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A Techno-Economic Feasibility Study: Carboxymethyl Cellulose Production from Date Palm Biomass for Industrial Applications

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***Abstract:** This research focuses on a techno-economic process of building and designing equipment for isolating polymers from local resources for industrial purposes; the objective was to increase national revenues from the utilization of native resources and a reduction in the cost and foreign dependence on imported polymers. The study had an aim of synthesizing and characterizing CMC from leaves of Phoenix dactylifera L. (date palm) through the process of etherification using sodium monochloroacetic acid and sodium hydroxide. The optimization of parameters included a temperature of 55°C, and a total reaction time of 4 hrs., providing the highest degree of substitution (DS) at 0.77. Models of a material balance and heat generation were derived from the reactor's operational performance and were developed to determine the mechanical design of the reactor, the reactor volume calculated out to be 2435.26 dcm³, reactor capital cost, and the economic viability of the plant. Taking all equations into account, with equipment costs amounting to $103,823.5 and total capital investment of $233,311.24. The study analyzed five different price-evaluation-and-feasibility scenarios until it arrived at the conclusion that it had become economically feasible to produce approximately 3000 tons/year of sodium carboxymethyl cellulose with 4 batches per day/three-hundred-day operation year (plus 60 maintenance days) each. The given cost-and-profit analysis considered critical criteria such as raw-material cost, labor cost, selling price for the product, and process optimization. This highlighted the very encouraging financial effects the production of CMC propelled forward to an overall worth. Lastly, the review also dealt with issues of environmental compliance, regarding the manufacture of sodium carboxymethyl cellulose (CMC).*

***Keywords:** Sodium Carboxyl Methylcellulose, Date Palm, Production Process, Production Cost, Economic Evaluation, Feasibility Scenarios*

Abbreviations:
CMC: Carboxymethyl Cellulose
SCMC: Sodium Carboxymethyl Cellulose
NPV: Net Present Value
ROI: Return on Investment
PBP: Payback Period
NP: Net Profit
LCA: Life Cycle Assessment

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I. INTRODUCTION

The research emphasizes the growing interest in developing efficient and cost-effective methods to treat agricultural waste, aiming to protect the environment, reduce reliance on imported polymers, and boost national income. It focuses on designing industrial processes to extract polymers from local materials, particularly lignocellulosic biomass, which is renewable and abundant. Lignocellulosic fibers, rich in lignin, hemicellulose, and cellulose, offer significant advantages due to their composition and physical properties, making them highly suitable for a wide range of industrial applications. By maximizing the use of natural resources and reducing dependence on imports, this approach not only enhances sustainability but also contributes to economic growth and environmental preservation [1].

Lignocellulosic materials, primarily derived from abundant agricultural waste, are valuable renewable feedstocks for biopolymer production and biorefinery applications. While global fiber production experienced a decline of 0.8 million tons annually over the past two decades, recent trends indicate a plateauing. Cellulose, a crucial component of lignocellulose, is a chemically versatile, rigid, and highly crystalline polysaccharide, insoluble in most organic solvents, making it ideal for structural engineering. Its content varies considerably depending on the source, ranging from 30% in wheat straw to 80-95% in seed hair [2]. A commercially significant cellulose derivative is carboxymethyl cellulose (CMC), a water-soluble polyelectrolyte produced through chemical modification of cellulose. First conceptualized and commercially produced in Germany, CMC boasts widespread industrial applications due to its unique properties. These materials offer promising opportunities for sustainable industrial development by leveraging their renewable nature and diverse characteristics [3].

Carboxymethyl cellulose (CMC), a prominent cellulose derivative, is synthesized by reacting alkali cellulose with monochloroacetic acid, modifying the free hydroxyl groups in anhydro glucose units. Studies have demonstrated the production of CMC with varying degrees of substitution from sources like *Eucalyptus globulus* pulp, treated in a formic acid-peroxyboric acid medium and subjected to chlorine-free bleaching [4]. The rheological properties, solubility, and molar mass of CMC are influenced by its degree of substitution, enhancing its versatility. Carboxymethylation, a widely studied process due to its simplicity, involves activating polysaccharides with sodium hydroxide and reacting them with monochloroacetic acid or its sodium salt. As an anionic polyelectrolyte, CMC exhibits unique properties in aqueous solutions, depending on its grade and solution conditions. These characteristics make CMC a significant material with broad industrial applications, contributing to its importance as a sustainable and functional cellulose derivative [5].

Carboxymethyl cellulose (CMC) is a non-toxic, versatile compound with extensive applications across pharmaceuticals, medicine, and the food industry. It functions as a film-forming agent, producing mechanically and chemically resistant films, and serves as a binding agent, stabilizer, water retention agent, and protective colloid. These properties enable CMC to suspend particles, retain moisture, and stabilize solutions effectively [6]. In the oil and gas sector, CMC is utilized in drilling fluids, as demonstrated in the Block 6 Ballia field in South West Sudan, where it enhanced fluid viscosity, reduced filtration volume, and improved overall drilling performance [7]. While cellulose itself is insoluble in common solvents due to its hydrogen-bonded structure, its water-soluble derivatives, such as CMC, have broad industrial applications. CMC is widely used in food, pharmaceuticals, detergents, and cosmetics, where it acts as a preservative, thickener, and coating agent. For example, it is applied to coat fresh fruits and thicken pharmaceutical formulations, often after swelling cellulose fibbers in concentrated sodium hydroxide. These diverse functionalities make CMC a critical material in multiple industries, leveraging its unique properties for innovative and sustainable solutions [8].

II. LITERAURE REVIEW

The synthesis of carboxymethyl cellulose (CMC), a versatile and widely used polymer with applications in pharmaceuticals, food, oil and gas, and other industries [9], is a critical process that typically takes place in a Continuous Stirred-Tank Reactor (CSTR). The CSTR is a well-established industrial reactor designed to ensure efficient and uniform chemical reactions. Its operation relies on perfect mixing, achieved through continuous agitation by a mechanical stirrer, which ensures that the reactor's contents are homogeneously blended. This uniformity is essential for maintaining consistent temperature and concentration profiles throughout the reactor, directly influencing the quality and properties of the final product [10]. The synthesis process involves the carboxymethylation of cellulose, where alkali cellulose reacts with monochloroacetic acid or its sodium salt to introduce carboxymethyl groups, resulting in the formation of sodium carboxymethyl cellulose (SCMC)[11] To optimize this process, it is crucial to understand and simulate the kinetics of SCMC formation. Kinetic modelling allows researchers to calculate the rate constants of the synthesis reactions, providing insights into reaction mechanisms and enabling the fine-tuning of process parameters. This optimization is vital for improving reaction efficiency, yield, and overall product quality. The CSTR system integrates multiple scientific and engineering principles, including chemical kinetics, thermodynamics, fluid mechanics, heat transfer, and mass transfer. These principles collectively determine the efficiency, scalability, and economic viability of the process. Proper temperature control within the reactor ensures optimal reaction rates while minimizing side reactions that could compromise product quality. Additionally, economic considerations are factored into reactor design and operation to reduce energy consumption, minimize raw material waste, and enhance production efficiency A key advantage of the CSTR is its ability to maintain steady-state conditions, where the temperature and concentration of the reactor contents are identical to those of the final product. This characteristic ensures consistent product properties and enables continuous production, making the CSTR a reliable and scalable method for large-scale CMC synthesis. By leveraging the principles of perfect mixing and kinetic modelling, the synthesis of CMC in a CSTR represents a robust and efficient approach to producing this valuable polymer for diverse industrial applications. The well-mixed nature of the CSTR simplifies kinetic analysis and allows for precise control over reaction conditions, enabling manufacturers to tailor CMC properties to meet specific application requirements [10].

Cost estimation is crucial for successful project management, particularly in industrial settings like CMC synthesis. It involves accurately predicting the financial and resource needs to complete a project within a defined scope. This includes assessing factors like raw materials (e.g., lignocellulosic biomass, chemical reagents), labor, equipment, energy consumption, waste management, and Research and Development (R&D) [12]. Accurate cost predictions are essential for determining project feasibility, optimizing operations, and maintaining competitive pricing. Invoice discounting, a financial tool, helps manage cash flow by allowing businesses to leverage outstanding invoices for immediate funding, which is especially helpful in long production cycles. Several key components contribute to industrial cost estimation. Material costs, including feedstock and chemicals, are primary drivers. Labor and equipment costs, encompassing salaries, maintenance, and depreciation, must be considered. Energy consumption for processes like stirring and temperature control is a significant factor [13]. Waste management and environmental compliance add to expenses. Finally, investments in R&D are crucial for product improvement and process optimization. Invoice discounting enables businesses to access working capital by selling unpaid invoices, supporting ongoing operations and covering essential expenses [14]. In CMC production, cost estimation is linked to process optimization, where engineers and financial analysts collaborate to maximize yield, minimize waste, and enhance energy efficiency through advanced simulation and process refinement [15].

This study will evaluate the suitability of date palm biomass, a potential resource, for CMC extraction, specifically for petroleum applications, by characterizing and Optimize pre-treatment methods, maximizing cellulose yield and purity while minimizing environmental impact, will be developed. A full-scale production unit, including reactor design and process optimization tailored for date palm-derived CMC, will be designed. A thorough techno-economic analysis, considering raw material costs, energy consumption, and market demand, will be conducted. A comprehensive life-cycle assessment, from biomass sourcing to final product application and disposal, will assess the unit's sustainability. The study's novelty lies in demonstrating the feasibility and economic viability of using date palm biomass for petroleum-grade CMC production, developing a tailored production process, and providing a detailed cost analysis and environmental impact assessment.

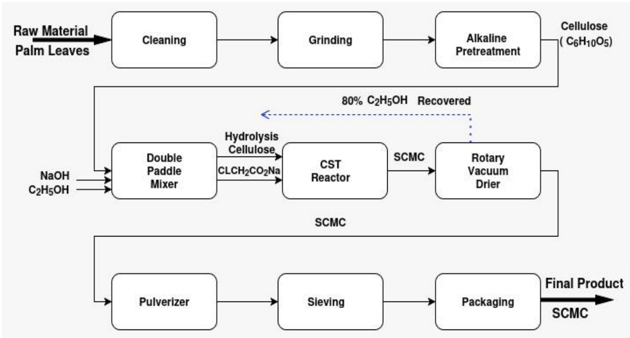
III. MATERIALS AND METHOD

This study investigates the extraction, isolation, and carboxymethylation of cellulose from locally sourced palm fronds at the Sudan University of Science and Technology and Central Petroleum Laboratories. The process begins with pre-treatment of the palm fronds. Mechanical chipping, milling, or grinding reduces particle size, increasing surface area for subsequent fractionation and improving material handling. Chemical pre-treatment then employs alkaline hydrolysis with sodium hydroxide (NaOH), potentially with added oxygen or air, to enhance delignification, crucial due to the high lignin content of palm fronds.

The two-step CMC synthesis involves first treating the extracted cellulose with NaOH, sometimes with an inert solvent, to create alkali cellulose. This swelling facilitates NaOH penetration for the subsequent reaction. The carboxymethylation itself occurs in a 2435.26 dm^3 CSTR (designed according to reference). A mathematical model, based on reaction kinetics, will determine the reaction rate constant, incorporating stoichiometry, chemical kinetics, and reactor design principles. Optimized conditions for SCMC synthesis will be used (2g cellulose, 6g MCAA, 40% NaOH, 55°C). The alkali cellulose then reacts with monochloroacetic acid (MCAA) to form SCMC, potentially substituting all three hydroxyl groups in each glucose unit, creating derivatives with varying degrees of substitution. XRD analysis will track crystallinity changes during purification and SCMC formation [10].

The synthesis of Sodium Carboxymethyl Cellulose (SCMC) is a multi-step process integrating chemical kinetics, thermodynamics, fluid mechanics, heat transfer, and mass transfer. Alkali cellulose reacts with monochloroacetic acid (MCA) in an aqueous medium within a Continuous Stirred-Tank Reactor (CSTR). The exothermic reaction, reaching 80°C, is controlled by a chiller, cooling the mixture to 25°C over 60-95 minutes, producing SCMC with 12-18% moisture. Perfect mixing in the CSTR ensures uniform temperature and concentration. The SCMC slurry is then dried in a vacuum drier at 75-80°C for 120 minutes, reducing moisture to 5-8% and yielding purified SCMC. This drying process recovers 100% of the water and 80% of the ethyl alcohol, which is condensed. The dried SCMC is pulverized into particles 74 mm or smaller, then sieved, with coarser particles recycled. The final product is a fine SCMC powder, ready for industrial use. This final SCMC product, an anionic cellulose ether, will be characterized. It is expected to be a white or slightly yellow powder or flocculent fibber, odorless, tasteless, and non-toxic, soluble in hot and cold water, forming a viscous solution. Solubility in other solvents will also be assessed. Key properties, including surface tension, molecular weight, melting point, boiling point, heat capacity, latent heat, and enthalpy of formation will be determined. Light and heat stability, and the influence of temperature on viscosity, will also be measured.

All of the previous studies and laboratory analyses were taken into account, and a process description for all of the above steps followed, which yielded the block flowsheet shown below figure (1).



[Fig.1: The Proposed Production Process for Obtaining SCMC]

The economic analysis of the proposed CMC production unit encompasses both capital and operating costs. Plant location will be strategically selected to optimize raw material accessibility. The plant will operate 300 days annually (360 days total, with 60 days allocated for maintenance and potential downtime), producing 10 tons of CMC per day. With a 6-hour batch cycle, this equates to four batches daily.

Equipment costs will be updated to present value using the Chemical Engineering Plant Cost Index (CEPCI) (Equation 1). These costs will then be adjusted for the specific production capacity (10 tons/day) using the six-tenths factor rule (Equation 2), employing a typical exponent of 0.6 [16].

$$Cost\ Item\ (20XX) = Cost\ Item\ (20XX) \times \left[\frac{Cost\ Index\ 2023}{Cost\ Index\ (20XX)}\right] \quad \dots \quad (1)$$

$$Cost\ New\ Capacity = Cost\ Old\ Capacity\ \times \left[\frac{New\ Capacity}{Old\ Capacity}\right]^{0.6} \quad \dots \quad (2)$$

The methodology for evaluating total capital investment includes the total installed cost of major process equipment (including auxiliary equipment, which is 10% of the main equipment cost), total product cost (including operational labor), cash flow projections based on product selling price, and sensitivity analysis. This approach follows established principles for cost estimation [12]. The total equipment cost, including auxiliary equipment, is USD 103,823.5. The CSTR will be constructed of stainless steel with a carbon steel jacket. This analysis will provide a comprehensive assessment of the project's economic viability.

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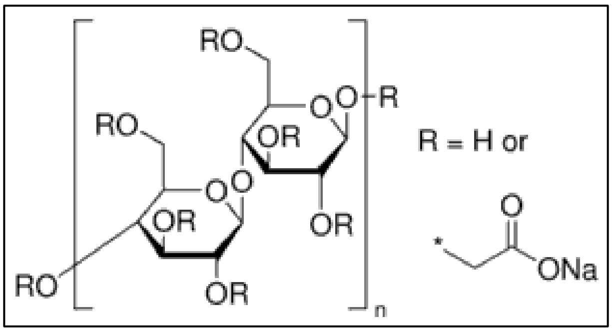
IV. RESULTS AND DISCUSION

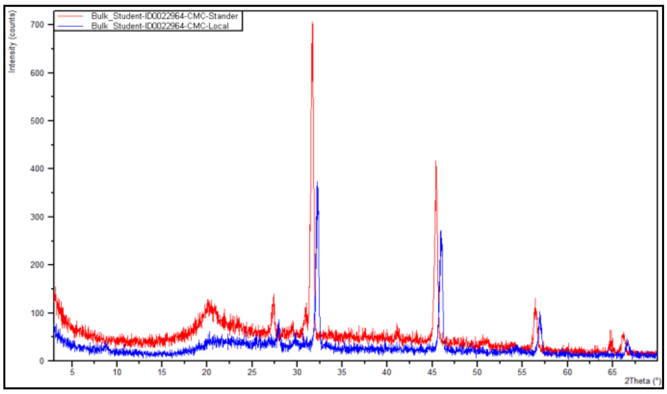
Figure (2) visually documents the transformation of untreated palm fronds into carboxymethyl cellulose (CMC), showcasing key steps in the extraction and synthesis process. The initial image depicts the raw, fibrous palm fronds, highlighting their lignocellulosic nature and the need for pre-treatment to isolate cellulose. The subsequent image of extracted cellulose reveals a refined, white, cotton-like material, indicating successful delignification and removal of non-cellulosic components. This transition underscores the effectiveness of the likely alkaline and bleaching treatments used in the extraction process. The final image showcases the synthesized CMC with a degree of substitution (DS) of 0.77, appearing as a swollen, white, gel-like substance. This DS value suggests moderate substitution, suitable for various applications, and the homogenous, water-absorbed texture indicates effective etherification of the cellulose. The progression from raw biomass to purified cellulose and then to functionalized CMC visually confirms the successful conversion of agricultural waste into a valuable biopolymer.

[Fig.2: Transformation of Palm Fronds into Carboxymethyl Cellulose (CMC)]

The synthesized sodium carboxymethyl cellulose (SCMC) was thoroughly characterized to determine its key physical and chemical properties. Analysis revealed a surface tension of 71 mN/m, a molecular weight of 242.12 g/mol, a melting point ranging between 300 and 310°C, and a boiling point of 527°C. Additionally, the heat capacity was measured at 17.7 Cal/mol at 25°C, with a latent heat of 11,000 Cal/mol and an enthalpy of formation of -68,000 Cal/mol at the same temperature. SCMC exhibited notable stability against both light and heat, with viscosity decreasing as temperature increased. Furthermore, its ability to form derivatives with varying degrees of substitution enhances its versatility, making it valuable for applications such as swelling agents, ion-exchange chromatography, and weak acid cation exchangers. Specifically, SCMC is used for separating basic and neutral proteins at a pH of 4 and above, Figure (3). In addition to characterizing SCMC, this study examined the structural modifications of cellulose fibbers resulting from the carboxymethylation reaction, comparing the synthesized SCMC with a commercially available SCMC sample. X-ray diffraction (XRD) analysis (Figure 4) was employed to assess the crystallinity of both purified cellulose and synthesized SCMC. The XRD patterns confirmed a structural transition from the crystalline nature of cellulose to the more amorphous structure of SCMC. Notably, the results indicated minimal structural differences between the laboratory-synthesized SCMC and its commercially available counterpart, further validating the effectiveness of the synthesis process.



[Fig.3: Molecular Structure of Carboxymethylcellulose Sodium Salt (Cellulose Derivative)]



[Fig.4: XRD Patterns of CMC (Lab-Synthesized (Blue) and Commercial (Red))]

This research, building upon the reactor design detailed in previous publication [10], focuses on calculating equipment procurement costs, the basis of invested capital (Table I and Figure 5). Table (I) and Figure (5) details the Total Capital Investment (TCI) of $233,311.236, comprising Total Fixed-Capital Investment (A), Auxiliary Investment (B), and Working Capital (C).

Total Fixed-Capital Investment (A), $186,648.989, is divided into Direct Plant Costs (A1) and Indirect Plant Costs (A2). Direct Plant Costs (A1), $156,318.528, cover purchased equipment (27.51% of FCI, or $51,323.50), installation (10% of FCI), instrumentation, piping, electrical systems, buildings, yard improvements, service facilities (19% of FCI, or $35,462.31), and land. Indirect Plant Costs (A2), $30,330.461, cover engineering and supervision (12.5% of FCI), construction, legal expenses, contractor fees, and miscellaneous costs. These costs were derived using percentage ranges from Peter's reference [16], selecting average percentages (Column 3) and calculating percentages relative to equipment cost (Column 4).

Auxiliary Investment (B), $27,997.348, covers auxiliary buildings (15% of TFCI), water supply, electrical substations, process water systems, fire protection, roads, and communication, all calculated as percentages of TFCI. Working Capital (C), 10% of the TFCI, or $18,664.899, represents operational funds for the project's initial phase.

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Table-I: Total Capital Investment for Base Case

Item	Components	Range of FCI %	Selected of FCI %	Normalized of FCI %	Estimation cost $
	Total Capital Investment A + B + C				2,33,311.24
A	***TOTAL FIXED-CAPITAL INVESTMENT A1+A2***				**1,86,648.99**
A1	***TOTAL DIRECT PLANT COST 1-9***				**1,56,318.53**
1	Purchased Equipment	15 - 40	27.5	100	1,03,823.50
2	Installation	Jun-14	10	7.491	7777.041
3	Instrumentation & Control	02-Dec	7	5.243	5443.929
4	Piping	Apr-17	10.5	7.865	8165.893
5	Electrical Installed	02-Oct	6	4.494	4666.225
6	Building	Feb-18	10	7.491	7777.041
7	Yard improvement	02-May	3.5	2.622	2721.964
8	Service Facilities	Aug-30	19	14.232	14776.378
9	Land	01-Feb	1.5	1.124	1166.556
A2	***TOTAL INDIRECT PLANT COST 10 - 14***				**30, 330.461**
10	Engineering & Supervision	Apr-20	12.5	9.363	9721.301
11	Construction	Apr-17	10.5	7.865	8165.893
12	Legal Expenses	01-Mar	2	1.498	1555.408
13	Contractor Fee	02-Jun	4	2.996	3110.816
14	Miscellaneous	May-15	10	7.491	7777.041
B	***AUXILIARY INVESTMENT 15 - 21***				**27,997.35**
15	Auxiliary Building			5%	15 % OF T F C I
16	Water Supply			4%	
17	Electrical Sub			1.50%	
18	Process Water System			1%	
19	Fire Protection Equipment's			2%	
20	Road			1%	
21	Communication			0.50%	
C	***WORKING CAPITAL 10 % OF T FCI***				**18,664.90**

The cost analysis presented in Table (II) and Figure (5) reveals a total product cost (TPC) of $3,721,474.26, partitioned into $3,195,633.38 (85.9%) in manufacturing costs (C) and $525,840.88 (14.1%) in general expenses (D). The analysis identifies raw materials ($1,082,838, 34% of C, 29% of TPC) and operating labor ($967,169.70, 30% of C, 26% of TPC) as the dominant cost drivers. This finding highlights the need for optimization strategies in raw material procurement (supplier negotiations, alternative materials, and efficient inventory management) and operating labor efficiency (process streamlining, automation, and targeted training).

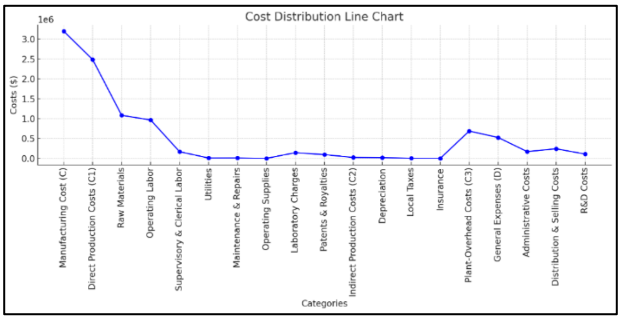
Plant overhead ($688,574, 21.5% of C, 18.5% of TPC), calculated as 60% of operating labor, supervisory labor ($169,254.69), and maintenance and repairs ($11,198.94), requires further investigation to pinpoint specific cost contributors and explore potential reductions. Preventative maintenance programs and other cost-saving measures within plant overhead should be considered. Distribution and selling costs ($243,167, 6.5% of TPC) also warrant attention, with potential optimizations in distribution channels, marketing efficiency, and packaging. While smaller, indirect production costs (depreciation: $18,664.90; local taxes: $4,666.23; insurance: $746.60) and general expenses (administrative costs: $172,143.50; R&D: $159,781.67) should be periodically reviewed for potential savings, the focus should remain on the larger cost drivers. A detailed examination of manufacturing costs reveals a material-intensive production process (raw materials: 43.6% of direct production costs) and a significant labor component (operating labor: 38.9% of direct production costs) [20]. Direct production costs (C1), totaling $2,482,981.66 (77.7% of C), are primarily driven by raw materials and operating labor. Other components of C1 include supervisory labor (6.8%), utilities (0.4%), maintenance and repairs (0.45%), operating supplies (5.8%), laboratory charges (5.8%), and patents/royalties (4%) [21].

Indirect production costs (C2), at $24,077.72 (0.75% of C), appear well-managed. However, the substantial plant overhead (21.6% of C) suggests potential administrative inefficiencies that warrant further scrutiny. General expenses (D), comprising administrative costs, distribution and selling costs (11% of C), and R&D (5% of C), require ongoing review. The significant distribution and selling costs indicate a focus on market expansion, but more cost-effective strategies should be explored. The allocation of 5% of manufacturing costs to R&D is a positive indicator of a commitment to innovation.

Prioritizing cost control in raw materials, labor, and plant overhead, coupled with a thorough analysis of distribution and selling costs, is crucial for improving profitability. Future research should include a more in-depth analysis of these key cost drivers, incorporating data such as production volumes, market conditions, competitor pricing, and the fixed capital investment value to refine these insights and inform strategic decision-making.

Table-II: Total Annual Product Cost for the Base Case

	ITEM		COST $
C	***MANUFACTURING COST***	***C1 + C2 + C3***	**3195633.379**
C1	***DIRECT PRODUCTION COSTS***	***1 to 8***	**2482981.655**
1	Raw materials (calculated)	-	1082838
2	Operating labor (calculated)	-	967169.7
3	Direct supervisory and clerical labor (17.5% of operating labour)	17.5%	169254.69
4	Utilities (calculated)	-	10265.69
5	Maintenance and repairs (6% of fixed-capital investment)	6.0%	11198.94
6	Operating supplies (15% of cost for maintenance and repairs)	15.0%	1679.841
7	Laboratory charges (15% of operating labor)	15.0%	145075.5
8	Patents and royalties (4% of C1.1 to C1.7)	4.0%	95499.294
C2	***INDIRECT PRODUCTION COSTS***	***9 to 11***	**24077.72**
9	Depreciation (10% of fixed-capital investment)	10.0%	18,664.898
10	Local taxes (2.5% of fixed-capital investment)	2.5%	4,666.225
11	Insurance (0.4% of fixed-capital investment)	0.4%	746.596
C3	***PLANT-OVERHEAD COSTS (60 % of 2 + 3 + 5)***	***60.0%***	**688574.004**
D	***GENERAL EXPENSES***	***14 to 16***	**525840.88**
14	Administrative costs (15% of 2 + 3 + 5)	15.0%	172143.501
15	Distribution and selling costs (11% of manufacturing cost)	11.0%	243166.95
16	Research and development costs (5% of manufacturing cost)	5.0%	110530.43
	TOTAL PRODUCT COST	**C + D**	**3721474.259**



[Fig.5: The Cost Breakdown of the Manufacturing Process]

The financial analysis examines the economic viability of the SCMC production project. With a projected annual production of 10 tons per day and a selling price of $3,000 per ton, the annual sales revenue is estimated as follows:

Annual Sales = (Production Rate per Day × Days per Year) × Price per Ton

Annual Sales = (10 tons/day × 300 days/year) × $3,000/ton = $9,000,000

Subtracting the total manufacturing cost (C) of $3,195,633.38 yields the gross profit:

Gross Profit = Annual Sales - Manufacturing Cost (C)

Gross Profit = $9,000,000 - $3,195,633.38 = $5,804,366.62

A 20% tax is applied to the gross profit to calculate the net profit:

Net Profit = Gross Profit - (Tax Rate × Gross Profit)

Net Profit = $5,804,366.62 - (0.20 × $5,804,366.62) = $4,643,493.30

The current project is designed to achieve this estimate with a notional accuracy of (-15 ± 30) percent in related costs and estimating methods, even if it can be reached with little data and at low cost [17].

The payback period (PBP) is calculated as the ratio of the initial investment to the average annual cash flow (approximated by the net profit in this simplified analysis) [18]:

PBP = Initial Investment / Average Annual Cash Flow

Using the provided initial investment and the calculated net profit as the annual cash flow the PBP approximately is 1.32 years.

The Lang factor method is used to estimate the total capital investment (TCI) based on the purchased equipment cost. The formula is:

TCI = Lang Factor * Purchased Equipment Cost

$$C_{TM} = F_{lang} \sum_{i=1}^{n} C_{p,i}$$

where:

C_{TM} is the total plant cost

F_{lang} is the Lang factor

$\sum_{i=1}^{n} C_{p,i}$ is the sum of the cost of all purchased equipment

With a Lang factor of 4.9 for solid-fluid processing plants and a purchased equipment cost of $103,823.50:

TCI = 4.9 * $103,823.50 = $508,735.15

Return on investment is the ratio between net profit and total capital investment (TCI); net profit is the total revenue less costs of manufacture (COM). It is a measure of the degree of profitability of the investment.

ROI = (revenue − COM) / TCI×100%,

the lang factor to calculate TCI for solid-fluid processing plants was select with a Flang equal to 4.9.

TCI = 4.9×103,823.5 = 508,735.15 $

ROI = (Net Profit / TCI) * 100%

(46434932.97 -3195633.379**)** / (508735.15) ×100% = 2.846%

The net present value (NPV) is calculated using the following formula:

NPV = ∑ (Net Annual Cash Flow (1 + Discount Rate) ^Year) - Initial Investment

For a 10-year project lifetime and a 10% discount rate:

NPV = ∑ ($4,643,493.30 (1 + 0. 10)^Year) for Year 1 to 10 - $233,311.24

NPV = $81,172,000 ≈ **$81.172 million**

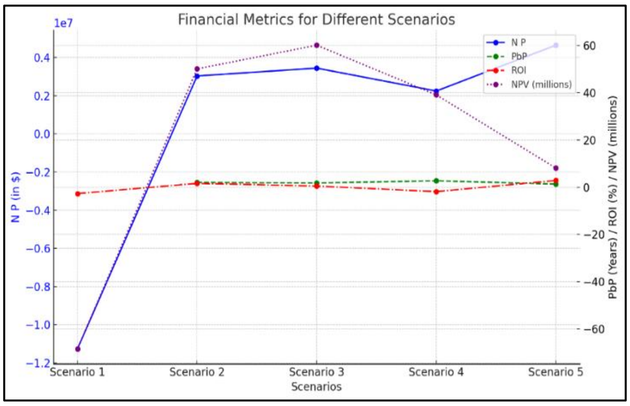
This financial analysis, incorporating a sensitivity analysis, examines the SCMC production project's economic viability. Initial calculations, based on a $3,000/ton selling price and 10 tons/day production, project annual sales of $9,000,000, a gross profit of $5,804,366.62 (after subtracting $3,195,633.38 manufacturing costs), and a net profit of

$4,643,493.30 (after 20% tax). A sensitivity analysis was therefore performed to understand the impact of variations in key parameters. Raw material costs (varied by ±10% and ±20%) and operating labor costs (varied by ±10% and ±20%), both major cost drivers, demonstrated a direct correlation with profitability. Raw material costs exhibited a more pronounced impact, highlighting the need for accurate estimation and effective procurement. Selling price variations (±5% and ±10%) also significantly affected profitability, emphasizing the importance of market research and competitive pricing. Production volume variations (±10% and ±20%) linearly impacted sales and profit, underscoring the need for accurate capacity planning.

Five scenarios were built as provided in table (III) and represented by Figure (6) reveals a complex financial landscape for the SCMC production project. Five scenarios were evaluated, showcasing the impact of varying conditions on Net Profit (NP), Payback Period (PBP), Return on Investment (ROI), and Net Present Value (NPV). Scenario (1) presents a stark contrast to the others, with substantial losses across all metrics, likely representing a worst-case scenario driven by highly unfavorable conditions. Scenarios (2, 3, and 4) demonstrate a general trend of improvement, although with some fluctuations, particularly in ROI. Scenario (5) emerges as the most promising, boasting the highest profit and shortest payback, though not the highest NPV. The figure (6) effectively visualizes these trends, highlighting the interplay between the different financial metrics.The wide range of outcomes across scenarios underscores the project's sensitivity to underlying assumptions and market conditions. This sensitivity analysis, while not explicitly labelled, emphasizes the need to understand the specific drivers behind each scenario. Identifying the factors influencing raw material costs, selling price, production volume, and discount rate will be crucial for robust risk assessment and informed decision-making. Figure (6) effectively highlights the trade-offs between different financial metrics. For example, a higher ROI might be achieved at the cost of a longer payback period or a slightly lower NPV. Therefore, a holistic evaluation is essential to optimize the project's overall value.

Table-III: Financial Metrics of Different Scenarios

Item	Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)	Scenario (5)
N P	-11,259,271.16 $	3031513.133$	3443493.297$	2243493.297$	4643493.297$
PBP	infinite	2.02 Years	1.78 Years	2.73 Years	1.32 Years
ROI	-2.7 %	1.614 %	0.487 %	-1.872%	2.846%
NPV	- 68.42 million $	50,114 million $	60.135 million $	39.097 million $	81.172 million $



[Fig.6: Financial Metrics for Different Scenarios]

The research and development of Sodium Carboxymethyl Cellulose (SCMC) production must prioritize environmental sustainability to minimize ecological harm and align with global environmental standards. A key focus is on raw material sourcing and production, where research can assess the sustainability of feedstocks like cellulose derived from agricultural residues or recycled sources, potentially reducing carbon emissions by up to 30% compared to traditional wood pulp. Additionally, optimizing the production process to minimize waste and recover byproducts can achieve a 20% reduction in waste generation, while identifying safer chemical alternatives can lower environmental toxicity by 25% [19].

Energy consumption and greenhouse gas emissions are another critical area. Research can enhance energy efficiency by 20-25% through the adoption of energy-efficient equipment and renewable energy sources, which can also reduce greenhouse gas emissions by up to 50%. Water usage, another significant factor, can be reduced by 30-40% through wastewater recycling and water-efficient processes, while advanced wastewater treatment methods can ensure 95-98% efficiency in removing harmful chemicals.

A Life Cycle Assessment (LCA) provides a comprehensive evaluation of the environmental impacts from raw material sourcing to end-of-life disposal, highlighting opportunities for improvement. For instance, using recycled materials can reduce the overall environmental impact by 25-30%, while designing SCMC for biodegradability can further lower its footprint by 15-20%. Compliance with environmental regulations, such as ISO 14001 standards, ensures adherence to legal requirements and reduces compliance risks by 30-40%. Implementing real-time environmental monitoring systems can also decrease environmental incidents by 50-60%, ensuring proactive management of ecological impacts.

Beyond environmental benefits, sustainable practices enhance the project's social and economic viability. By adopting green technologies, the project can create 10-15% more jobs in local communities and achieve annual cost savings of 50,000−100,000 through energy efficiency and waste reduction. This holistic approach not only strengthens the project's long-term viability but also fosters community acceptance and aligns with global sustainability goals.

In conclusion, integrating environmental research into the SCMC production project is essential for minimizing its ecological footprint, ensuring regulatory compliance, and enhancing economic and social benefits. By prioritizing sustainability, the project can serve as a model for environmentally responsible industrial practices, contributing to a greener and more sustainable future.

V. CONCLUSION

This research successfully demonstrated the feasibility of synthesizing carboxymethylcellulose (CMC) from date palm fronds through effective cellulose extraction and carboxymethylation. The produced CMC falls within the medium-weight range, making it suitable for applications in pharmaceuticals, food, cosmetics, water treatment and as a viscosity-enhancing agent in Gas and oil industry.

The economic analysis indicates that SCMC production is financially viable, with an estimated manufacturing cost of USD 1.07 per kilogram and a final product cost of USD 1.24 per kilogram. Key cost drivers include raw materials and labor, while opportunities for cost reduction exist in material procurement, automation, and process efficiency improvements. Sensitivity analysis confirms the project's profitability, highlighting its potential to reduce reliance on imported CMC and generate substantial revenue.

Building upon previous work [10], this study details the design of an isothermal continuous stirred tank reactor (CSTR) optimized for industrial-scale sodium carboxymethyl cellulose (CMC) production. A comprehensive model, incorporating material balance principles and heat generation equations, was used to derive the reactor's functional parameters. The resulting design specifies a reactor volume of 24355.2557 dcm^3, a diameter of 14.5845 dm, and a length of 21.87689 dm. The reactor itself is constructed from austenitic stainless steel, while the surrounding jacket, measuring 228.9766 dm in length, is composed of carbon steel. Five spiracles are incorporated into the design to promote efficient mixing and heat transfer. These specifications establish a foundation for the effective and controlled manufacture of CMC at an industrial level.

Sustainability is integral to long-term success, with strategies such as waste reduction (20%), energy efficiency improvements (20-25%), greenhouse gas emission reduction (50%), water conservation (30-40%), and advanced wastewater treatment (95-98% efficiency). Conducting a Life Cycle Assessment (LCA) minimizes environmental impact, while adherence to regulations like ISO 14001 reduces compliance risks. Implementing sustainable practices also fosters community acceptance, creates 10-15% more local jobs, and provides annual cost savings of $50,000–$100,000 from energy efficiency and waste reduction.

Ultimately, this research highlights the potential of utilizing agricultural waste for high-value biopolymer production. By integrating innovation, cost optimization, and environmental responsibility, SCMC production can serve as a model for sustainable industrial practices, contributing to economic growth and a greener future.

RECOMMENDATIONS

To enhance the project's profitability and sustainability, several key recommendations are proposed. These include optimizing material procurement strategies, implementing automation and process control technologies to improve production efficiency, and streamlining administrative procedures to reduce plant overhead. Furthermore, a cost-benefit analysis of distribution channels will help optimize marketing expenditures.

To minimize environmental impact, the project should prioritize sustainability through waste reduction strategies, such as process optimization and byproduct recovery. Energy efficiency can be improved by 20-25% by integrating renewable energy sources, leading to a 50% reduction in greenhouse gas emissions. Water usage can be reduced by 30-40% through recycling and efficient process design. Implementing advanced wastewater treatment systems will ensure 95-98% efficiency in removing harmful chemicals. Conducting a Life Cycle Assessment (LCA) will help identify and address environmental hotspots.

Adherence to environmental regulations (e.g., ISO 14001) is crucial to minimize compliance risks. Implementing real-time environmental monitoring systems will enable proactive management of environmental impacts and ensure compliance.

Continuous investment in (R&D), allocating 5% of manufacturing costs, is essential for exploring new applications for SCMC, improving production processes, and maintaining a competitive edge.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** Yes, It is relevant. The study's supporting data can be obtained from the [Ministry of Energy and Petroleum - Sudan]. However, it is important to note that there are restrictions on public access to these data since they were utilized under a licensing agreement for this specific

research. Nonetheless, the authors are willing to provide the data upon a reasonable request, subject to approval from the [Energy and Petroleum Ministry - Sudan].

- **Authors Contributions:** This article reflects the equal contributions of all authors, who participated in all stages of its development. This included the initial conceptualization and drafting of the abstract, introduction, and literature review, as well as the execution of the experimental work encompassing cellulose and CMC extraction and characterization, and CSTR design. Moreover, all authors collaborated on the Techno-Economic and Feasibility assessment for CMC production, evaluated its potential for industrial applications, and were significantly involved in the writing and refinement of the manuscript. We, the authors, collectively affirm our endorsement of this research, its conclusions, and our adherence to the principles of transparency and reproducibility within our scientific community. The final manuscript has been thoroughly reviewed and approved by all authors.

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