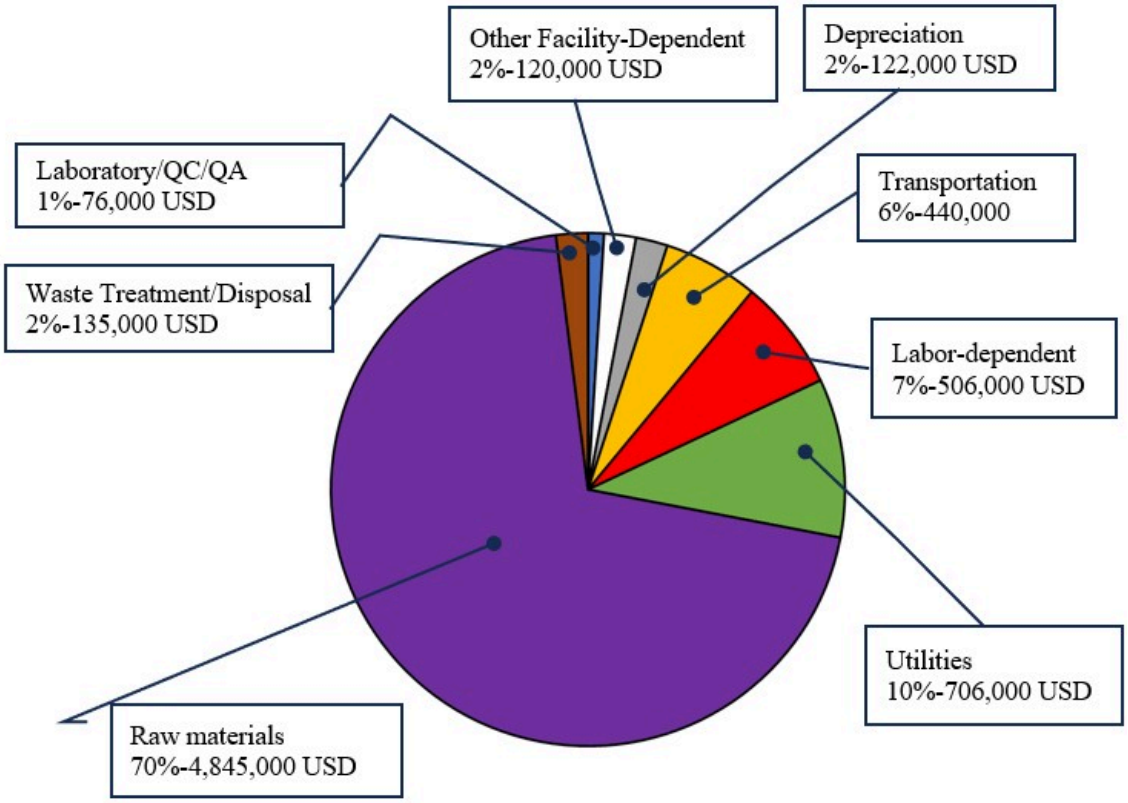


Figure 5 Operational Cost Breakdown and Classifications

Figure 5

Operational Cost Breakdown and Classifications

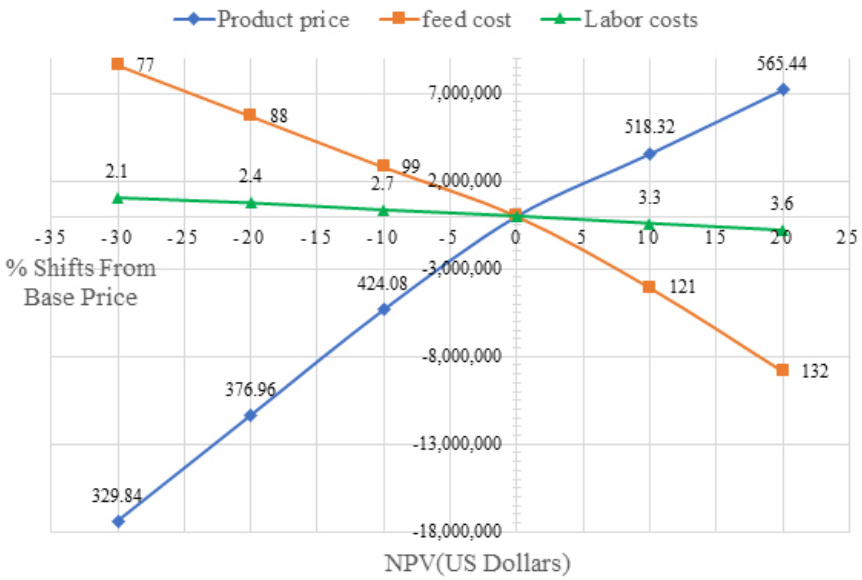


Figure 6

NPV Sensitivity Analysis Graph of the Production Line, Split Between Product Price, Feed Cost and Labor Costs

Supplementary Files

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- CarrageenanEconomicGeneratedReport.xls
- CarrageenanMaterialGeneratedReport.xls