

Techno-Economic Analysis of an Integrated Membrane-Based Harvesting and Effluent Recycling Strategy for Microalgal Biomass Production in Raceway Ponds

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Abstract

Microalgae-based systems offer a sustainable route for biomass production and carbon dioxide (CO₂) capture; however, their economic feasibility remains scale-dependent. This study presents a techno-economic analysis (TEA) of *Monoraphidium* sp. KMC4 cultivated in open raceway ponds (ORPs) using low-cost kaolin-based ceramic membranes, integrated with a three-batch effluent recycling system. Four scenarios (S1–S4) were evaluated to assess the influence of production scale (1–100 hectares) and electricity subsidies. Capital expenditure (CAPEX) and operating expenditure (OPEX) were quantified, and a sensitivity analysis was conducted for plant life, discount rate, biomass selling price, and utility and labor costs. Results show that small-scale systems with subsidies (S1) yield marginal profitability (net present value, NPV: \$0.28 million), while unsubsidized small-scale systems (S2) remain unviable. Industrial-scale production (S4) demonstrated favorable economics, with a unit biomass cost of \$7.50 per kilogram, a payback period of 5.3 years, and an NPV of \$145.78 million. The sensitivity analysis confirmed that the biomass selling price and utility costs are the most influential parameters that affects economic viability. Overall, the findings emphasize that economics of scale, process optimization, and resource recovery are key to widespread adoption and feasibility of algae-based systems.

Keywords: *Microalgae cultivation; Techno-economic analysis; Net present value, Sensitivity analysis; Monoraphidium* sp. KMC4; *Ceramic membrane; Circular bioeconomy; Membrane filtration*

Synopsis: This work presents a scalable membrane-integrated microalgae system that enables sustainable water reuse and economically viable biomass production.

1. Introduction

With the global population on the rise and the growing demand for food, energy, and valuable products, microalgae have emerged as a significant resource in the bio-based economy^{1,2}. These microorganisms, which rely on photosynthesis, efficiently use sunlight to convert carbon dioxide and nutrients into biomass that can be applied across various industries^{3,4}. Due to their natural ability of biological carbon capture, microalgae play significant role in CO₂ sequestration. Another key advantage of microalgae is that they can be cultivated without the need for arable land or freshwater, making them a more sustainable option compared to traditional food production methods that often strain natural resources³⁻⁵. Additionally, the ability to cultivate microalgae throughout the year adds to their commercial potential⁶⁻⁸. However, the situation is more complex, with several challenges hindering the widespread adoption and establishment of microalgae. One major obstacle is the need for biorefining of algal biomass using a cascade approach, which remains difficult to achieve. Despite several advantages, the readiness of technologies for cultivation and commercialization has been a topic of recent debate^{9,10}. In this context, microalgae also present a promising biological route for CO₂ capture from atmosphere or industrial sources due to their high photosynthetic efficiency and rapid growth. The resulting biomass, in turn, holds significant potential for conversion into a wide range of products including biofuels, chemicals, animal feed, pigments, and nutraceuticals, as part of an integrated biorefinery approach^{11,12}. To highlight this broader application scope, Fig. 1 illustrates the potential pathways for biomass fractionation and multi-product valorization. However, the economic feasibility of large-scale microalgal cultivation continues to be a key barrier to commercial deployment. High production costs, energy-intensive harvesting and dewatering processes, substantial water and nutrient requirements, and limited recycling of nutrients and effluents hinder its viability. These constraints justify the need for a detailed techno-economic analysis (TEA) to understand the cost dynamics of microalgal biomass production.

Microalgae harvesting is a critical step in the production of algal biomass, with various techniques like centrifugation, flocculation, and membrane filtration being utilized to enhance efficiency and reduce costs¹³. Among these, membrane-based separation processes are particularly attractive due to their high separation efficiency and ability to maintain the integrity of the biomass ¹⁴. While traditional polymeric membranes are commonly used, they often face challenges such as fouling and limited chemical stability, which can impact long-term operational efficiency. In contrast, ceramic membranes offer superior chemical and thermal stability, making them more suitable for microalgae harvesting, although their high production costs have limited broader adoption^{15,16}. Recent studies have explored the use of low-cost ceramic membranes, particularly those based on kaolin, as a more economical alternative, demonstrating effective microalgae separation with reduced material costs^{17,18}. Furthermore, the treatment of effluents using methods like activated carbon adsorption has been shown to improve water quality, enabling the reuse of treated water in subsequent cycles¹⁹. While previous research has largely focused on single-pass filtration and effluent disposal, the incorporation of a three-batch recycle approach with powdered activated carbon treatment of the effluent offers a novel strategy for enhancing process sustainability and economic viability.

Techno-economic analysis (TEA) is a critical approach for evaluating the scalability and viability of emerging water and biomass technologies. Prior studies have assessed the costs and benefits of algal systems under varying cultivation strategies, strain choices and harvesting methods. Schipper et al. (2021), for instance, compared various cultivation systems-horizontal tubular, vertical stacked tubular, flat panel photobioreactors, and open raceway ponds, revealing major differences in capital costs and biomass productivity across configurations²⁰. The choice of algal strain has also been shown to influence economic outcomes, with species such as *Nannochloropsis* sp. exhibiting favourable productivity and robustness under specific cultivation conditions⁹. The harvesting of algal biomass remains one of the major contributors to operating costs in microalgae-based systems. The study by Fasaee et al. (2018) highlights that dewatering alone can constitute a major portion of the operating expenditure²¹. Further,

Xin et al. (2016) showed how integrating wastewater streams into cultivation could help offset nutrient costs and reduce overall production expenses²². However, most existing TEAs either focus on isolated components or assume idealized process conditions, with limited consideration of integrated strategies such as effluent recycling, the impact of energy subsidies, or the implications of scaling from pilot to industrial levels.

The present study addresses these challenges by integrating low-cost kaolin-based ceramic membrane filtration with a three-batch effluent recycle loop, aiming to reduce both CAPEX and OPEX while promoting resource efficiency. Four scenarios (S1 to S4) are considered to examine the effects of facility scale (1, 10, and 100 hectares) and the presence or absence of electricity subsidies on overall economic feasibility. The technical feasibility of microalgal biomass harvesting using low-cost kaolin-based ceramic membranes and effluent recycle system has been established through prior experimental work^{18,19}. However, before scaling up to pilot or commercial scales, it is essential to assess whether this integrated approach can offer cost-effective biomass production and ensure the economic viability of the proposed system.

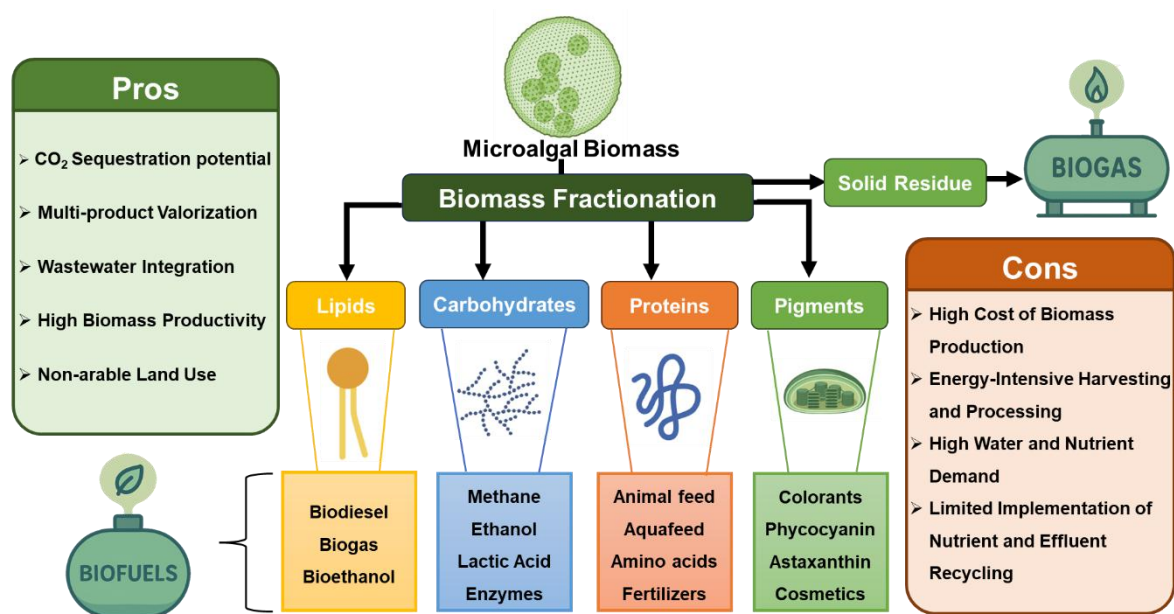


Fig. 1 Microalgal biorefinery showing biomass fractionation into valuable products with pros and cons

2. Methodology

All parameters for the definition of the scenarios were sourced from the earlier conducted experimental studies^{18,19}. In these studies, the authors evaluated the harvesting of *Monoraphidium* sp. KMC4 using an indigenously fabricated low-cost kaolin tubular membrane and then treated the harvested effluent using powdered activated carbon before using it for three batch recycle studies. When grown in standard BG11 medium, this strain gave a promising biochemical composition comprising 31.04% carbohydrates, 33.7% proteins, and 31.4% lipids along with high elemental carbon content (51.04%) and a calorific value of 22.14 MJ/kg, highlighting its potential for biofuel and bioproduct applications²³. Utilizing actual experimental data and assumptions drawn from the literature, this study focuses on the cultivation of *Monoraphidium* sp. KMC4 in open raceway ponds covering 1 hectare (ha) area in IIT Guwahati, India. The production follows a batch-harvest system, meaning that after each complete harvest, a new batch is initiated. In total, there are four batches in one cycle comprising of one fresh batch and three recycle batches. Overall, six cycles are analyzed in this study. The project's total duration is taken as 22 years, comprising a two-year period for construction and commissioning, followed by twenty years of production.

2.1. Process Description

The biomass production process for microalgal strain *Monoraphidium* sp. KMC4 is reported in our previous studies^{18,19}. A simplified scheme for the pilot plant evaluation is shown in Fig. 2. The process begins with preparation of culture medium using freshwater and essential nutrients (nitrates and phosphates). Approximately 60 m³ of medium was prepared per batch, with five such units installed to meet daily demand. The medium was delivered to a 1-hectare raceway pond system using a 150 m³/h feed pump operating continuously. A special absorber system introduces CO₂ to improve photosynthetic efficiency, while 1.74 kW paddle wheels maintain mixing to ensure even distribution of light and nutrients.

The system runs on natural illumination and ambient temperature, with biomass growth taking place over a 13-day cycle. A 10% volume loss due to evaporation was assumed for each batch, compensated by freshwater addition prior to each recycle stage to maintain growth conditions²⁴. Following cultivation, the algal broth is routed via a membrane filtration unit consisting of 40 housings, each containing 100 tubular membranes (6 m long, 25 mm in diameter), allowing for the energy-efficient separation of biomass from the culture media. The calculation of housings was done based on the obtained flux from our previous study¹⁸. The harvested biomass was stored in storage tanks, and the filtrate is treated with powdered activated carbon (PAC) (30 mg/L) in a static mixer to remove residual organics. The treated effluent was recycled to the culture medium preparation unit, where it was replenished with the required amount of nutrients and reused over three consecutive batch cultivation cycles. This step minimizes water consumption thereby enhancing system sustainability. A decanter centrifuge with a capacity of 100 m³/h is added downstream and the finished biomass is dried using a spray dryer (1 kWh/kg culture) to provide a storable product. This process flow serves as the foundation for the techno-economic evaluation under various scale and subsidy scenarios by facilitating effective nutrient usage, water reuse, and continuous biomass recovery.

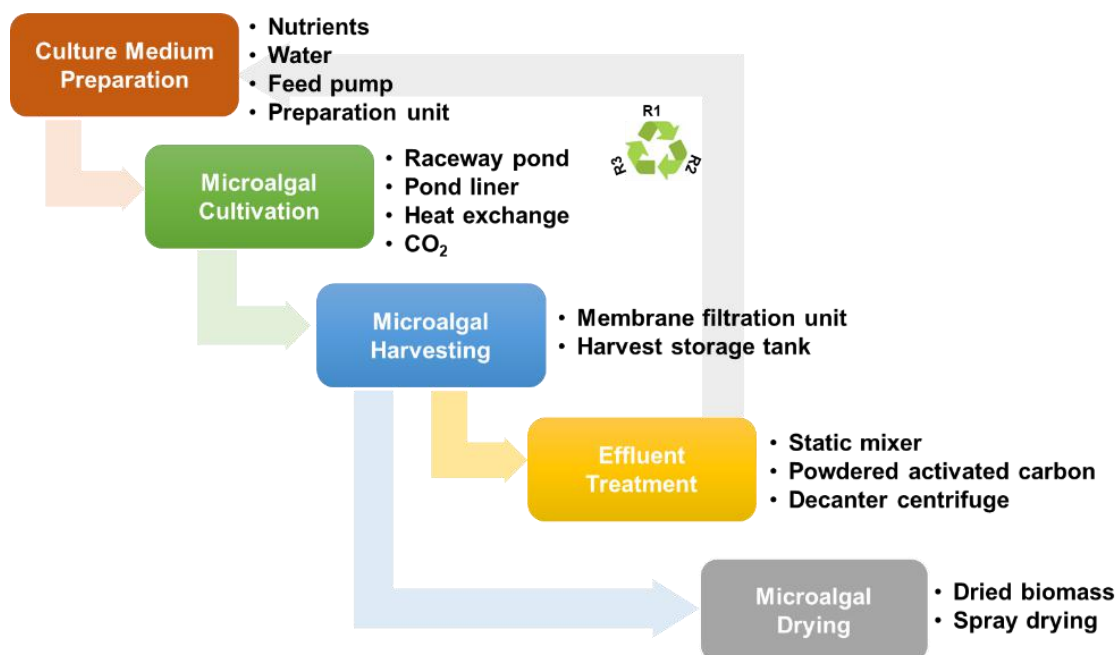


Fig. 2 Process flow diagram for microalgal biomass production

2.2. Scenarios

To evaluate the techno-economic performance of microalgal harvesting with low-cost kaolin-based ceramic membranes and a three-batch recycle system, four scenarios (S1-S4) were formulated. These scenarios investigate variations in scale, energy expenses, and operational configurations, using a raceway pond cultivation system located in Guwahati, India, with an annual biomass productivity of 81.29 t year⁻¹ (dry weight basis) for 1-hectare systems (S1 and S2), 812.9 t year⁻¹ (dry weight basis) for the 10-hectare facility (S3), and 8129 t year⁻¹ (dry weight basis) for the 100-hectare industrial-scale operation (S4).

Scenario 1 (S1) represents a small-scale microalgae production facility utilizing 1 hectare of raceway ponds and subsidized electricity. This scenario assumes access to treated microalgal effluent, along with basic infrastructure and energy-efficient membrane filtration for microalgal harvesting. The electricity subsidy plays a key role in reducing operational costs, making this setup financially feasible despite its small size. This scenario aims to assess how policy-driven support mechanisms can improve the financial outlook of microalgae production in decentralized or resource-constrained areas.

Scenario 2 (S2) depicts the same 1-hectare system as in S1, but with no utility subsidies. It serves as the baseline, capturing the actual cost of microalgae production under unsubsidized conditions. The lack of subsidies raises the burden of utility expenses, particularly the electrical costs associated with paddle wheel mixing, membrane filtration, and drying. This scenario demonstrates the economic challenges that small standalone systems face when operating in standard market conditions.

In Scenario 3 (S3), the facility is expanded to 10 hectares, corresponding to a medium-sized commercial microalgae production operation²⁵. The increased production capacity allows for the partial realization of economies of scale, even though electricity is still not subsidized. Equipment like harvesting unit, pumps, and drying systems are used more effectively, and capital and operating expenses per unit of biomass

start to decline. This setup aids in assessing the transitional stage between small pilot systems and full-scale deployment, as well as investigating the impact of scaling up without policy incentives.

Scenario 4 (S4) represents a full-scale industrial microalgae production system covering 100 hectares²⁵. The system gains from process integration, labour distribution optimisation, and large-scale procurement, all of which significantly lower the cost of production per unit. Even if no subsidies are assumed, economies of scale considerably improve profitability and financial sustainability. This scenario intends to show the long-term potential of microalgae-based systems when deployed at industrial scale and under standard operational conditions.

2.2. Process Economics Analysis

The hypothetical plant is located in Guwahati, Assam, India, so the relevant material costs and hourly wage rates are used. However, the economic evaluation is conducted in US dollars (\$) to facilitate easy comparison with existing literature. The costs are adjusted to the year 2024 based on Chemical Engineering Plant Cost Index. Only the primary nutrient components of the BG11 medium such as NaNO_3 and K_2HPO_4 were considered in the nutrient cost calculations, as they represent the major share of input costs. The minor constituents, including trace elements and micronutrients, were excluded due to their relatively negligible contribution to overall cost (<10%) and to simplify the economic model. The basic assumptions adopted for economic analysis are shown in Table 1, while Table 2 summarizes the biomass productivity of the process for the base case (S2), accounting for the expected reduction in performance (20-40%) typically observed when scaling up from lab to raceway pond systems^{9,19}. In this analysis, we have conservatively assumed 80% of the lab-scale productivity to reflect realistic operational performance at large scale.

Table 1 Basic assumptions and inputs defining the production conditions for the base case (S2)

Parameters	Value	Unit	Reference
Location	Guwahati, Assam, India	n.a.	n.a.
Raceway pond area	1	Ha	n.a.

Liquid velocity in pond	0.30	m s ⁻¹	26
Number of ponds	1	n.a.	n.a.
Raceway pond depth	30	cm	26
Growth period of one batch	13	Days	n.a.
Growth period of one cycle	55	Days	n.a.
Number of batches in one cycle	4	n.a.	n.a.
Number of cycles annually	6	n.a.	n.a.
Annual biomass production	81.29	Ton	n.a.
Electricity price	0.0876	\$/kWh	27
NaNO ₃ price	0.483	\$/Kg	28
K ₂ HPO ₄ price	1.20	\$/Kg	29
Water price	0.24	\$/1000L	30
CO ₂ price	0.233	\$/Kg	31
PAC price	0.24	\$/Kg	32

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Table 2 Productivity of the process for base case (S2)

	Fresh media	R1	R2	R3	Total
Culture density (g L ⁻¹)	1.24	1.21	1.108	0.968	n.a.
Biomass per batch (kg)	3690	3630	3325	2904	13549
Annual biomass production (Ton)	22.14	21.78	19.95	17.42	81.29

185 The total capital investment (TCI) or CAPEX for the plant is calculated by combining the direct fixed capital
186 (DFC) cost and working capital cost. The DFC includes direct costs, indirect costs, a contractor's fee, and
187 project contingency, with the latter two set at 5% and 10% of the combined direct and indirect costs,
188 respectively. Direct costs encompass the purchase of equipment, along with expenses for piping,
189 instrumentation, insulation, electrical systems, buildings, and yard improvements, which account for 40%,
190 15%, 6%, 12%, 15%, and 10% of the total equipment cost, respectively. Indirect costs cover engineering
191 and construction expenses, each representing 10% of the direct costs ³³.

192 The annual operating expenses (OPEX) include major utility expenditure (MUE), labour expenses, and
193 other costs such as maintenance, overheads, and contingencies. The MUE accounts for all essential
194 utilities required throughout the entire production process, from medium preparation to biomass drying.

The total production cost is the sum of total CAPEX and OPEX, and, the biomass production cost can be calculated by dividing the total biomass production by manufacturing price.³⁴ Detailed cost assumptions for the base case (S2) are presented in Table 3, while the assumptions for Scenarios 1, 2, and 3 are provided in Tables S1-3, S3-3, and S4-3, respectively.

The techno-economic analysis was extended to evaluate the performance across 10- and 100-hectares facility. For equipment's whose cost data were not available directly, the purchase cost was extrapolated using a standard scale-up formula (equation 1)²⁵. It applies either the six-tenths rule or equipment-specific scaling factors. In equation 1, cost B represents the projected cost of the equipment at the new scale (size B), while cost A corresponds to the known cost of the reference equipment operating at capacity size A. The exponent n is the scaling factor, which is dependent on the equipment type and are mentioned in the supplementary tables. This method ensures consistent and reliable cost estimation across varying plant sizes.

$$Cost\ B = Cost\ A. \left(\frac{Size\ B}{Size\ A} \right)^n \quad (1)$$

2.3. Process Profitability Analysis

The Net Present Value (NPV) is a key measure for assessing a project's potential profitability, calculated with a 7% discount rate³³ over a 20-year economic life. Depreciation was also calculated using the straight-line method over the plant's operational life of 20 years. A positive NPV suggests that the plant is likely to achieve financial gains over its lifetime, indicating economic feasibility and justifying the initial investment. Alongside NPV, payback time and Return on Investment (ROI) were calculated. To evaluate the project's profitability further, a market analysis was conducted to determine the minimum selling price (MSP) across four scenarios needed to achieve a positive NPV by the end of the project's life. The MSP was determined based on a zero net present value (NPV = 0), which reflects a break-even point over the plant's operational life. The construction period is set for two years, during which no revenues are

expected. A positive NPV from this analysis signifies that the investment is financially viable. The equation for NPV calculation³⁴ is as follows:

$$NPV = \sum_{t=0}^T \frac{R_t}{(1+i)^t} \quad (2)$$

where T represents the total project duration of 22 years, including 2 years for construction, t denotes the year of cash flow, R_t is the net cash flow in the year t, and i is the applied discount rate. The net cash flow accounts for both inflows and outflows-where inflows are primarily derived from product sales revenue, while outflows include total CAPEX, OPEX, and loan interest.

2.4. Process Sensitivity analysis

A sensitivity analysis was carried out to examine the influence of key technical and economical parameters on the overall financial performance of the microalgal biomass production system. In this approach one parameter was varied at a time, keeping all other parameters constant. This was done to see the individual impact of each parameter on the NPV. Parameters considered included financial factors such as discount rate (varied from 5% to 10%) and plant operational life (15 to 25 years), as well as cost-related variables such as biomass selling price (\$8-12/Kg), and utility and labour costs (adjusted by $\pm$ 20%). The discount rate and plant operational life were chosen as they directly affect the NPV and Minimum Selling Price (MSP), and are commonly varied in techno-economic analysis (TEA) studies. The biomass selling price reflects market uncertainty and commercialization potential, while utility and labor costs are major recurring operational expenses known to fluctuate due to local factors. The percentage in NPV was calculated for each parameter change to understand how sensitive the system is to variations. This helped to identify the key parameters that are responsible for the sensitivity of the process

Table 3 Basic price assumptions for Scenario 2 (S2)

Section	Capacity/Value	Price (\$)	Source
Culture medium preparation unit ^a	60 m ³	144553	31
Medium feed pump ^b	150 m ³ /h	45059	6
Raceway pond liner (PVC)	9.085 \$/m ²	100843	31
Paddle wheel	1.74 kW	24380	26
CO ₂ absorber or mixer	1 unit	69909	26
Heat exchange	620 kW	159920	35
Membrane filtration unit ^c	Length: 6 m, Diameter: 25 mm	358350	18
Harvest storage tank	Same as culture medium preparation unit	144553	31
Static mixer	Same as CO ₂ absorber or mixer	69909	26
Decanter Centrifuge ^b	100 m ³ /h	686615	6
Spray drying	1 kWh/kg culture	155980	21

241 ^a no. of units required: 5

242 ^b assuming working 24h daily

243 ^c Number of housings: 40, Tubes per housing: 100

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245 3. Results and Discussions

246 3.1. Total Capital Investment

The Total Capital Investment (TCI) for the microalgae production facility across four scenarios were evaluated by aggregating direct costs (DC), indirect costs (IC), and other costs (OC) for all the four processing stages: cultivation (raceway pond infrastructure), medium preparation (culture medium units), harvesting (centrifugation and filtration), drying and utilities (spray drying and auxiliary systems), as detailed in Table 4, S1-4, S3-4, and S4-4. In Scenario 1 (S1, baseline with subsidized electricity, 1 Ha), and 2 (S2, base case, 1 Ha), the TCI remains identical at \$7,692,269.47, with DC contributing \$4,782,573.24 (62% of TCI) and an MEC of \$1,960,071. The costs are distributed as 4.9% for cultivation, 41.2% for harvesting, 35.8% for medium preparation, and 18.1% for drying and utilities (Fig. 3). The high share of harvesting costs reflects the capital-intensive nature of equipment such as centrifuges and membrane filtration unit, which poses a significant challenge for small-scale facilities. Although S1 benefits from subsidized electricity, its TCI remains the same as S2, indicating that capital expenditures are not influenced by reductions in operational energy costs. This highlights the importance of developing more affordable and scalable harvesting technologies to improve the economic viability of small-scale microalgae production systems.

Scaling to 10 Ha in Scenario 3 (S3) raises the TCI to \$29,646,471.29, a 285% increase over S1, while Scenario 4 (S4, 100 Ha) raises the TCI to \$148,495,490.16, a 400% increase over S3 (Tables S3-5, S4-4). Both scenarios (S3 and S4) show a shifted cost distribution: 4.7% for cultivation, 47.8% for harvesting, 32.7% for medium preparation, and 14.9% for drying and utilities. These shifts highlight two key insights: first, harvesting costs increase significantly with biomass throughput due to greater infrastructure and energy demands; and second, medium preparation and utility systems benefit more from economies of scale, as their fixed costs are distributed over a larger production volume.

Table 4 Total CAPEX of Scenario 2

Factor	Value	Unit
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Direct investment cost	MEC	1	1960071	\$
	Installation	0.2	392014.2	\$
	Piping	0.4	784028.4	\$
	Instrumentation	0.15	294010.65	\$
	Insulation	0.06	117604.26	\$
	Electrical system	0.12	235208.52	\$
	Building	0.15	294010.65	\$
	yards improvement	0.1	196007.1	\$
	Service	0.2	392014.2	\$
	Land	0.06	117604.26	\$
	Total DC		4782573.24	\$
Indirect	Engineering and supervision	0.3 DC	1434771.972	\$
	Construction expenses	0.05 DC	239128.662	\$
	Total IC		1673900.634	\$
Other costs	contractor's fee	0.03 DC	143477.1972	\$
	contingency	0.08 (DC+IC)	516517.9099	\$
	Total OC		659995.1071	\$
	Total fixed capital		7116468.981	\$
	Lifetime		20	year
	Discount rate		7	%
	Depreciation		355823.4491	\$/year
	property tax		3558.234491	\$/year
	Insurance		2134.940694	\$/year
	Purchase tax		23096.84944	\$/year
	Total annual CAPEX		384613.4737	\$/year
Total CAPEX			7692269.474	\$

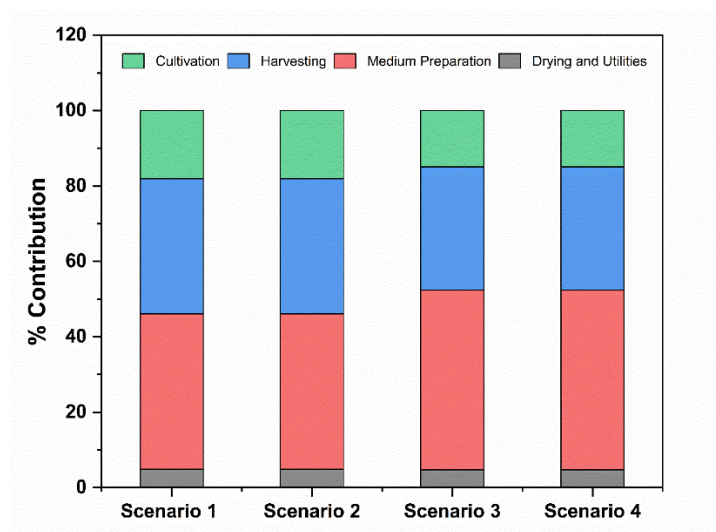


Fig. 3 Percentage contribution of different processing stages towards TCI for the four scenarios.

3.2. Operating Cost

274 The annual operating costs (OPEX) for the microalgae production facility across four scenarios were
275 determined by first calculating the primary utility cost (PUC), which aggregates expenses from materials
276 (e.g., NaNO_3 , water) and utilities (e.g., membrane filtration, heat exchangers), and then adding costs for
277 maintenance, operating supplies, labour, overheads, and contingency, as detailed in Table 5, 6, S1-5 to
278 S4-6. In Scenario 1 (S1, baseline with subsidized electricity, 1 Ha), the OPEX totals \$31,192.74, with a
279 PUC of \$13,129.70. Scenario 2 (S2, base case, 1 Ha) shows a higher OPEX of \$529,117.11, with a PUC
280 of \$459,119.28, reflecting increased utility demands without subsidies. Scaling to 10 Ha in Scenario 3
281 (S3) results in an OPEX of \$5,291,171.14 (PUC: \$4,591,192.78), while Scenario 4 (S4, 100 Ha) escalates
282 the OPEX to \$52,911,711.43 (PUC: \$45,911,927.81).

283 Fig. 4 shows the percentage contributions of individual cost components to AOC. It highlights the
284 significant variations in the primary contributor which is dependent on the mode of plant operation. The
285 graph illustrates the percentage contribution of various cost components to the total annual cost for four
286 microalgae production scenarios (S1 to S4), offering a clear comparison of how cost distribution changes
287 with subsidies and production scale. Scenario 1 (S1), which benefits from subsidized electricity,
288 depreciation is the major cost contributor, accounting for approximately 92% of the total annual cost. The
289 utility costs are almost zero, reflecting the significant reduction in operational expenses due to subsidies.
290 Other components such as labour (2.59%) and raw materials (2.92%) contribute only a small portion,
291 highlighting the cost-saving benefits of subsidies for small-scale facilities. In contrast, scenario 2 (S2),
292 which does not get any subsidies, shows a different cost pattern. Here, the utilities make up about 49%
293 of the total cost, while depreciation is about 42%. The labour costs stay low at 1.18% and other costs
294 such as maintenance and contingency are also relatively small. This shows how expensive utilities can
295 become when subsidies are not available. As the production scale increases to 10 hectares in scenario 3
296 (S3) and 100 hectares in scenario 4 (S4), the graph shows a noticeable shift towards higher operational
297 expenses. The utility costs become the largest contributor of the total cost, reaching 65% in S3 and 73%
298 in S4, indicating the growing impact of scaling on utility costs. Also, the proportional contribution of

depreciation declines with scale, from 22% in S3 to 12% in S4, indicating economies of scale in capital expenditure. The labour costs remain nearly constant across all scenarios, contributing approximately 2%, indicating that labour expenses do not grow significantly in relation to production size. Other costs, such as maintenance, factory expenses, and contingencies, fluctuate slightly but remain minor components of the total cost, with a slight increase at larger scales.

Table 5 Primary Utility Cost for scenario 2

Unit	Price (\$/ year)
<u>Process Units</u>	
Medium Preparation unit	126.144
Feed pump	1261.44
Paddlewheel	1207.19
Heat exchanger	430151.04
Centrifuge	6307.2
Membrane filtration unit	840.96
Spray drying	7095.6
<u>Material input</u>	
NaNO ₃	8017.92
K ₂ HPO ₄	576
Water	2232
CO ₂	1264.89
PAC	38.88
Total	459119.27

Table 6 Total OPEX of Scenario 2

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	Factor	Value	Unit
Materials and Utilities	1 PUC	459119.2781	\$/year
maintenance	0.04 PUC	18364.77112	\$/year
Operating Supplies	0.004 PUC	1836.477112	\$/year
General plant overheads	0.55 (labour + maintenance)	16040.62412	\$/year
Contingency	0.05 PUC	22955.9639	\$/year
Labour	3 full time labours	10800	\$/year
Total annual OPEX		529117.1143	\$/year
Total OPEX cost		6349405.372	\$

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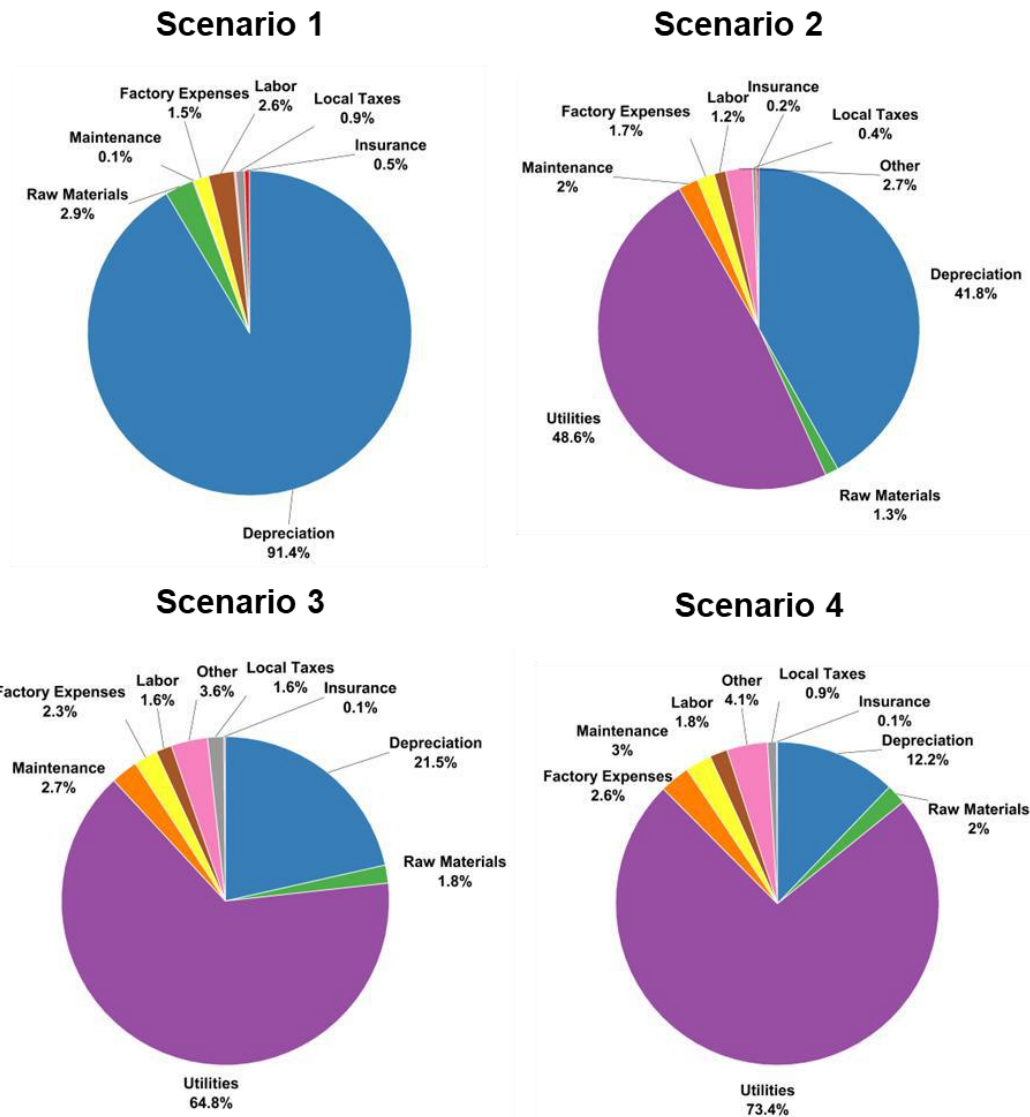


Fig. 4 Percentage contribution of various components towards AOC for the four scenarios

3.3. Profitability Analysis

The main revenue of the microalgal biomass production system across the four scenarios comes from the sale of biomass, with annual biomass output increasing significantly as the facility scales up. The detailed summary of the economic performance indicators such as capital investment, annual operating costs, net profit, return on investment, payback time, and NPV of the different scenarios is highlighted in Table 7. In addition, Fig. 5 shows the relationship between production sale and unit production cost across the four scenarios. As the production capacity increases, biomass output rises substantially while the cost per kilogram of biomass decreases.

The economic assessment of microalgae production across four scenarios (S1-S4) shows that scale and subsidies have a significant impact on viability. With scale, total capital investment rises dramatically, from \$7.69 million in S1 and S2 to \$29.65 million in S3 and \$148.5 million in S4. In contrast, operating costs vary more sharply in S1 because of an electricity subsidy that keeps its OPEX incredibly low at \$0.03 million, compared to \$0.53 million in S2, \$5.29 million in S3, and \$52.91 million in S4. The stacked bar chart clearly shows that while CAPEX rises with scale, operational efficiencies at larger capacities help in controlling the relative increase in OPEX (Fig. 6). The cost-competitiveness of biomass production was determined by comparing the net unit production cost with the minimum selling price (MSP), which represents the price point where total revenues equal overall costs, resulting in a NPV of zero. Despite higher absolute costs on a larger scale, operational efficiencies at higher capacities help to lower per-unit prices. Net unit production costs are lowest in S1 (\$5.12/kg) and S4 (\$7.50/kg), with S2 costing the most at \$11.24/kg. When compared to the minimum selling price (MSP) required to achieve zero NPV, larger-scale scenarios (S3 and S4) demonstrate improved market competitiveness, with S4 showing the lowest MSP at \$8.23/kg (Fig. 6). The financial performance of each scenario was further evaluated through net profit and NPV. The S4 stands out with a \$27.78 million net profit and a highly favourable NPV of \$145.78 million at a discount rate of 7%. In contrast, S2 and S3 exhibit negative NPVs, indicating that they are not financially viable under present assumptions in the absence of policy or price intervention. The S1, despite its modest size, generates a positive NPV of \$0.28 million, owing mostly to subsidized utility costs and reduced OPEX (Fig. 6). Long-term viability was also evaluated using Return on Investment (ROI) and Payback Time. With an 18.7% ROI and a 5.3-year payback period, S4 provides the highest financial return. The S1 and S3 have moderate ROIs of 9.79% and 9.17%, respectively, with payback periods around 10 years (Fig. 6). With a weak ROI of 3.31% and a payback period greater than 20 years, S2 is not commercially appealing without additional optimization or financial support.

Several techno-economic analyses (TEAs) from previous studies provide valuable context to evaluate the performance of our integrated microalgae cultivation system (Table 8). In terms of cultivation system

configuration and economic outcomes, the current study can be compared to the TEA presented by Schipper et al. (2021), which serve as valuable reference in microalgae process optimization²⁰. They evaluated various algal cultivation systems including horizontal tubular, vertical stacked tubular, flat-panel photobioreactors (FP-PBRs), and open raceway ponds (ORPs), concluding that ORPs had the lowest investment and operational costs per unit biomass. While FP-PBRs provided greater biomass quality and areal productivity, they had much higher capital costs, making ORPs more suitable for large-scale applications. These findings resonate strongly with the present study, where ORP-based cultivation with integrated ceramic membrane harvesting and three-cycle effluent reuse yielded a net unit production cost of \$7.50/kg in S4 (100 ha). The cost-effectiveness and scalability shown here support Schipper et al.'s conclusion that ORPs are the most promising platform for bulk biomass production.

Tredici et al. (2016) investigated the use of GWP®-II photobioreactors (PBRs) at a small scale and reported a biomass production cost (BPC) of \$13.76/kg³⁵. Their high operational expenditure (\$383,068/year) and capital costs (\$112,398/year) limited the scalability of the system. Our results show a reduction in costs at the industrial scale due to the use of low-cost kaolin-based ceramic membranes and process integration, yielding a BPC of \$7.50/kg in S4. Similarly, Acien et al. (2012) reported a BPC of \$89.01/kg for tubular PBR systems used to cultivate *Scenedesmus almeriensis*, indicating that despite the high control offered by PBRs, their capital intensity severely impacts economic viability³⁶.

In contrast, Branco-Vieira et al. (2020b) demonstrated favourable economics in a 15.2-hectare open raceway pond (ORP) system that produced 1,811 tonnes of biomass annually, achieving a BPC of \$2.29/kg³⁷. This was primarily enabled by large-scale land use and sunlight availability, aligning with our findings that scalability is key to cost reduction. Huang et al. (2021) studied flat-panel PBRs and reported wide range in BPC (\$3.00–26.67/kg), with productivity of ~36.7 t/ha/year, indicating the impact of geographical and design-specific factors³⁸. While these results are competitive in some configurations, their sensitivity to design parameters makes scaling challenging. These results reinforce the cost advantage of our large-scale ORP system.

Other studies have also explored cost optimization through resource reuse. Xin et al. (2016) employed a multi-layer PBR with centrate wastewater integration and achieved a break-even biodiesel price of \$2.23/gal²². This aligns with our approach of using treated effluent in recycled cultivation loops, which significantly reduced nutrient and water consumption²². Fei et al. (2015) presented a promising cost-effective method using heterotrophic cultivation with volatile fatty acids, achieving a biodiesel production cost of \$2.30 per gallon³⁹. Although this technique increases lipid productivity, the dependency on external organic carbon and controlled fermentation processes may pose challenges for large-scale deployment. On the other hand, the current work uses open raceway ponds for autotrophic outdoor cultivation while still achieving favourable economics through operational optimization.

Overall, these comparisons highlight the novelty and competitiveness of the present study. By using scalable raceway pond cultivation with low-cost ceramic membranes and multiple cycles of reuse, the proposed set-up differs from traditional TEA configurations. It also aligns well with the ongoing shift towards sustainable algae-based production under circular bioeconomy.

Table 7 Economic Analysis Results of the Four Scenarios

Metric	S1	S2	S3	S4
Total Capital Investment (million US\$)	7.69	7.69	29.65	148.50
Annual Operating Cost (million US\$)	0.03	0.53	5.29	52.91
Biomass Sale (main revenue) (million US\$)	0.81	0.81	8.13	81.29
Net Unit Production Cost (NUPC) (US\$/kg)	5.12	11.24	8.48	7.50
Minimum Selling Price (US\$/kg)	8.65	14.77	9.95	8.23

Net Profit (after taxes) (million US\$)	0.75	0.25	2.72	27.78
Return on Investment (%)	9.79	3.31	9.17	18.70
Payback Time (years)	10.2	>20	10.9	5.3
NPV (@ 7.0% discount rate) (million US\$)	0.28	-4.99	-0.85	145.78

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392 **Table 8** Comparison of Techno-Economic Performance of Microalgal Biomass Production System

393 Across different studies

Sl. No.	Microalgae	Cultivation mode	Harvesting Method	Scale	Productivity (t/year)	Cost Metric	Value	Key Insights	Ref.
1.	<i>Not specified</i>	ORP, Flat panel, Tubular PBRs	Flocculation / Centrifuge	1-10 ha	Varies	BPC	Wide range	Compared multiple systems; ORPs found most cost-effective at scale.	²⁰
2	<i>Tetraselmis suecica</i>	GWP®-II PBR	Centrifugation	Pilot (PBR)	36	BPC	\$13.76/kg	High CAPEX (\$112K) and OPEX (\$383K); low scalability	³⁵
3	<i>Scenedesmus almeriensis</i>	Tubular PBR	Filtration	Lab	Not reported	BPC	\$89.01/kg	High cost and low scalability	³⁶
4	<i>Phaeodactylum tricornutum</i>	ORP	Centrifugation	15.2 ha	1,811	BPC	\$2.29/kg	Co-product synergy with biodiesel; favourable economics at scale	³⁷
5	<i>Chlorella</i> sp.	Multi-layer PBR	Flocculation	Pilot	Not reported	Break-even Biodiesel	\$2.23/gal	Wastewater reuse reduced nutrient costs	²²
6	<i>Chlorella protothecoides</i>	Heterotrophic	Dewatering + Extraction	Pilot	Not reported	Biodiesel Cost	\$2.30/gal	High lipid yield but relies on costly organic carbon inputs	³⁹
7	<i>Chlorella vulgaris</i>	Flat panel PBR	Sedimentation	Pilot	~36.7/ha	BPC	\$3.00–26.67/kg	High-cost variability; strong design dependency.	³⁸
8	<i>Monoraphidium</i> sp. KMC4	ORP + Effluent Recycle	Ceramic Membrane Filtration + Effluent Treatment using PAC	100 ha	8,129	NUPC	\$7.50/kg	High net profit (\$27.78M), payback 5.3 years; scalable and resource-efficient	This study

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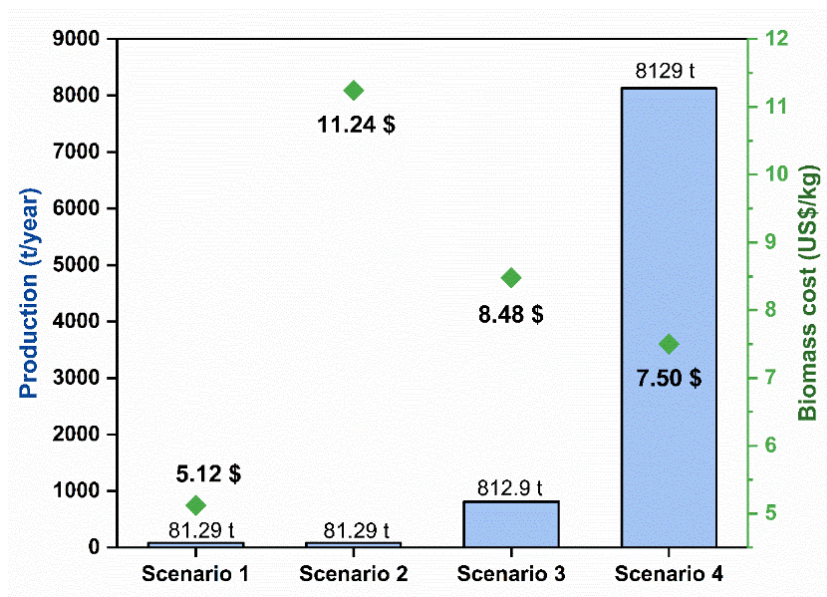


Fig. 5 Microalgae biomass production and corresponding unit production cost across the four scenarios

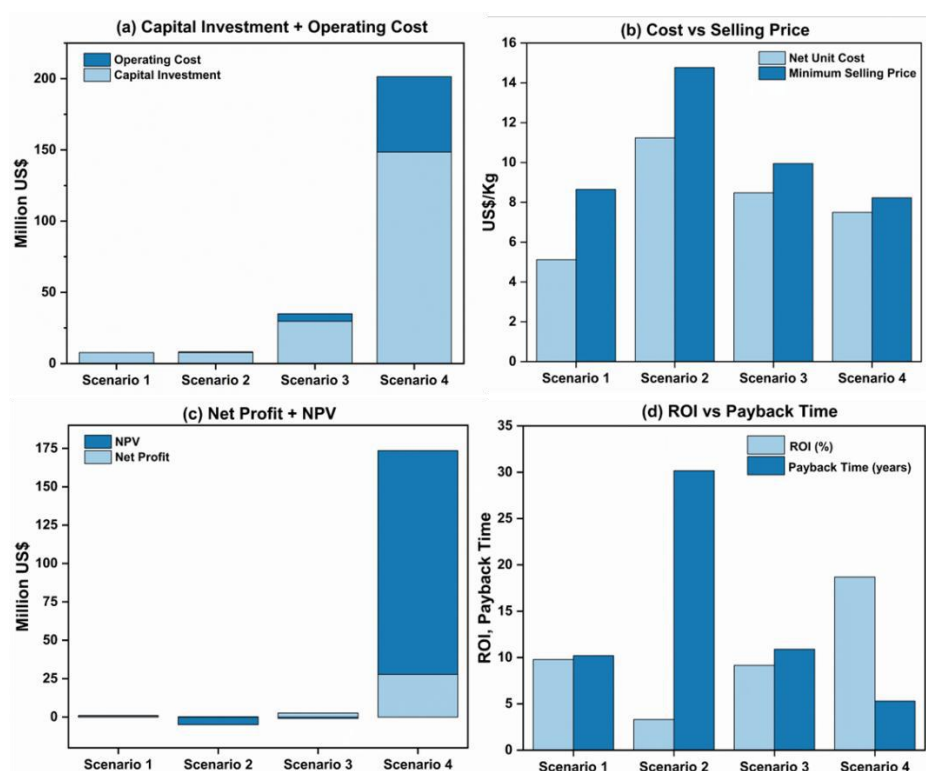


Fig. 6 Comparative techno-economic metrics for four microalgae production scenarios (S1-S4). The subplots illustrate (a) capital investment and operating cost, (b) net unit production cost versus minimum selling price, (c) net profit and net present value (NPV), and (d) return on investment (ROI) vs payback time.

3.4. Sensitivity Analysis

To evaluate the robustness of the microalgae production system under changing economic conditions, a sensitivity analysis was conducted by varying five critical parameters, such as discount rate, plant life, microalgal biomass selling price, utility cost and labour cost across the four scenarios (Fig. 7). Using a 7% discount rate³³ and a 20-year plant life, the base NPVs derived were \$0.28 million (S1), -\$4.99 million (S2), -\$0.85 million (S3), and \$145.78 million (S4). The following parameters were individually adjusted within realistic bounds: discount rate (5-10%), plant life (15-25 years), selling price (\$8,000-\$12,000/ton), and utilities and labour costs ($\pm 20\%$), while others remained constant.

The discount rate, which represents the time value of money and investor risk, has a considerable impact on NPV across all scenarios, with the size of change heavily influenced by scale and capital intensity. In S1, the NPV increased by 492.8%, from \$0.28 million to roughly \$1.69 million, when the discount rate was lowered from 7% to 5%. This sharp rise is due to the higher present value of future cash flows in a capital-intensive system with low operational expenses as a result of electricity subsidies. On the other hand, NPV decreased by 550.4% to -\$1.28 million when the discount rate was raised to 10%, highlighting the fragility of small-scale, subsidy-reliant systems in unfavourable financial conditions (Fig. 7a). S2 and S3 showed a $\pm 10.55\%$ change in NPV when the discount rate was varied, mainly because their capital and operating costs were more evenly distributed (Fig. 7b and 7c). The scenario S4, even though it operates at a much larger scale, showed a similar percentage change, but the absolute change in NPV was much higher due to its higher base value (Fig. 7d). These results suggest that having access to low-interest financing or financial support is especially important for smaller facilities to stay economically viable over the long term.

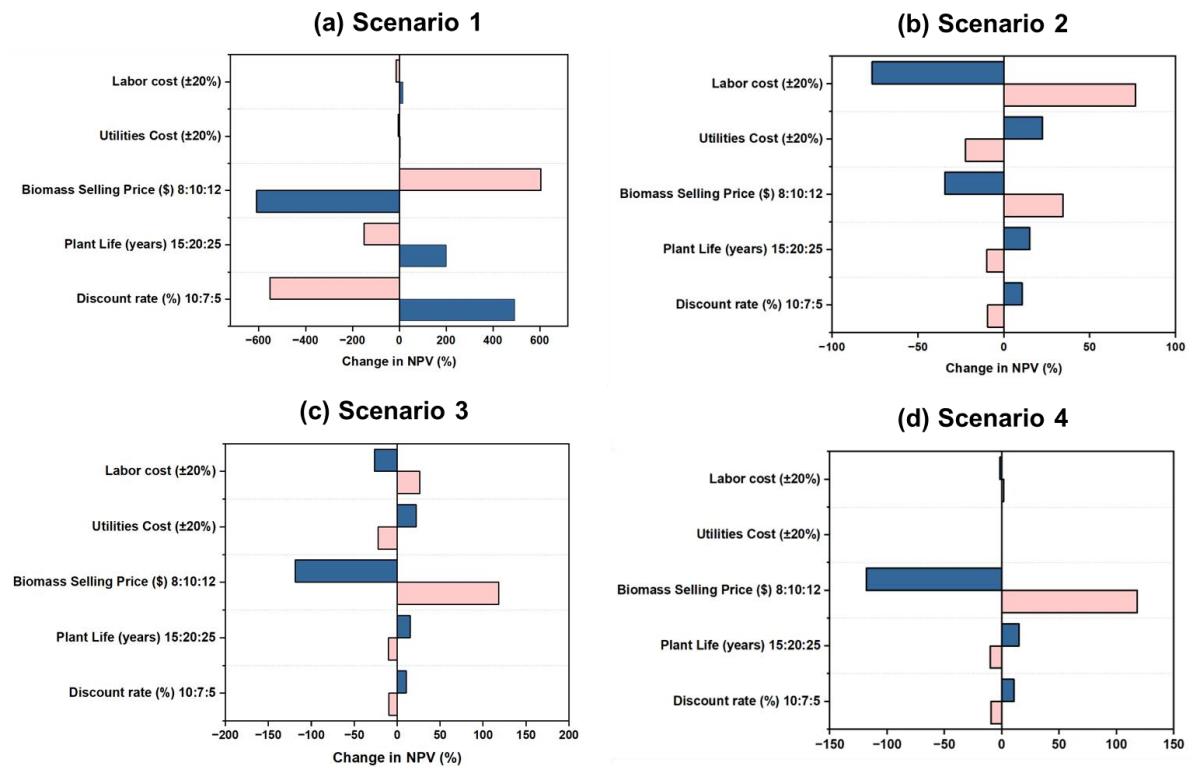


Fig. 7 Percentage variation in NPV compared to the base conditions for different technical and economical parameters for (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4

The plant operational life, which determines the period of income generation and capital cost recovery, was also identified as a significant factor, particularly for S1. The NPV increased by 54% when the plant life was extended to 25 years, lowering the yearly depreciation from \$384,613 to \$307,691. Reducing plant life to 15 years raised depreciation to \$512,818, resulting in a 394% decrease in NPV, with the value remaining marginally positive at \$0.06 million (Fig. 7a). This demonstrates that in small-scale systems such as S1, how long the plant operates has a considerable impact on the economic outcome because capital expenditure is a major factor. The changes in NPV for Scenarios 2 and 3 were relatively moderate ($\pm 15\%$ and $\pm 10\%$), as operational costs make up a larger portion of the total expenses compared to capital costs (Fig. 7b and 7c). Scenario 4 (S4) also showed a $\pm 15\%$ change in NPV, meaning that even at large scale, a longer plant life can still improve profitability (Fig. 7d). Overall, running the plant for a

greater duration of time helps spread out capital expenses and makes the project more financially secure, especially when there is a large capital investment or subsidies involved.

Among all parameters evaluated, the biomass selling price had the greatest impact on the project's economic outcome. In Scenario 1 (S1), the NPV dropped by 607.7% when the selling price was lowered to \$8,000 per ton, yielding a negative value of -\$1.45 million. However, the NPV increased by 605.2% to \$2.01 million when the price was hiked to \$12,000 per ton (Fig. 7a). This significant change occurred because small-scale systems like S1 had limited revenue to begin with, thus, even minor changes in selling price create substantial shifts in profitability. Changing the selling price in scenarios 2 and 3 resulted in a change of $\pm 34.4\%$ and $\pm 118.2\%$ NPV, respectively (Fig. 7b and 7c). The NPV for the large-scale scenario 4 (S4) also showed a variation of $\pm 118.2\%$, ranging from -\$26.41 million to \$307.58 million (Fig. 7d). This demonstrates that all systems, particularly large ones like S4, are highly sensitive to the selling price of biomass.

The impact of utility costs, which include water, electricity, and process heat, on NPV varied according on the facility's size and the availability of subsidies. Utility costs had a negligible impact on NPV in scenario 1 (S1) due to the subsidized electricity, which kept operating costs low (Fig. 7a). However, the NPV was significantly more sensitive in S2 and S3, where there were no subsidies available and utility costs accounted for a significant portion of overall operating expenses (49% in S2 and 65% in S3). For S2 and S3, the NPV changed by $\pm 22.4\%$ and $\pm 22.1\%$, respectively, in response to a $\pm 20\%$ change in utility costs (Fig. 7b and 7c). This means that changes in utility prices can significantly impact the profitability of these systems. In S4, increases in utility costs had a minimal impact ($\pm 0.1\%$) due to the large production scale, which spreads expenses over a larger output, making them less significant (Fig. 7d). This demonstrates that subsidies are extremely beneficial for small facilities, whereas large facilities benefit from economies of scale, which shield them against variations in utility costs. For medium-scale projects like S3, either increasing the production scale or getting utility subsidies would be important to make the system economically viable.

The impact of labour costs on NPV reduced as facility size increased. A change of $\pm 20\%$ in labour expenses resulted in a $\pm 14.4\%$ change in NPV in S1 (Fig. 7a). The S2 had a greater impact of $\pm 76.6\%$, indicating that small, unsubsidized facilities are more sensitive to labour cost fluctuations. This is due to the fact that, in the absence of subsidies and labour, utilities account for a sizable amount of overall operating costs (Fig. 7b). In S3, the sensitivity to labour cost decreased to $\pm 26.4\%$ (Fig. 7c), whereas in large-scale S4, it was very low at $\pm 1.57\%$ (Fig. 7d). This reduced impact in S4 is most likely the result of automation, process efficiencies, and economies of scale, all of which improve labour productivity. These findings highlight the need of using labour efficiently in small and medium-sized facilities. Using methods like automation, training workers to handle multiple tasks, or sharing workers between units can help lower costs and improve the overall performance.

Conclusions

This study demonstrates the techno-economic potential of integrating ceramic membrane harvesting with effluent recycling for microalgae production at varying operational scales. The results show that scaling up from small to large-scale systems significantly boosts financial performance, emphasizing the importance of scale for cost-effectiveness. While policy incentives remain essential for small scale facilities, industrial-scale operations benefit from lower per unit capital costs and more efficient operations, allowing them to achieve profitability independently. The use of ceramic membrane in this study ensures chemical-free biomass recovery, producing clean effluent that can be treated with powdered activated carbon (PAC) and reused in subsequent cultivation cycles. This closed-loop approach significantly reduces water and nutrient demand, aligning the system with circular bioeconomy principles.

The future work will focus on evaluating the environmental impact of the system through life cycle assessment (LCA) to better understand its sustainability. Additionally, exploring the valorization of microalgal biomass into multiple value-added products like biofuel, carbohydrates, proteins, pigments, and nutraceuticals could improve overall profitability of the system. Also, creating economic models

suitable to specific regions will enhance scalability and adaptability of such systems in diverse geographical locations and conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supporting Information

Equipment cost breakdowns, process assumptions and supplementary tables for Scenarios 1, 3 and 4

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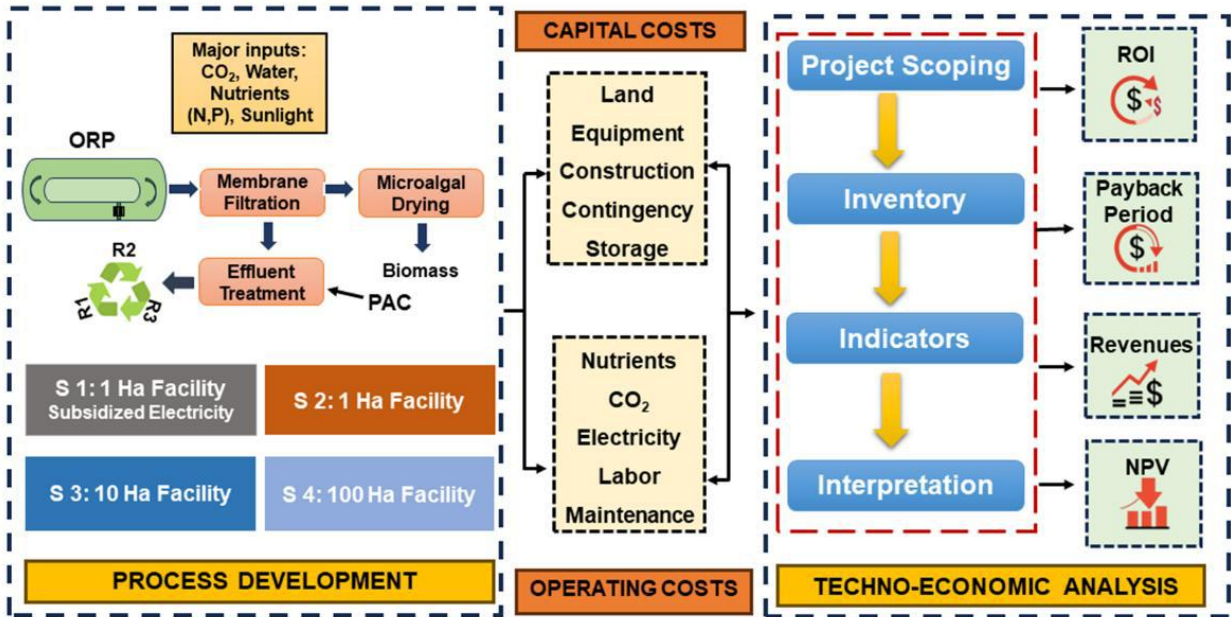
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