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Beyond tradition: charting a greener future for cassava starch industry using multi-criteria decision-making

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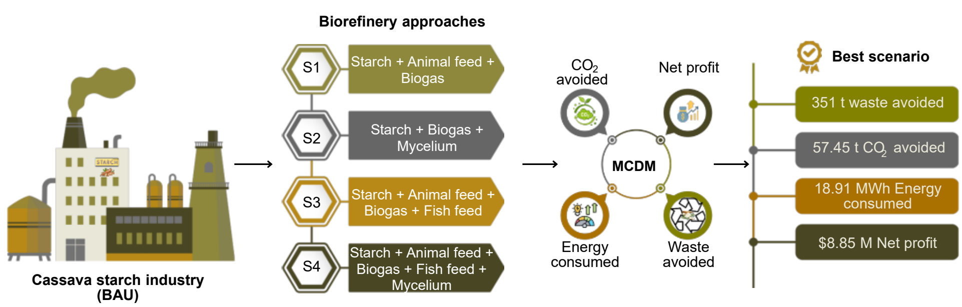
HIGHLIGHTS

- ➢ Cassava starch plant uses 4.58 MWh to process 75 t of cassava root.
- ➢ Best biorefinery was identified using decision-making on energy, profit, emission, and waste.
- ➢ Global warming potential of the best biorefinery scenario was -434 kg $CO_{2eq./t}$ root.

Best biorefinery scenario led to 18.91 MWh, USD8.85 M profit, 350 t waste avoided, and 57.45 t CO_2 avoided.

GRAPHICAL ABSTRACT



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ABSTRACT

Cassava, a staple food crop, is widely used for starch production, but its inconsistent supply, price volatility, and substantial waste generation pose challenges to the cassava industrial market's growth. This study aims to identify a sustainable biorefinery pathway by optimizing conventional cassava starch plants (business-as-usual, BAU) for economic and environmental benefits. Four scenarios were evaluated: animal feed from peel waste (Scenario 1), fungal protein from thippi waste (Scenario 2), fish feed from digested wastewater (Scenario 3), and conversion of all waste streams into animal feed, fish feed, and fungal protein (Scenario 4). Scenario 4 emerged as the best pathway using the multi-criteria decision-making (MCDM) approach, with a performance score of 0.282. Despite the highest energy consumption (18.91 MWh), Scenario 4 was favored for producing four value-added products alongside starch, yielding the highest profit at USD 8.85 million. In contrast, profits for BAU, Scenario 1, Scenario 2, and Scenario 3 were 1.91, 2.30, 5.01, and USD 8.79 million, respectively. Waste valorization in Scenarios 1, 2, 3, and 4 resulted in CO_2 avoidance of 36.5., 42.6., 21.7, and 57.45 t $CO_{2eq.}$, respectively. However, producing value-added products increased energy consumption by 13, 73, 7, and 74% compared to BAU (4.58 MWh). The global warming potential analysis showed negative values for scenarios 2 and 4, at -436 and -434 kg $CO_{2eq.}$/t root, respectively. This study highlights the potential of a biorefinery approach for sustainable cassava starch production, providing insights for future research and policy development.

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Contents

Abbreviations

MCDM	Multi-criteria decision-making
BAU	Business-as-usual
COD	Chemical oxygen demand
AHP	Analytical hierarchy process
LCA	Life cycle assessment
LCI	Life cycle inventory
GWP	Global warming potential
CI	Consistency ratio
CR	Consistency index

1. Introduction

Cassava (*Manihot esculenta*) is a staple crop with significant economic value, particularly due to its high starch content. It is extensively cultivated for its role in various industrial processes, where it serves as a primary source of starch. Additionally, cassava is an important raw material in the production of biofuels and serves as a key component in animal feed formulations. Cassava is also a primary food source for over 800 million people and is the third largest carbohydrate source in the tropics (Narayanan et al., 2019). Global cassava production was about 314 million tons in the year 2021, and a major share (~91%) of it came from African and Asian countries (FAO, 2021). In terms of productivity, India is ranked 4th (20.96 t/ha) against the global average of 11.08 t/ha (FAOSTAT, 2019) (**Fig. 1**). Southern states of India, including Tamil Nadu, Andra Pradesh, and Kerela, dominate cassava production and contribute about 96% of total cassava production in India (Prakash et al., 2022). About two-thirds of cassava is used for starch production, and the remaining is consumed as food in India (Prakash et al., 2022).

Cassava starch is widely preferred for its purity and viscosity with wide applications in the textile, paper, and food industries (Mwizerwa et al., 2017). The starch production process involves several steps, including washing, peeling, cutting, rasping, water addition, filtration, sedimentation, and drying (Wang et al., 2022). Although cassava starch is a versatile feedstock used in the production of bioethanol, sugars, fumaric acid, volatile fatty acids, and other bioproducts, the industry encounters numerous challenges (Edama et al., 2014). The most pressing challenge facing the cassava starch industry is the volatility in the price of raw cassava roots. For instance, in 2024, the cost of cassava ranged between 0.12 – 1.02 USD/kg (10-85 ₹/kg) (IndiaMART, 2024), which fluctuates ca. 88%. This price instability poses significant difficulties for the industry, affecting both production costs and overall profitability. Moreover, the generation of substantial quantities of solid and liquid waste during cassava starch production exacerbates environmental concerns if not managed appropriately. Nonetheless, implementing biorefinery techniques to repurpose these wastes can enhance sustainability within the cassava starch industry by reducing environmental impact and creating additional value from by-products (Costa et al., 2022).

Biorefineries are crucial in facilitating the production of various products from biomass, which significantly helps in improving the process economics and lowering the carbon footprint. With a high starch content of 60% and the associated production of solid and liquid wastes, the adoption of a biorefinery approach becomes a more viable option for cassava (Deng et al., 2023a). Potential value-added products derived from the cassava starch industry include biogas, succinic acid, ethanol, maltose, and other organic acids (Andrade et al., 2022). The recovery of these products from cassava wastes not only brings economic benefits but also aids in mitigating the carbon footprint.

Evaluating the economic gain and ecological impacts caused by adopting cassava biorefinery pathways is essential for comprehending the overall advantages. However, no research has yet tackled this issue. Most of the studies have investigated either techno-economic analysis or life cycle assessment (LCA) in an isolated context (**Table 1**). The literature also revealed that the focus has been primarily on energy products, neglecting the potential of bioproducts that have significant market demand. Additionally, numerous factors affect the choice of optimal pathway selection, such as raw material cost, processing methods, energy consumption, environmental impact, carbon avoidance, and net profit, which need to be considered while gauging different biorefinery pathways. The multi-criteria decision-making (MCDM) approach can be employed to analyze cassava biorefinery pathways based on these parameters and identify the best pathway (Torkabadi et al., 2018).

Previous studies have reported the use of MCDM to assess the repurposing potential of existing pulp mills as wood-based biorefineries (Martinkus et al., 2019). These studies incorporated economic, environmental, and social metrics, which helped identify optimal locations for converting existing pulp mills into integrated biorefineries. Further, the complexity of producing energy from agricultural wastes due to multiple social, economic, and environmental criteria was analyzed by a hybrid MCDM model to rank biomass alternatives for optimal bio-oil yield (Dhanalakshmi et al., 2022). However, previous studies have failed to identify the optimal pathway for a cassava biorefinery plant using MCDM

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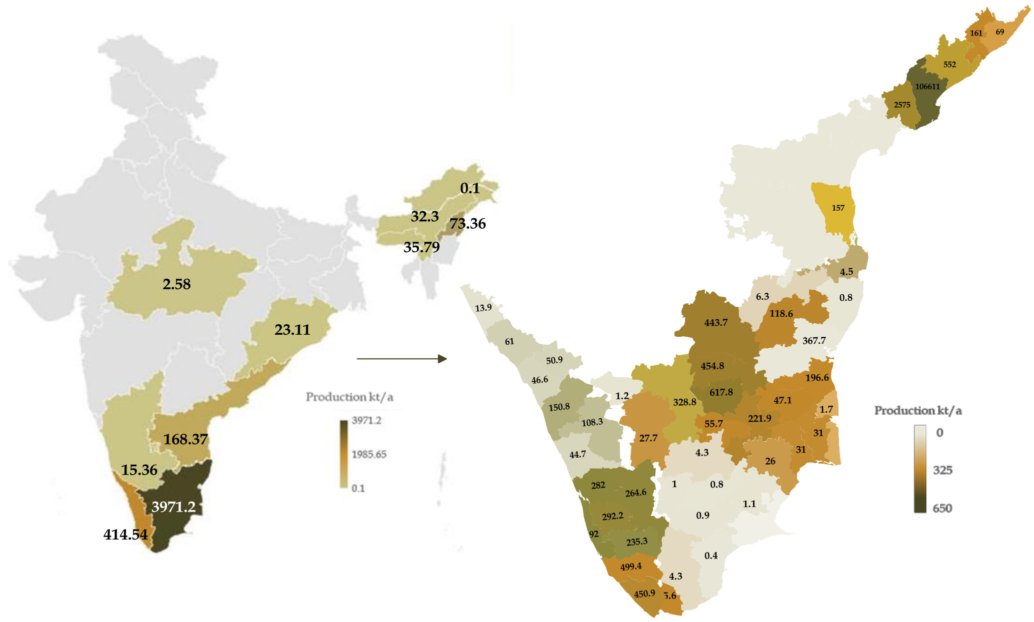

Fig. 1. Heatmap distribution of cassava production in India for the year 2021–2022 (APEDA, 2022). The gray color stands for no production in that region, while cream, orange, and green show a low, medium, and high number of productions, respectively, in a particular state.

in terms of economic, environmental, and technical perspectives. This study aims to find an optimal biorefinery pathway for a cassava processing plant by implying an MCDM approach *via* four alternative pathways. The objective of the study includes (i) Estimating and analyzing the energy consumption pattern of various pathways, (ii) determining the net profit and CO_2 avoidance of all the scenarios, and (iii) identifying the best biorefinery pathway using multi-criteria decision-making.

2. Methodology

2.1. Scenario description

The scenarios were evaluated based on the data from an existing cassava starch plant operating in Salem, Tamil Nadu, India. The industry functioning at 75 t/d capacity was considered in the business-as-usual (BAU) scenario. The current operations were altered using four pathways, including the production of animal feed, fungal protein, and fish feed (Fig. 2). A detailed description of the scenarios is given below:

- *BAU:* This scenario considers the co-production of starch, biogas, and animal feed. Cassava starch is produced using the conventional method, with thippi waste converted into animal feed, while the peel waste is left untreated. Additionally, the biogas produced from cassava wastewater is utilized as an energy source for electricity generation.

- *Scenario 1:* This scenario also considers the co-production of starch, biogas, and animal feed. However, unlike the BAU scenario, where the peel waste is left untreated, this scenario involves converting peel waste into animal feed in addition to the other operations involved in BAU.

- *Scenario 2:* This scenario considers the co-production of starch, biogas, and fungal protein. In this scenario, unlike the BAU approach, thippi waste is utilized as a substrate to produce fungal protein mycelium, which is applicable in sustainable food industries.

- *Scenario 3:* This scenario considers the co-production of four products: starch, biogas, animal feed, and fish feed. This scenario includes all the operations involved in the BAU, with additional usage of digested wastewater for microalgal culture and conversion of microalgal biomass to fish feed.

- *Scenario 4:* This scenario considers the co-production of four products: starch, biogas, animal feed, fungal protein, and fish feed. All waste streams are converted into value products: peel waste is transformed into animal feed, thippi waste into fungal protein, wastewater is utilized for biogas production, and digested wastewater is used for microalgal culture to produce fish feed.

2.1.1. Business as usual

A conventional cassava starch plant operating in Tamil Nadu, India was considered in this study with a processing capacity of 75 t/d cassava root. The cassava root density (≥810 kg/m^3) was checked, thus ensuring the quality of the root for starch production. In the process, roots are washed with an equal amount of water (1:1) and peeled. The peeling process produces about 23% of peel waste from cassava roots. The peeled cassava roots were crushed to a finer size (<1 mm) and mixed with water (about three times the quantity of peeled roots). The ground mixture was filtered, leaving 50% of thippi as residue, which was further dried to obtain cattle feed (30% per t root), while the filtered extract was called starch milk. This filtered starch milk was allowed to settle in the sediment basin with a maximum residence time of 3 h. Following this, the resultant wet starch was sun-dried until its moisture content reached about 25%.

Finally, the wastewater produced during the starch production was processed in an anaerobic digester of volume 147.5 m^3, which can process 118 m^3 of wastewater daily. The characteristics of wastewater fed to the digester are represented in Table 2. The influent wastewater was rich in starch and degradable sugars, with a chemical oxygen demand (COD) of 31.2 g/L at pH 4. After anaerobic digestion of the wastewater, the pH was increased to 6.8, and 95% of organic components were degraded into methane and carbon dioxide, thereby reducing COD to 1,650 mg/L (Table 2). The generated biogas was used as an energy source for electricity production which in turn satisfied the energy required for running the cassava starch plant.

2.1.2. Scenario 1

All the unit operations were the same as BAU. However, the peel waste (200-350 kg/t of cassava root) discarded in BAU was utilized for producing high-quality animal feed (Allaboutfeed.net, 2021). The International Tropical Agriculture and International Livestock Research Institute has developed a method to convert cassava peel waste to animal feed, which is widely adopted in Nigeria (Amole et al., 2022). The methodology and operations outlined in Amole et al. (2022) served as the primary data source

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Table 1.
Overview of recent research works conducted on cassava biorefinery.

Feedstock	Product	Waste	Product from waste	Assessment mode	Ref.
		Cassava wastewater + cassava bagasse + cassava stalks	Combined heat and power		
		Cassava bagasse + cassava wastewater	Bioethanol		
		Cassava stalks	Combine heat and power		
		Cassava wastewater + cassava bagasse + cassava stalks (10%)	Bioethanol		
		cassava stalks (90%)	Combined heat and power	TEA	Padi and Chimphango (2020b)
		Cassava stalks (10%) + cassava bagasse + cassava wastewater	Glucose syrup and bioethanol		
	Starch	Cassava stalks (90%)	Combine heat and power		
		Cassava stalks (10%) + cassava bagasse + cassava wastewater	Succinic acid and bioethanol		
		Cassava stalks (90%)	Combine heat and power		
		Cassava pulp	Bioethanol	LCA	Rewlay-ngoen et al. (2021)
		Cassava wastewater	Biogas		
		Cassava wastewater + cassava bagasse	Biogas	LCA	Padi and Chimphango (2021)
		Cassava stalks (burned openly)	-		
Cassava root		Cassava leaves + cassava residues (peel and pulp)	Biogas	LCA	Lansche et al. (2020)
		Stillage	Methane/Hythane	TEA	Deng et al. (2023b)
	Ethanol	Stillage	Biogas	LCA	Zhan et al. (2022)
		CO_2	Dry ice		
		Cassava wastewater	Biogas	GWP+MCDM	
		Cassava thippi	Animal feed		
		Cassava wastewater	Biogas		
		Cassava thippi	Animal feed	GWP+MCDM	
		Cassava peels	Animal feed		
	Starch	Cassava wastewater	Biogas	GWP+MCDM	**Present Study**
		Cassava thippi	Fungal protein (Mycelium)		
		Cassava wastewater	Biogas		
		Cassava thippi	Animal feed	GWP+MCDM	
		Digested effluent	Microalgal culture for fish feed		
		Cassava wastewater	Biogas	GWP+MCDM	

Table 2.
The biochemical properties of influent and effluent of anaerobic digestion of cassava wastewater in BAU.

Parameter	Influent	Effluent	Change (%)
pH	3.96 ± 0.004	6.81 ± 0.03	58 Increase
Total Suspended solids (g/l)	5.93 ± 0.56	1.23 ± 0.49	20 Decrease
Total Dissolved solids (g/l)	0.67 ± 0.08	0.104 ± 0.001	15 Decrease
Total solids (g/l)	6.6 ± 0.6	1.34 ± 0.48	20 Decrease
COD (mg/l)	31200	1650	5.28 Decrease
Phosphorus (mg/l)	424	151	35 Decrease
NO_3	66.8	6.6	9.88 Decrease
NO_2	132	21	15 Decrease
ORP (mV)	90.6	25.6	28 Decrease

for Scenario 1, which details the conversion of cassava peels into animal feed.

The process involves several steps: firstly, the peel waste was grated and pressed to remove excess water, leaving the resultant product with 30-40% moisture. Following the dewatering step, the peel was further pulverized and sieved in a 2.5 mm sieve to ensure uniformity. Further, the sieved peel was dried until its moisture content reached 10-12% which can be used as animal feed.

2.1.3. Scenario 2

In this case, the thippi waste was used as a substrate for the production of the fungal protein mycelium using solid-state fermentation (Pintathong et al., 2021). Fungal protein is a high-value compound, with a market value of about 5.5 times compared to bioethanol (Bulkan et al., 2021). It was assumed that the fungal strain *Rhizopus stolonifer* utilizes 70% of the starch and 81% of cellulose present in thippi waste within 8 d. During the process, the protein content of the fermented broth was enhanced by 1.85 times

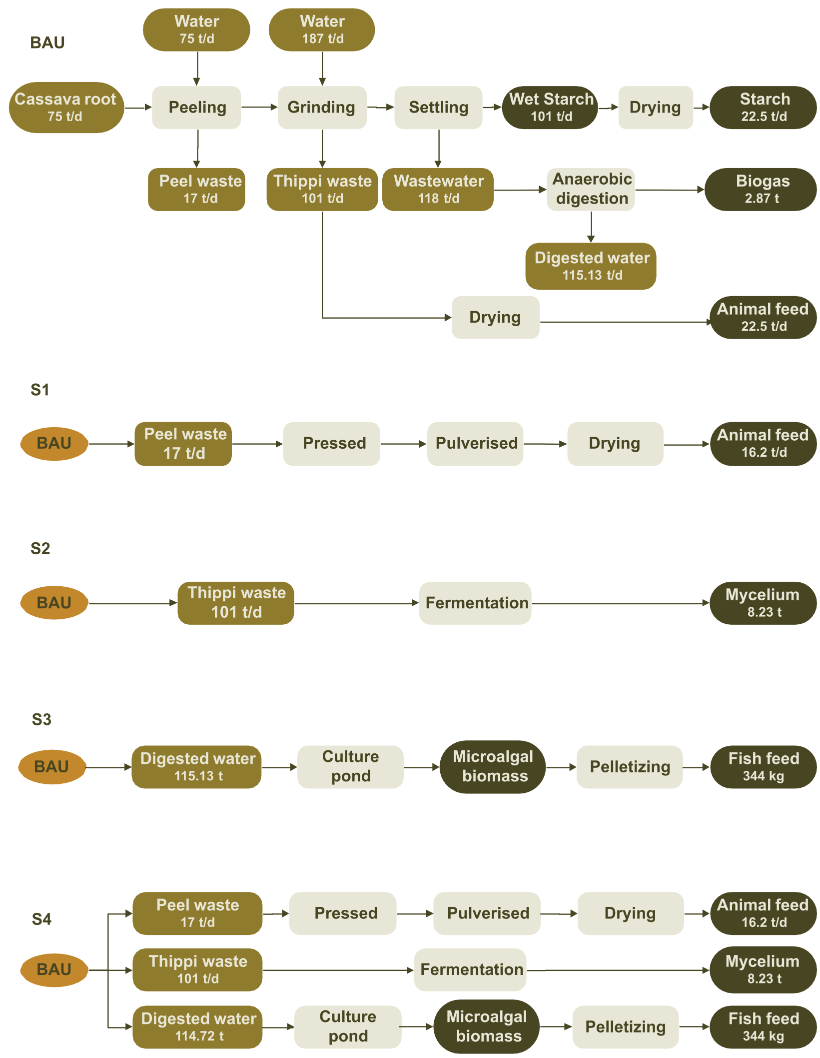

Fig. 2. Mass balance of block flow diagram of BAU and other alternative scenarios in this study. BAU: Business as-usual, S1: Scenario 1, S2: Scenario 2, S3: Scenario 3, and S4: Scenario 4. The dark green represents the products generated, light green is the input material, and cream represents the unit operations.

compared to the unfermented thippi waste. Further, the protein was obtained by centrifuging the fermented broth.

2.1.4. Scenario 3

During this scenario, the digested wastewater from an anaerobic digester in the BAU model was employed for cultivating microalgae. The process details and data were adapted from de Carvalho et al. (2018). The low solid content, along with the high nitrogen, phosphate, and other nutrients, makes it a suitable medium for microalgal culture. Microalgae cultivation was considered in an open pond under aerated conditions with 5 aerators (5 cfm each). The productivity of the culture ranged between 2-4 g/L of digested wastewater. The resultant microalgal biomass was filtered and pelletized in a 70 kg/h pelletizer to obtain algal fish feed.

2.1.5. Scenario 4

In this pathway, all the waste streams were converted to produce a value-added product. The thippi waste, peel waste, and digested wastewater were transformed into fungal protein, animal feed, and fish feed, respectively. Fungal protein was generated by solid-state fermentation using *R. stoloinfer* inoculum, while the animal feed was derived from peel waste by pulverizing and drying. Additionally, microalgae were cultivated in digested wastewater for fish feed production, followed by pelletization. The increase in the production of value-added products (animal feed, fish feed, biogas, and mycelium) from solid and liquid waste produced during starch production aided in adopting a sustainable biorefinery approach.

2.2. Mass balance

The mass balance of the cassava root processing (75 t/d) to produce starch and other byproducts was conducted using **Equation 1**, where generation, accumulation, and consumption were considered zero based on the principle that mass can neither be created nor be destroyed in a system (Gowd et al., 2022). The mass flow happening across the unit operations in the plant was designed as per the conventional cassava starch industry.

$$Accumulation = Input + Generation - Output - Consumption \qquad \text{Eq. 1}$$

The mass flow across the unit operations was designed by considering the key parameters, which encompass raw material, waste used, solid wastes, liquid wastes, moisture content, and products. In all scenarios, both

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the individual unit operations and the overall system were balanced to enhance accuracy.

2.3. Energy production and consumption

The electrical energy consumption was estimated based on the load in each unit operation and the operating hours of the machine. The conventional cassava starch plant (i.e., the BAU) operates for 16h/d and all the other scenarios were designed within this time frame; however, the fermentation processes were completed in 8 d (Pintathong et al., 2021). Energy consumption analysis helped in understanding the complexities of each unit operation required to produce a specific product. The biogas produced by anaerobic digestion was utilized to generate electricity required for plant operation, and was calculated based on **Equation 2** (Afotey and Sarpong, 2023).

$$Q_E = LCV_M \times CH_4 \times B_P \times \eta \qquad \text{Eq. 2}$$

where Q_E is the quantity of electricity generated (kWh), LCV_M stands for the lower calorific value (6 kWh/m^3) (Lijó et al., 2014; Abdeshahian et al., 2016), CH_4 is the percentage of methane in biogas produced (55%) (based on BAU), B_P is the amount of biogas produced (m^3), and η denotes the overall efficiency of the conversion of biogas (30%) (Benito et al., 2015; Çetinkaya and Yetilmezsoy, 2019).

To calculate the energy use for starch production, the energy required for operating conveyor belt, washing and peeling drum, grinder, and motor were considered in the analysis. All the units were considered to operate at a load of 90%, and the motor efficiency was assumed as 75% (Mehta and Rohit, 2008). The calculation for conveyor belts was based on **Equation 3** where the total pull includes belt pull and gravity pull. The required belt pull was determined by multiplying total weight with frictional coefficient. The frictional coefficient was considered as 0.5.

$$Power = Total\ pull\ \times Liner\ speed \qquad \text{Eq. 3}$$

The energy consumption of the pumps was calculated as per **Equation 4**.

$$Power\ P\ (W) = \frac{Q\left(\frac{m^3}{s}\right)\times\ \rho\left(\frac{kg}{m^3}\right)\times\ g\ \left(\frac{m}{s^2}\right)\times\ H(m)}{\eta\ (\%)} \qquad \text{Eq. 4}$$

where Q is the flow rate, ρ stands for the density, g is the gravitational pull, H is the head of water pumped, and η denoted the pumps efficiency (75%). The calculations for these unit operations are represented in the **Supplementary Material**.

2.4. Environmental and economic analysis

Life cycle assessment was conducted using a cradle-to-gate approach, following the ISO 14040 standards to evaluate the global warming potential (GWP) of all the scenarios. A consequential LCA approach was applied to analyze the scenarios by compiling data on inputs (cassava root, water, and energy), outputs (starch, animal feed, fish feed, and mycelium), and waste (thippi, peel waste, and wastewater) in the life cycle inventory (LCI) based on Ecoinvent 3 and Agri-footprint databases. SimaPro V9.3.0.3 software was used for LCA by employing the ReCiPe 2016 midpoint method to assess the GWP. The products from valorizing the wastes (thippi, peel, wastewater, and digested wastewater) were considered as avoided products (system expansion approach). The literature analysis showed that CO_2 avoidance of animal feed, fish feed, and fungal protein on average was 0.88, 2.6, and 1.18 kg $CO_{2eq.}$, respectively (**Table S1**). The electricity derived from biogas as an energy source was also included in the avoided products, while the remaining electricity consumed during different scenarios was assumed to be supplied from a high-tension grid. Furthermore, the carbon reduction by using electricity produced from biogas was considered as 0.716 kg $CO_{2eq.}$/kWh (Ministry of Power, 2022).

The economic analysis was conducted by analyzing the production cost for each scenario. The production cost included the cost of cassava root (0.078 USD/kg) (6.5 ₹/kg) (Kharlyngdoh et al., 2018), water usage price (0.14 USD/m^3) (12 ₹/m^3) (Times of India, 2024), labor cost (2.13 USD/d) (178 ₹/d) (India-briefing, 2024), and other variable cost and electricity cost (0.075 USD/kWh) (6.29 ₹/kWh) (Statista, 2024). Furthermore, the average selling price of the various products was starch (0.62 USD/kg) (52 ₹/kg) (IndiaMART, 2024), animal feed (0.11 USD/kg) (9 ₹/kg) (IndiaMART, 2024), mycelium (3.98 USD/kg) (331.88 ₹/kg) (Bulkan et al., 2020), and algal fish feed (34.62 USD/kg) (2,890 ₹/kg) (IndiaMART, 2024). The net profit was calculated by cost-benefit analysis considering various parameters like equipment cost, salvage cost, depreciation cost, operational cost, annual operating cost, gross profit, etc. (**Supplementary Material**).

2.5 Analytical hierarchy process for multi-criteria decision-making

The analytical hierarchy process (AHP) was an MCDM technique (Saaty, 1988) that was employed in this study to simplify decision-making by comparing different criteria through a pairwise comparison matrix. The matrix was framed by comparing the criteria with the scenarios and criteria with criteria.

The criteria selected for the analysis included profit, energy consumed, CO_2 avoided, and waste avoided. The criteria were chosen based on their relevance to the sustainability and economic viability of cassava biorefinery processes: (i) Profit measures the economic viability of each scenario, (ii) Energy Consumption reflects the energy efficiency of each process, (iii) CO_2 avoided indicates the environmental impact in terms of greenhouse gas emissions reduction, and (iv) Waste avoided addresses the environmental issue of waste management.

The principal right eigenvector of the matrix was computed as 'w' as in **Equations 5** and **6** (Taherdoost, 2017). However, when the condition $a_{ik}\ \times a_{kj} = a_{ij}$ is not met for all k, j, and i, then the Eigenvector method is used (Jalaliyoon et al., 2012). At the same time, if the matrix is not compatible or when it lacks consistency, the columns are normalized to obtain vector 'w'.

$$e^T = (1,1, \dots ,1) \qquad \text{Eq. 5}$$

$$w = \lim_{k\to\infty} \frac{A^k.e}{e^T.A^k.e} \qquad \text{Eq. 6}$$

In this study, a positive matrix was obtained by comparing the criteria when applying the Saaty table (Saaty, 1988). Hence, an eigenvector technique was used, where A is raised to the power of k to achieve convergence among answers through repeated iterations, which gives the priority values for the criteria. The normalized weight vector 'w' was calculated using the formula in **Equations 7-9**.

$$Aw = \lambda_{max}w, \lambda_{max} \geq n \qquad \text{Eq. 7}$$

$$\lambda_{max} = \frac{\sum ajwj-n}{w1} \qquad \text{Eq. 8}$$

$$A = \{a_{ij}\}\ with\ a_{ij} = \frac{1}{a_{ij}} \qquad \text{Eq. 9}$$

where A is the pair wise comparison, w is the normalized weight vector, λ_{max} is the maximum eigen value of the matrix, and Aa_{ij} is the numerical comparison between the values i and j.

The scenarios were compared under each criterion by calculating the percentage difference between them. A matrix was formed using values from the Satty table corresponding to the obtained percentage differences. The percentages difference were equally divided and values between 1 to 9 from the Satty table were assigned to calculate the performance score. After comparing scenarios for each criterion, criteria *vs.* criteria pairwise matrix was constructed using the Pearson correlation (r) value scores. These scores provided insights into the correlation between criteria, with high correlation scores receiving a value of "1" (equally important) from the Satty table, while lesser scores were assigned values based on the r-value. The criteria *vs.* criteria pairwise matrix was then checked for consistency.

The performance scores obtained from the criteria *vs.* criteria matrix were used as weightage and were multiplied by the values from the scenario *vs.* scenario matrix for each criterion based on their weights. The scenario with the highest performance score obtained through the MCDM process was identified as the best optimal scenario.

To further validate the AHP result, the consistency index (CI) was determined using **Equation 10**. Meanwhile, the value of the consistency ratio (CR) was determined by calculating the ratio between the consistency index and the random index. A consistency ratio lower than 0.10 indicates that the comparison results were reliable. **Figure 3** shows the MCDM framework, and the calculations are provided in the **Supplementary Material**.

$$Consistency\ index = \frac{\lambda max - n}{n-1} \quad \text{Eq. 10}$$

2.6. Sensitivity analysis

The sensitivity analysis was performed by varying the three critical factors of raw material cost (cassava root), cost of energy (electricity), and selling price of product (starch). As the scenarios have multiple products, the selling price of the starch alone was varied as it is the only common product manufactured in all the scenarios. Furthermore, these factors were analyzed by varying between ±10% to ±20% with a step interval of ±10%, and the MCDM was performed for all the factors to evaluate the change in performance score and their ranking positions.

3. Results and Discussion

3.1. Mass balance and energy consumption

The mass flow analysis results revealed significant variations in material flows between the different scenarios, providing insights into water usage, waste generation, and product yield. In the case of BAU, 75 t/d cassava root was processed to produce 22.5 t of starch (**Fig. 4**). During this process, 118 m^3/d of wastewater was produced which was fed to an anaerobic digester for biogas production. Cassava roots, unloaded from trucks, were transferred at a rate of 4.69 t/h to the peeling drum *via* a conveyor belt, consuming 787.2 kWh of electricity for the transfer and processing of the cassava roots in the washing and peeling drum.

The electrical energy required for the washing and peeling of 4.69 t/h of cassava was 1,917 kWh. The washing and peeling of 75 t cassava resulted in 75 t of wastewater and 17 t of peel waste. The electrical energy consumed by the conveyor system, and the washing and peeling drum, was the same among all the scenarios (3,543 kWh). The peeled cassava root (58 t) was transferred to the grinder (3.63 t/h) through the conveyor belt, which resulted in the consumption of 784 kWh of electricity. During the crushing of peeled roots, 187 t of water was added to the grinder thereby ending up in 245 t of ground mixture. The energy consumed during the grinding process was 1,026 kWh. Further, the ground mixture was filtrated to produce 144 t of starch milk along with 101 t of thippi waste. The starch milk was allowed to settle in a sedimentation basin for 3 h. After the completion of the sedimentation process, 101 t of wet starch was obtained by draining out 43 m^3 of wastewater from the settling tank. The wet starch was sun-dried to produce 22.5 t dry starch (moisture < 23%). In the overall process, 118 m^3 of wastewater was produced, which was fed to the anaerobic digestor (retention time of 24 h), leading to the production of 2.87 t of biogas. The biogas generated was used as an energy source to produce 2,319 kWh/d of electricity for the plant operation (4,576 kWh/d in BAU). The electrical energy generated from the biogas derived from wastewater remained the same for all the scenarios.

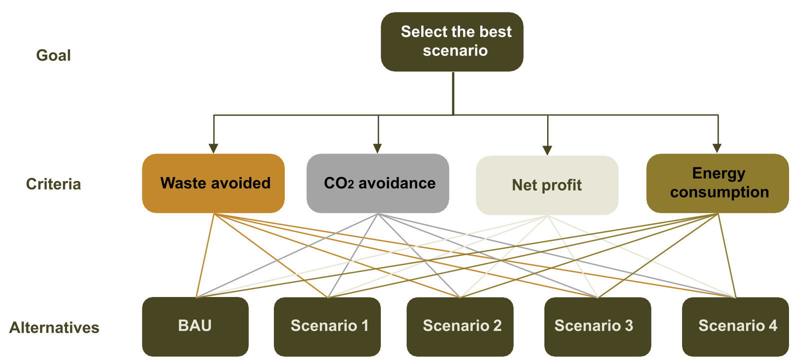

Fig. 3. Framework of the MCDM analysis performed on different scenarios. The weightage calculated by the AHP process is applied in the MCDM as shown.

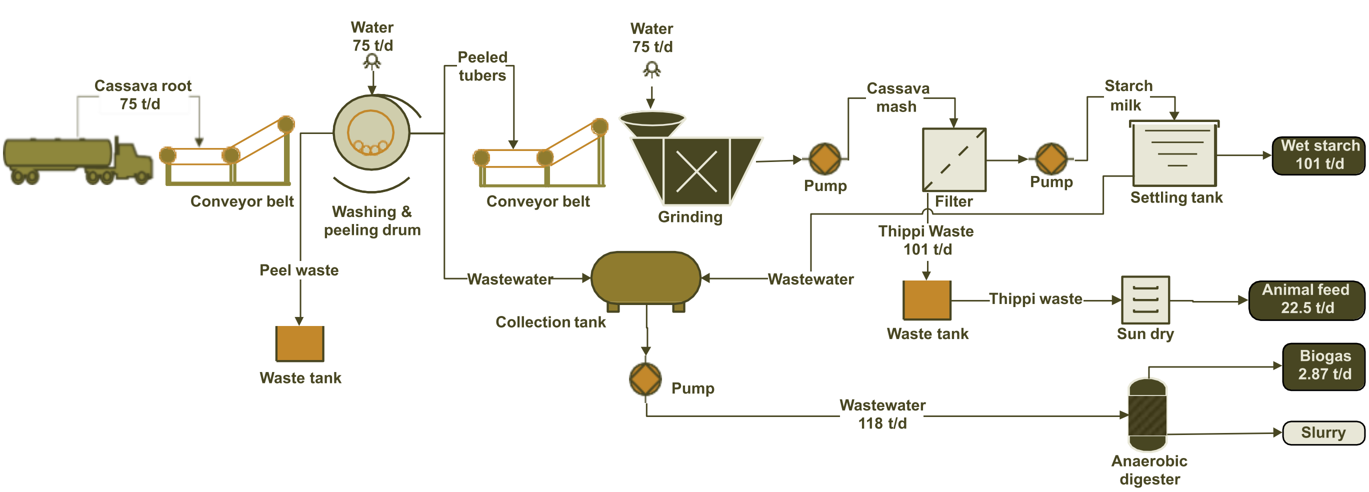

Fig. 4. Process flow diagram of a conventional cassava starch plant (i.e., BAU). The unit operations involved in starch production from cassava root and processes involved in the conversion of the waste by-products into animal feed and biogas are shown.

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All unit operations included in the BAU were also carried out in Scenario 1. However, in Scenario 1, the untreated peel waste (17 t) from the BAU was converted into 16.2 t/d animal feed, resulting in the consumption of 761 kWh of electricity. During animal feed production, the cassava peels were grated (85.1 kWh) and pressed hydraulically (192 kWh), leading to the removal of 0.5 t of water from the peels. The remaining pressed peels (16.5 t) were further pulverized (463.3 kWh) and sieved (20.6 kWh) to produce 16.3 t of animal feed, leaving behind 0.2 t of solid waste. Finally, the animal feed is sun-dried, leading to the loss of 0.1 t of moisture, thereby resulting in 16.2 t of high-quality animal feed.

In Scenario 2, instead of producing animal feed from 101 t of thippi waste, it was processed through solid-state fermentation, resulting in the production of 8.23 t of mycelium (fungal protein). About 13.76 MWh of electricity was consumed in the process that encompassed both fermentation (12.76 MWh) and decantation (273 kWh). Hence, the total energy consumed during Scenario 2 was 13.03 MWh. Unlike Scenario 2, Scenario 3 consumed 544.03 kWh of electricity in addition to the BAU for producing 344 kg of algal fish feed by culturing microalgae in 115.13 t/d digested cassava wastewater. The production of fish feed includes subunits, namely, aerator, decanter, and pelletizer, which consumed 198, 287, and 59 kWh of electricity, respectively. **Figures S1-5** show the mass balance of all scenarios framed in this study. Scenario 4 was a combination of all the scenarios, which was framed to convert all the waste generated during starch production into a value-added product. During this process, 16.2 t of animal feed (peel waste), 8.23 t of mycelium (thippi waste), and 344 kg of fish feed (digested wastewater), along with 22.5 t of dried starch, were produced. The overall waste avoided in each scenario is represented in **Figure 5b**. Since all the waste was converted into value-added products, the energy consumption in this scenario was the highest (18.91 MWh) compared to all the other scenarios (**Fig. 5a**). **Figure S6** represents the energy consumption of Scenario 4. The overall energy consumption and mass balance are represented in **Table 3**.

3.2. Environmental and economic analyses

The waste generated during the BAU was converted into value-added products in other scenarios thereby mitigating the carbon dioxide emission. Additionally, products generated from the wastes produced during the BAU also aided in mitigating the CO_2 emission, which was evaluated by the environmental analysis. The usage of electricity derived from biogas aided in avoiding 0.716 kg CO_{2eq}/kWh, thus enabling the mitigation of 1.66 t $CO_{2eq.}$ in all the scenarios due to the production of 2.32 MWh of electricity from biogas. Because all the waste generated during starch production was converted into value-added products, CO_2 avoided was maximum in Scenario 4 (57.59 t $CO_{2eq.}$). **Figure 5d** presents the CO_2 avoidance of all the scenarios.

The GWP of all scenarios was measured using LCI data analyzed with the ReCiPe 2016 midpoint method in SimaPro software. The BAU, utilizing biogas for electricity and converting thippi waste into animal feed, had a GWP of 154.3 kg $CO_{2eq.}$/t root. Scenario 1 showed a slightly higher GWP of 156 kg $CO_{2eq.}$/t root due to the usage of peel waste also for producing animal feed. The production of fish feed from digested wastewater in Scenario 3 aided in avoiding GWP of 16.21 kg $CO_{2eq.}$/t root, thereby reducing the GWP to 146.8 kg $CO_{2eq.}$/t root. Scenario 2 achieved negative GWP (-436 kg $CO_{2eq.}$/t root) by avoiding the production of fungal protein mycelium. On the other hand, the GWP of Scenario 4 (-434 kg $CO_{2eq.}$/t root) was lower than Scenario 2 despite producing three by-products due to high energy consumption. The GWP of all the scenarios is shown in **Figure 6**.

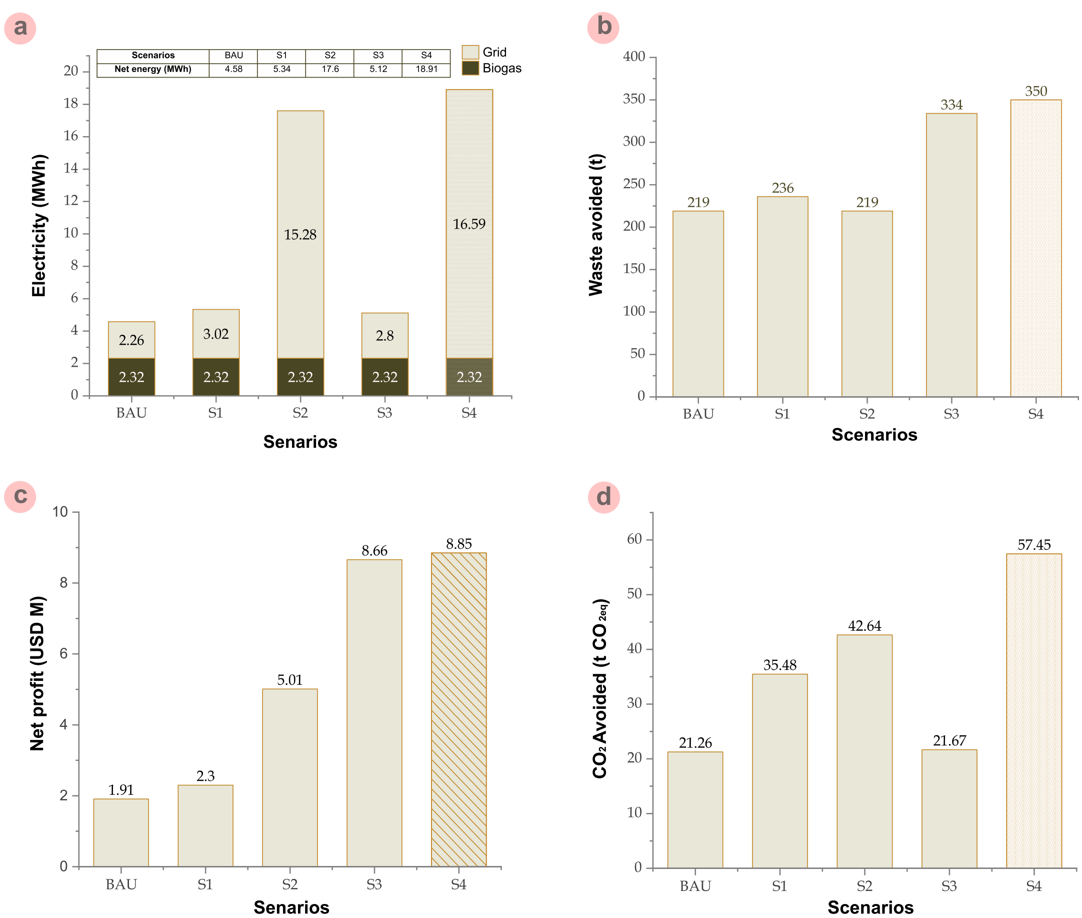

Fig. 5. Comparative analysis showing **(a)** electricity consumed, **(b)** waste avoided, **(c)** net profit, and **(d)** CO_2 avoided in all the scenarios. BAU: Business-as-usual, S1: Scenario 1, S2: Scenario 2, S3: Scenario 3, and S4: Scenario 4. The orange pattern shows the optimal scenario, i.e., S4.

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Table 3.
Mass balance, energy consumed, and cost analyzed in all the investigated scenarios.

Scenario	Raw Material (t) [i]	water Used (t) [i]	Liquid Waste (t)	Gaseous Waste (t)	Semisolid Waste (t)	Solid Waste (t)	Total Waste (t) [o]	Waste Avoided (t)	Products (t) [o]	Energy Consumed (MWh)	Energy Produced (MWh)	Energy Needed (MWh)	CO_2 Avoidance (t CO_{2eq})	Total Products (Nos)	Equipment Cost (USDM)	Depreciation Cost (USDK)	Raw material Cost (USDM/a)	Labor Cost (USDM/a)	Operational Cost (USDM/a)	Total selling Price (USDM/a)	Net profit (USDM/a)
BAU	75	262	0	157	115	17	289	219	22.5[a] 22.5[b] 2.87[c]	4.58	2.32	2.26	21.2	3	0.15	11.54	1.82	0.53	2.51	4.94	1.91
S1	75	262	0.5	157	115	0.2	273	236	22.5[a] 38.7[b] 2.87[c]	5.34	2.32	3.02	35.4	3	0.16	11.79	1.83	0.53	2.53	5.47	2.3
S2	75	262	0	79	216	17	303	219	22.5[a] 2.87[c] 8.23[d]	17.6	2.32	15.3	42.6	3	0.17	12.44	2.11	0.53	2.81	9.22	5.01
S3	75	262	139	157	0	18.4	311	344	22.5[a] 2.87[c] 0.34[e]	5.12	2.32	2.80	21.6	4	0.16	11.81	1.83	0.53	2.52	13.6	8.66
S4	75	262	182	79	101	1.6	287	351	22.5[a] 16.2[b] 2.87[c] 8.23[d] 0.34[e]	18.9	2.32	16.6	57.4	5	0.17	12.97	2.14	0.53	2.85	14.1	8.85

* The total waste added to the products gives the total input, thereby balancing the mass where i is the input and o is the output.
[a] Starch, [b] animal feed, [c] biogas, [d] mycelium, and [e] fish feed.

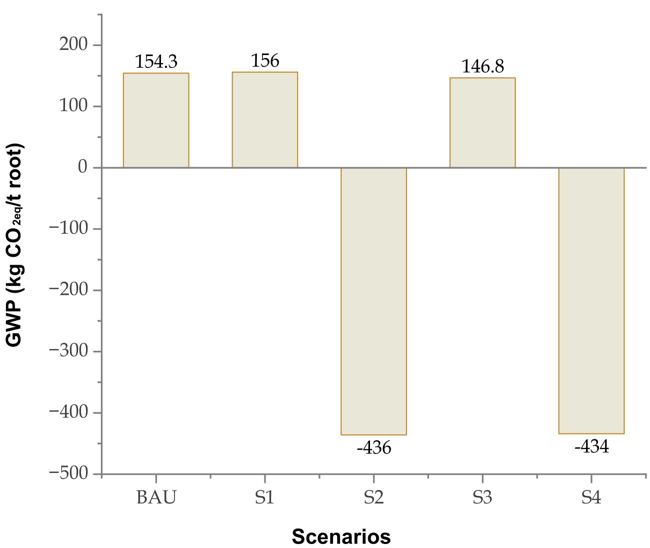

Fig. 6. The global warming potential (GWP) of all the scenarios presented in kg $CO_{2eq.}$ for processing 1 t of cassava root. BAU: Business-as-usual, S1: Scenario 1, S2: Scenario 2, S3: Scenario 3, and S4: Scenario 4.

Economic analysis was performed to evaluate the feasibility of manufacturing a product. In this regard, operational cost (water cost, labor cost, electricity cost, and raw materials cost) and the selling price of the product were considered to evaluate the net profit of the scenarios. The highest net profit of USD8.85 M was achieved in Scenario 4 (**Fig. 5c**), despite consuming higher energy when compared to all the scenarios, which can be attributed to the maximum number (5) of value-added products obtained.

3.3 Analytical hierarchy process for multi-criteria decision-making

MCDM (an AHP tool) helped to identify the best biorefinery pathway (among the different scenarios) adopted for cassava starch production. The criteria, namely waste avoided, net profit, energy consumption, and CO_2 avoided, were employed to develop the pairwise matrix based on the Saaty table. The priority of each criterion was identified in the matrix, which was 0.065 for waste avoided, 0.074 for net profit, 0.421 for energy consumed, and 0.44 for CO_2 avoidance. The consistency ratio for the framed pairwise matrix was calculated as 0.002, confirming the reliability. These matrix tables are provided in the **Supplementary Material**. Based on the obtained priority, the goal scores for the scenarios were calculated, which marked Scenario 4 as the best biorefinery pathway with a performance score of 0.282. The performance scores of all the scenarios are represented in **Figure 7**.

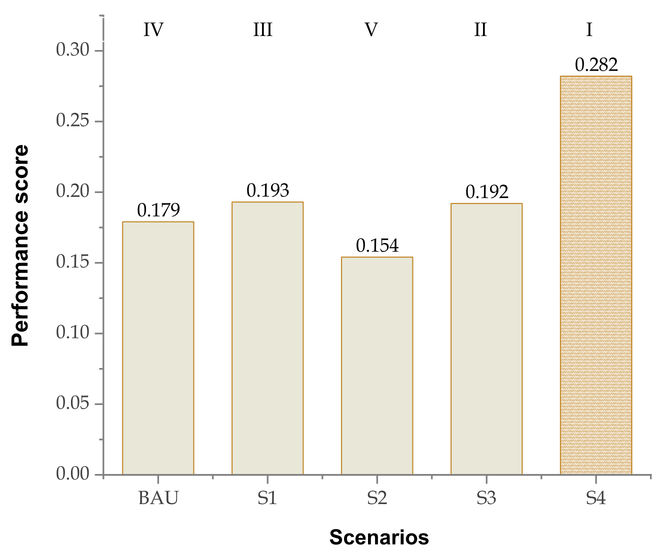

Fig. 7. The performance score of the scenarios obtained in the MCDM analysis. The highest score represents the best scenario and vice versa. The orange pattern shows the optimal scenario, i.e., S4. BAU: Business-as-usual, S1: Scenario 1, S2: Scenario 2, S3: Scenario 3, and S4: Scenario 4.

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3.4 Business-as-usual vs. Scenario 4

The prime aim of this work was to find the best biorefinery pathway in the cassava industry, thereby making the sector more sustainable and economically feasible. In comparing the BAU with Scenario 4, significant inconsistencies occurred in both environmental impact and economic viability. The BAU imposed a linear production process with limited value-added products, which led to considerable resource wastage. In contrast, Scenario 4 showed an effective biorefinery pathway for sustainable cassava starch production. Scenario 4 involved processes like conversion of peel waste to animal feed, and cultivating microalgae for fish feed and mycelium from thippi waste. Thus enabling effective utilization of resources, minimizing waste generation, and maximizing product diversification. Scenario 4 enabled the achievement of 2.69 times more $CO_{2eq.}$ avoidance than BAU (2 $tCO_{2eq.}$). Scenario 4 also demonstrated superior economic feasibility by yielding the highest net profit of USD8.85 M among other alternative scenarios.

3.5. Comparative analysis

The energy consumed during cassava starch production in this study was compared with various literature (**Fig. 8a**). The energy consumption showed minor differences (8%) between the literature (Yin et al., 2019) and this study. The unit operations involved were the same as the literature which included washing, peeling, grinding, and drying. The energy consumption in cassava starch plants of various sizes (small 1-2 t starch/d, big 100-200 t starch/d) was analyzed (Tran et al., 2015), which showed more energy consumption in drying the wet starch, unlike the present study which was sun-dried, thanks to the favorable ambient temperature. Furthermore, the energy consumed for starch separation (Pingmuanglek et al., 2017) was avoided by using a sedimentation tank. However, energy consumption in the literature was slightly higher as the conveyor belt was not included.

Further, there was an increase in energy consumption while moving to alternative scenarios (Scenarios 1-4) from BAU, which involved only starch production. This was due to the increase in the unit operations in the alternative scenarios, as they produced additional products along with starch, which encompassed the production of animal feed (Scenario 1), fungal protein (Scenario 2), fish feed (Scenario 3), and the combined production of all products (Scenario 4). As energy consumption increased, so did the revenue, which was due to the production of higher-value products (**Fig. 8b**).

Unstable energy supplies and raw material price fluctuations in cassava-producing countries pose a foreseeable risk to industrial operations and profitability (Padi and Chimphango, 2020a). However, in the present study, the increases in energy consumption have contributed to higher profits due to the production of additional products. Moreover, according to the bio-based value pyramid (Stegmann et al., 2020), products like mycelium play a crucial role in the development of food products, especially sustainable foods like vegan meat, tofu, etc., thereby increasing the overall net profit. These findings show the robustness to shift towards biorefinery, and that adopting the alternating scenarios in the present study facilitated increasing the profit.

The GWP for producing 1 t of cassava starch, excluding cassava root cultivation, ranged from 93-539 kg $CO_{2eq.}$ (Lansche et al., 2020). The utilization of cassava waste for higher-value products was explored in many studies to reduce the carbon footprint of starch production. Utilization of cassava wastes (thippi and leaves) to generate biogas led to a reduction in the GWP of starch production by 1.02 $CO_{2eq.}$/kg starch (Lansche et al., 2020). Furthermore, the GWP of bioethanol manufactured by utilizing a whole cassava plant resulted in 1.46 kg $CO_{2eq.}$\L ethanol (Lyu et al., 2020). Thus, the generation of biofuels reduced the GWP, yet it was unable to attain negative emissions. However, adopting alternative Scenarios 2 and 4 in this study facilitated to achievement of negative GWP of -436 and -434 kg $CO_{2eq.}$/t root, respectively (**Fig. 6**). The negative GWP was attained due to the CO_2 avoidance caused by the valorization of waste to multiple products.

3.6. Sensitivity analysis

The MCDM approach was based on four criteria and their weighted average was calculated through AHP. The sensitivity analysis was performed by varying the factors influencing the profit (cost of cassava root,

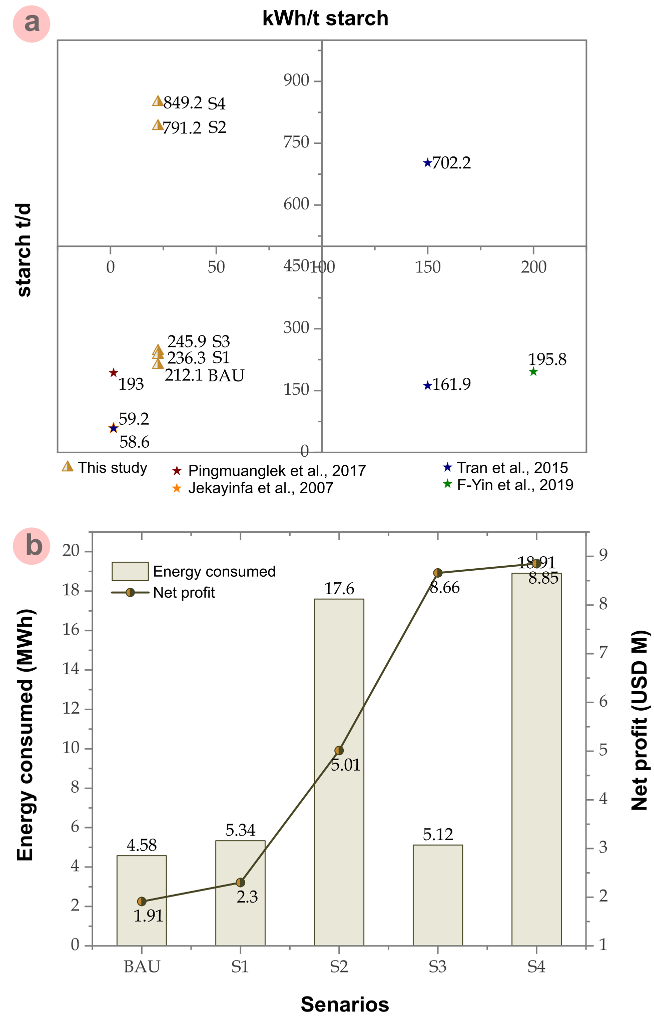

Fig. 8. (a) Comparison of the energy consumed for cassava starch production in various literature with BAU and alternative scenarios investigated in the present study, and **(b)** the relationship between energy consumption and net profit was analyzed, showing a positive correlation

the cost of electricity, and the selling price of cassava starch) by ±10% to ±20% with a step interval of ±10% to identify the change in performance score and ranking positions. Despite varying the cost of cassava root, the cost of electricity, and the selling price of cassava starch, the ranking position remained unchanged, affirming Scenario 4 to be the best scenario. Furthermore, the analysis showed slight variation in the value of the performance score which was mainly affected by varying the selling price of the starch. **Figure 9** shows the deviation in the performance score value while varying these factors.

3.7. Limitations of the present study

India is witnessing an increase in cassava productivity (Prakash et al., 2022). This industrial crop used in starch production has been chosen as one of the energy crops for the 1G and 2G ethanol blending scheme by the Government of India (Government of India, 2018). However, the year-round supply of cassava is a challenge as it is a seasonal crop. The demand for cassava varies seasonally, and the shelf life of cassava is only 48 h (Tomlins et al., 2021), thereby making it costly to store. The impact on food security, water usage, and other environmental parameters must be assessed before implementing the biorefinery pathway commercially. A uniform supply of cassava and appropriate policies for utilizing cassava in industry,

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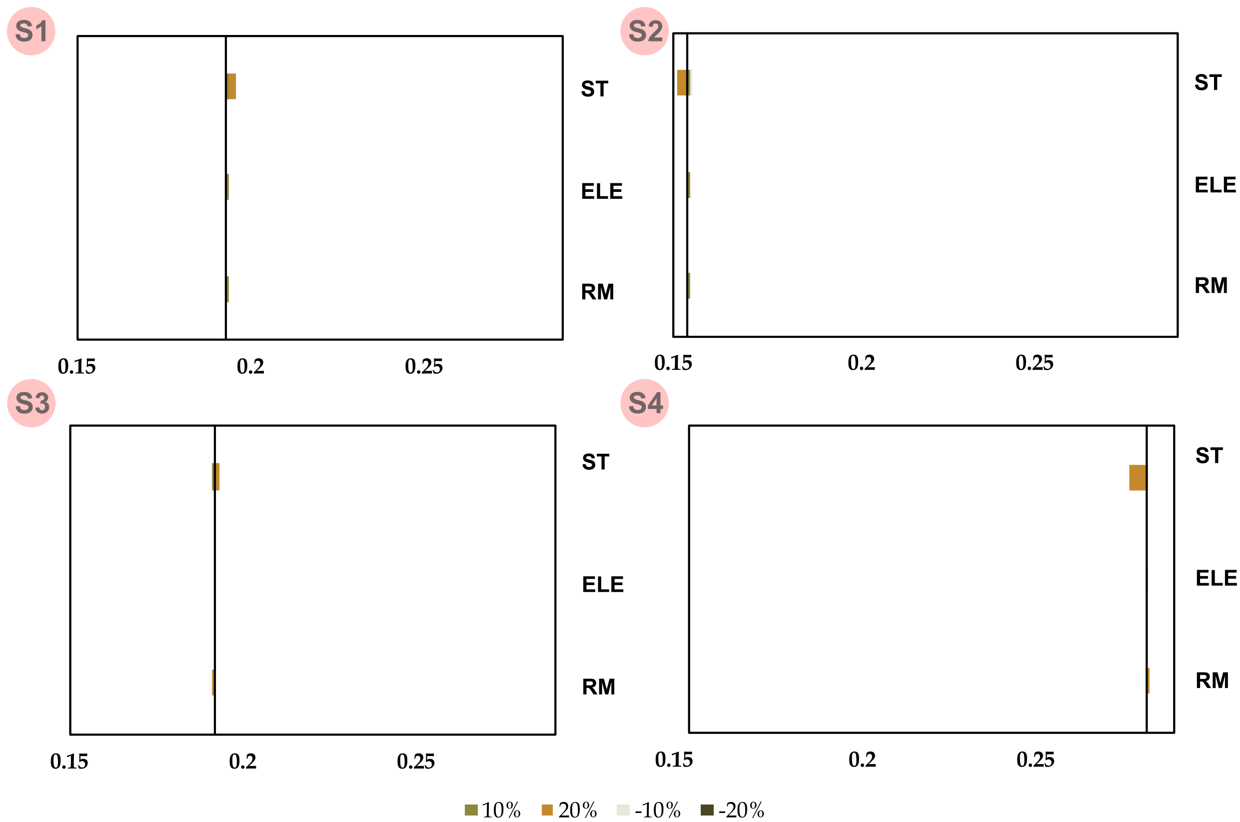

Fig. 9. The deviation in the performance score values considering the varying cost of raw material (cassava root) (RM), cost of electricity (ELE), and selling price of starch (ST).

food, or as energy crops will aid in making cassava a more beneficial crop.

4. Practical and Policy Implications

In India, cassava is grown as a rain-fed crop or irrigation crop that can be harvested in about 10-11 months (ICAR, 2024). In recent years, high-yielding cassava crops with a harvesting span of 6 months have been widely cultivated to improve the availability of feedstock in India. The shift towards high-yielding varieties can abet in achieving 20% blending ethanol with gasoline by 2025. The government of India also supports using cassava as feedstock under 1st generation ethanol production policy by setting a purchase price of ~0.68 USD/L of ethanol.

Cassava starch production is an energy-intensive process consuming 1.6 to 2.5 MJ of thermal energy and 0.17 to 0.25 kWh of electricity per kg (Padi and Chimphango, 2020b). The scenarios in this study aim to reduce energy consumption by using biogas generated from the anaerobic digestion of cassava wastewater for electricity production. Additionally, traditional sun drying and sedimentation methods have been adopted for yielding animal feed and starch, thereby decreasing energy use. Moreover, the energy consumption in alternative scenarios remains higher than in the BAU case, but it is still lower compared to the energy required to establish new facilities for producing byproducts such as animal feed, fish feed, and fungal protein. In addition, the valorization of wastes from cassava will facilitate reducing the carbon footprint and enhance the waste management practice.

5. Conclusions and Prospects

The profitability, robustness, and operability of the cassava starch industry are uncertain due to fluctuations in the price of raw materials and the generation of solid and liquid waste during starch processing can harm the environment when left untreated. To address these challenges and to find the potential possibilities in the cassava starch industry were explored in this study. In this study, four alternative scenarios were analyzed, which encompass animal feed from peel waste (Scenario 1), fungal protein from thippi waste (Scenario 2), fish feed from digested wastewater (Scenario 3), and all the waste streams transformed into value-added products, including animal feed, fish feed and fungal protein (Scenario 4). The energy consumption was maximum for Scenario 4 (18.91 MWh) and least for BAU (4.58 MWh). Due to the production of more value-added products, Scenario 4 achieved a maximum profit of (USD 8.85 M). In addition, the CO_2 avoidance potential was maximum for Scenario 4 (57.45 t $CO_{2eq.}$). Further, the MCDM approach was applied to find the best biorefinery pathway in the cassava starch industry. In the four alternative scenarios studied against BAU, Scenario 4 outperformed others with a performance score of 0.34.

Despite challenges like seasonal production and storage issues, these findings show the potential for sustainable cassava starch production and robustness to shift towards these biorefinery pathways according to the demands of the value-added products. These findings pave the way for future research and policy development in agro-industrial sustainability. In the future, these scenarios can be practically implemented to achieve sustainability. The scalability of the work can be further investigated by conducting LCA and TEA in detail, which will emphasize the potential of biorefinery in the cassava industry.

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https://scholar.google.com/citations?user=cYuJkRoAAAAJ&hl=en

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https://scholar.google.com/citations?user=kJ9DmtEAAAAJ&hl=en

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Supplementary Material

Energy Calculations

1. BAU - Cassava root to starch production, thippi to animal feed and wastewater to biogas

1. Conveyor belt

Length (L) = 16.27 m
Thickness (T) = 0.16 m
Width (W) = 1.49 m
Linear speed = 60 m/min
Height (H) = 3 m
Material weight = 70 kg/min

$$Total\ volume = L \times W \times T$$
$$Total\ volume = 16.27 \times 1.49 \times 0.16 = 3.88\ m^3$$

Rubber density = 1360 kg/m^3
Therefore, total belt weight = 5276.8 kg
Frictional coefficient = 0.5

$$Total\ weight = Belt\ weight + \ Material\ weight$$

$$Total\ weight = 5276.8 + 70 = 5346.8\ kg$$

$$Required\ belt\ pull = Total\ weight\ \times Frictional\ coefficient$$

$$Required\ belt\ pull = 5346.8 \times 0.5 = 2673.4$$

$$Gravity\ pull = \frac{Total\ weight}{Belt\ length} \times Height$$

$$Gravity\ pull = \frac{5346.8}{15} \times 3 = 1069.36$$

$$Total\ pull = Belt\ pull + Gravity\ pull$$

$$Total\ pull = 2673.4 + 1069.36 = 3742.76$$

$$Power = Total\ pull\ \times Linear\ speed$$

$$Power = 3742.76 \times 60 = 224565.6\ m\frac{kg}{min}$$

1 hp = 4564.29 m kg/min

$$\frac{224565.6}{4564.29} = 49.20\ hp$$

1 hp = 0.75 kW

$$49.20\ \times 0.75\ = 36.9\ kW$$

Assuming efficiency is 75%, then,

$$\frac{36.9}{0.75} = 49.2\ kW$$

Therefore, for 16 h, 787.2 kWh

2. Washing and peeling

The electricity consumed for washing – 4.25 kWh/t starch (15.4 MJ) (Tran et al., 2015).
Therefore, for 22.5 t starch electricity consumed = 96.3 kWh
The electricity consumed for peeling – 0.025 kWh/kg root (Precoppe and Parmar, 2021).
Therefore, for 75 t (75000 kg) root electricity consumed = 1875 kWh

3. Conveyor belt

Length (L) = 16.27 m
Thickness (T) = 0.16 m
Width (W) = 1.49 m
Linear speed = 60 m/min
Height (H) = 3 m

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Material weight = 50 kg/min

$$Total\ volume = L \times W \times T$$

$$Total\ volume = 16.27 \times 1.49 \times 0.16 = 3.88\ m^3$$

Rubber density = 1360 kg/m^3
Therefore, total belt weight = 5276.8 kg
Frictional coefficient = 0.5

$$Total\ weight = Belt\ weight + \ Material\ weight$$

$$Total\ weight = 5276.8 + 50 = 5326.8\ kg$$

$$Required\ belt\ pull = Total\ weight\ \times Frictional\ coefficient$$

$$Required\ belt\ pull = 5326.8 \times 0.5 = 2663.4$$

$$Gravity\ pull = \frac{Total\ weight}{Belt\ length} \times Height$$

$$Gravity\ pull = \frac{5326.8}{15} \times 3 = 1065.36$$

$$Total\ pull = Belt\ pull + Gravity\ pull$$

$$Total\ pull = 2663.4 + 1065.36 = 3728.76$$

$$Power = Total\ pull\ \times Liner\ speed$$

$$Power = 3728.76 \times 60 = 223725.6\ m\frac{kg}{min}$$

1 hp = 4564.29 m kg/min

$$\frac{223725.6}{4564.29} = 49.01\ hp$$

1 hp = 0.75 kW

$$49.01 \times 0.75 = 36.76\ kWh$$

Assuming efficiency is 75%, then

$$\frac{36.76}{0.75} = 49.01\ kWh$$

Therefore for 16h, 784.16 kWh

4. Grinding machine

The electricity consumed for crushing cassava = 45.61 kWh/t starch (164.2 MJ) (Tran et al., 2015).
Therefore, for 22.5 t starch electricity consumed = 1026.23 kWh

5.1. Motor pump 1

$$\text{Power P (kW)} = \frac{\text{Q}\left(\frac{\text{m}^3}{\text{s}}\right) \times \rho\left(\frac{\text{kg}}{\text{m}^3}\right) \times \text{g}\left(\frac{\text{m}}{\text{s}^2}\right) \times \text{H(m)}}{\eta\ (\%)}$$

Q – Flow rate

Required volume = 262 m^3, If the head space of the tank is 10% higher the volume of the tank is 288.2 m^3

$$Total\ volume = volume\ of\ water = 262\ m^3$$

The flow rate for filling the tank in 3 hr = 87.33 m^3/h ~ 0.025 m^3/s

ρ – Density of slurry

$$Density\ of\ water = 1000\ kg/m^3$$

H – Head of water pumped
η – Pump efficiency
Head of water pump is assumed to be 5 m with a pump efficiency of 75%
g – Gravity of earth = 9.8 m/s

$$\text{Power P (W)} = \frac{Q\,(\frac{m^3}{s}) \times \rho\,(\frac{kg}{m^3}) \times g\,(\frac{m}{s^2}) \times H(m)}{\eta\,(\%)}$$

$$Power = \frac{0.025 \times 1000 \times 9.8 \times 5}{0.75} \times \frac{1}{1000}$$
$$Power = 1.63\ kW$$

Therefore, for 3 h = 4.89 kWh

5.2. Motor pump 2

To fill the tank with volume of 4425 m^3, radius of 3.43 m and height of 4 m

$$Total\ volume = volume\ of\ water = 118\ m^3$$

The flow rate for 2 hr per day = 59 m^3/h ~ 0.01639 m^3/s

$$\text{Power P (kW)} = \frac{Q\,(\frac{m^3}{s}) \times \rho\,(\frac{kg}{m^3}) \times g\,(\frac{m}{s^2}) \times H(m)}{\eta\,(\%)}$$

Q – Flow rate
ρ – Density of slurry

$$Density\ of\ water = 1000\ kg/m^3$$

H – Head of water pumped
η – Pump efficiency
Head of water pump is assumed to be 2 m with a pump efficiency of 75%
g – Gravity of earth = 9.8 m/s

$$\text{Power P (W)} = \frac{Q\,(\frac{m^3}{s}) \times \rho\,(\frac{kg}{m^3}) \times g\,(\frac{m}{s^2}) \times H(m)}{\eta\,(\%)}$$

$$Power = \frac{0.01639 \times 1000 \times 9.8 \times 4}{0.75} \times \frac{1}{1000}$$
$$Power = 0.86\ kW$$

Therefore, for 2h = 1.72 kWh

2. Scenario 1: BAU + peel waste to animal feed

BAU calculations are given,

1. Grating machine (Amole, 2022)

For processing 500 kg in 1 h we need 7.5 HP motor
We need to process 2.13 t in 1 h. Therefore, we need 31.95 hp motor
Consider 32 hp motor,
1 hp = 0.75 kW
Therefore, 32 hp = 24000 W
So, if we run motor for 1 h = 24000 * 1 = 24 kWh

Therefore, for 8h = 192 kWh

2. Hydraulic presser (Alibaba.com – Hydraulic Press, 2024)

Capacity of the existing machine: 800-1000 kg/hour
We need 2.13t/h
Power of the existing machine: 4.0 kW
The capacity ratio between the two machines: $capacity\ ratio = \frac{New\ capacity}{Existing\ capacity}$

$$capacity\ ratio = \frac{2130}{800} = 2.66$$

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Assuming the power requirement is directly proportional to the capacity,

$$\text{Power for New Machine} = (\text{Power of Existing Machine}) \times \text{Capacity Ratio}$$

$$\text{Power for New Machine} = 4 \times 2.66 = 10.64$$

Therefore, for 8 h = 85.12 kW

3. Pulverizing machine (Brspowder.com - Pulveriser, 2024)

Capacity of the existing machine: 1800 kg/hour
We need 2.06 t/h
Power of the existing machine: 50.8 kW

$$The\ capacity\ ratio\ between\ the\ two\ machines: capacity\ ratio = \frac{(New\ capacity)}{(Existing\ capacity)}$$

Capacity ratio = 2060/1800 = 1.14
Assuming the power requirement is directly proportional to the capacity,

$$Power\ for\ New\ Machine = (Power\ of\ Existing\ Machine) \times Capacity\ Ratio$$

Power for New Machine = 50.8 ×1.14=57.91
Therefore, for 8 h = 463.28 kW

4. Sieving machine (Indiamart.com - Sieve, 2023)

0.8 t/h = 1 kW

Capacity of the existing machine: 800 kg/hour
We need 2.06 t/h
Power of the existing machine: 1 kW

$$The\ capacity\ ratio\ between\ the\ two\ machines: capacity\ ratio = \frac{(New\ capacity)}{(Existing\ capacity)}$$

capacity ratio= 2060/800 = 2.58

Assuming the power requirement is directly proportional to the capacity,

$$Power\ for\ New\ Machine = (Power\ of\ Existing\ Machine) \times Capacity\ Ratio$$

Power for New Machine = 1 ×2.58=2.58
Therefore, *for 8 h = 20.64 Kw*

3. Scenario 2: Thippi waste to fungal protein

BAU calculations are given,

1. Thippi waste to fermenter motor pipe

$$Density\ of\ cassava\ plup = \frac{Density\ of\ cassava + Density\ of\ water}{2}$$

$$Density\ of\ cassava\ plup = \frac{840 + 1000}{2} = 920\ kg/m^3$$

Volume of thippi to be filled = 109.78 m^3
To fill the tank with volume of 137.23 m^3, radius of 3.81 m and height of 3 m

$$Total\ volume = volume\ of\ water = 118\ m^3$$

The flow rate for 2 h = 54.89 m^3/h ~ 0.015 m^3/s
Head of water pump is assumed to be 3 m with a pump efficiency of 75%

$$\text{Power P (W)} = \frac{\text{Q}\left(\frac{\text{m}^3}{\text{s}}\right) \times \rho\left(\frac{\text{kg}}{\text{m}^3}\right) \times \text{g}\left(\frac{\text{m}}{\text{s}^2}\right) \times \text{H(m)}}{\eta\ (\%)}$$

$$Power = \frac{0.015 \times 920 \times 9.8 \times 3}{0.75} \times \frac{1}{1000}$$
$$Power = 0.541\ kW$$

Therefore, for 2 h = 1.08 kWh

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2. Solid state fermentation

Energy consumed for fermentation = 1.55 kWh/kg of fungal product (Brancoli et al., 2021)
Therefore, for producing 8.23 t at a HRT of 8 days, energy required = 8230 × 1.55 = 12756.5 kWh

3. Decanter centrifuge

The energy needed to centrifuge = 2.5 kWh/t (Timonen et al., 2019)
Therefore, $Energy\ needed\ to\ centrifuge\ 109.23\ t\ =\ 2.5 \times 109.23$
$Energy = 273.0$ kWh

4. Scenario 3: Microalgae from digested WW and biogas from microalgal biomass

1. Aerator

For designing the aerator, first we need find how much air required for the process.

BOD of influent = 0.386 $(COD)^{0.7645}$ (Bhat et al., 2004)
COD = 31200 mg/L (NIRT Industry data)
BOD = $0.386 \times 31200^{0.7645}$
BOD = 1052.85 mg/L

$$Oxygen\ required\ per\ day = BOD\left(\frac{mg}{L}\right) \times Average\ Flowrate\left(\frac{m^3}{d}\right) = 1052.85 \times 114.72$$

=120782.95 (kg/d) =120.79(m^3/d)
Air requirement is calculated based on oxygen percentage in natural air.
21% oxygen present in air.

$$Air\ required\ for\ the\ process\ (m^3) = \frac{Oxygen\ required\ (m^3)}{Oxygen\ present\ in\ 1m^3\ of\ Air} = \frac{120.79}{0.21} = 575.19\ m^3/d$$

HRT = 12 h/d

$Aeration\ rate\left(\frac{m^3}{s}\right) = \frac{Air\ required\ (m^3)}{HRT(h)} = \frac{575.19}{12} = 0.80\left(\frac{m^3}{min}\right)$ = 48 m^3/h ˜ 30 cfm,

So, 5 aerators with 5 cfm are applied
5 cfm aerator = 550 W (0.55 kW) (Amazon.com)

Therefore 6*5*0.55 = 16.5 kw

$$Power\ consumed\ by\ the\ aeration = Air\ power\ consumption\ rate\ \times Operating\ time = 16.5 \times 12 = 198\ kWh$$

2. Decanter centrifuge

The energy needed to centrifuge = 2.5 kWh/t (Timonen et al., 2019)

Therefore, $Energy\ needed\ to\ centrifuge\ 114.81176\ t\ (114.72\ t + 0.09176\ t) =\ 2.5 \times 114.81176 = 287.0294$

$Energy = 287.03$ kWh

3. Pelletizer (Made-in-China.com - Fish Feed, 2023)

Energy required to pelletize 68.83 kg/h = 11.8 kW
Therefore for 5h =59 kWh

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Figures

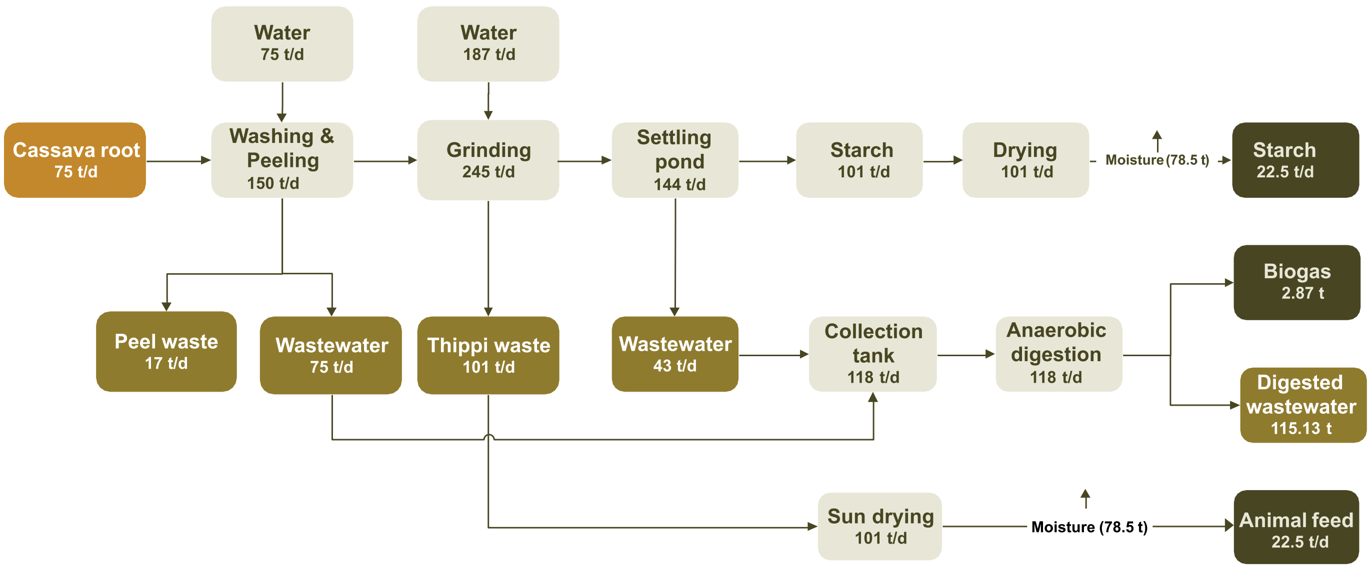

Fig. S1. Unit operations involved in BAU.

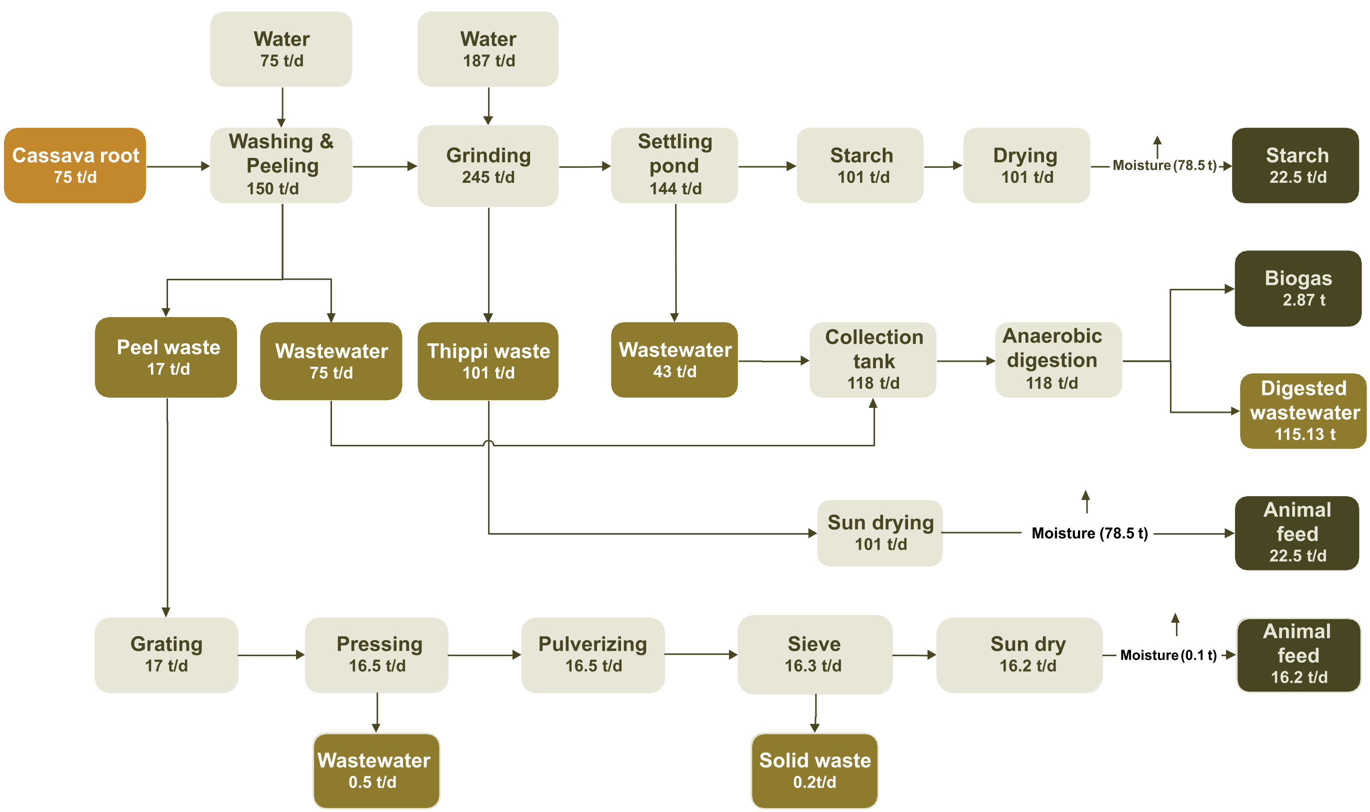

Fig. S2. Unit operations involved in Scenario 1.

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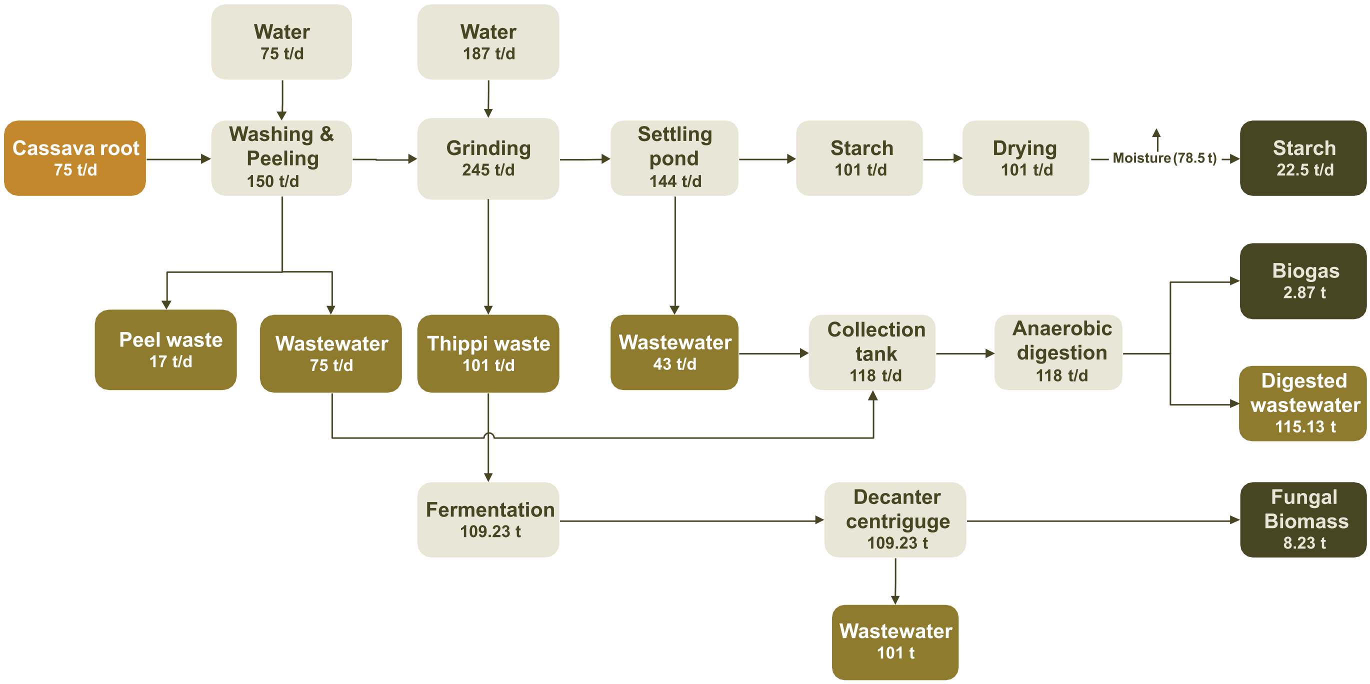

Fig. S3. Unit operations involved in Scenario 2.

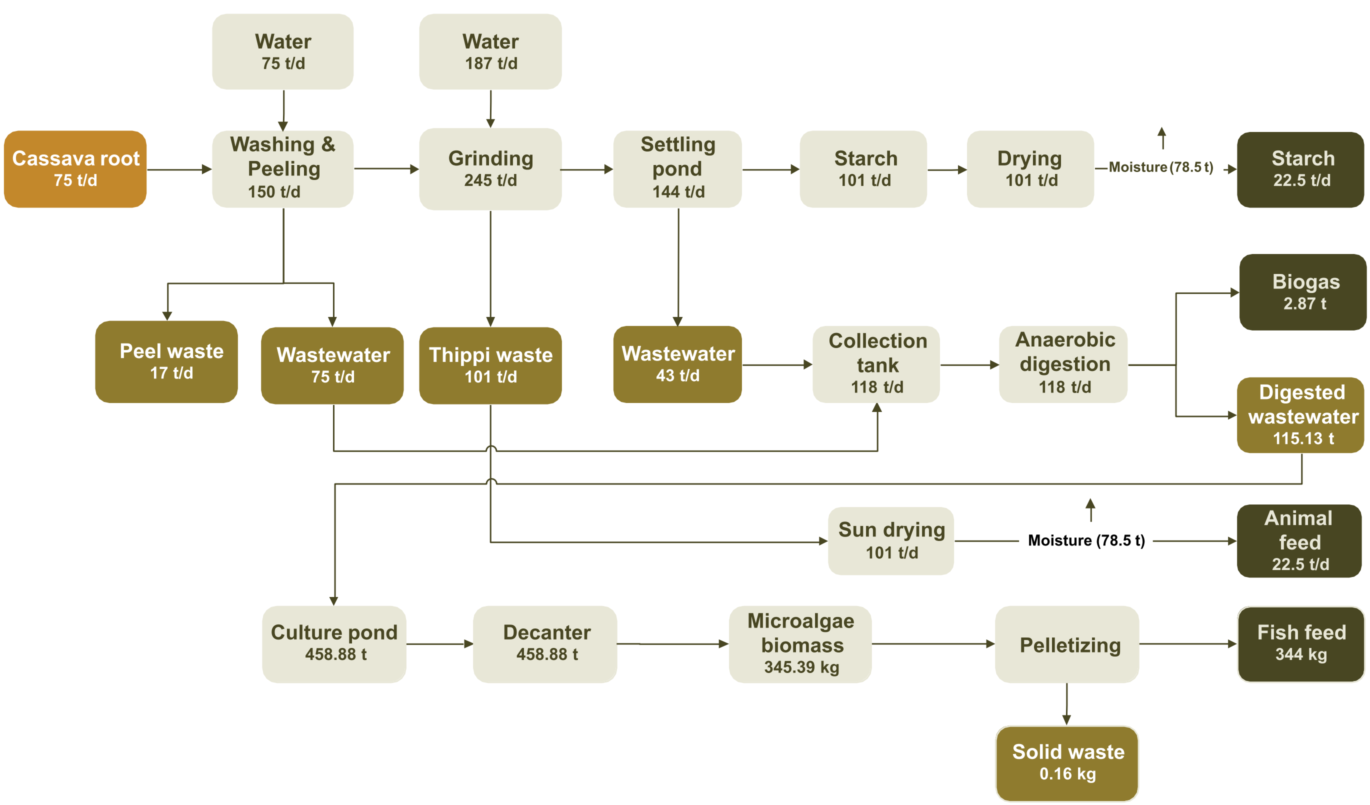

Fig. S4. Unit operations involved in Scenario 3.

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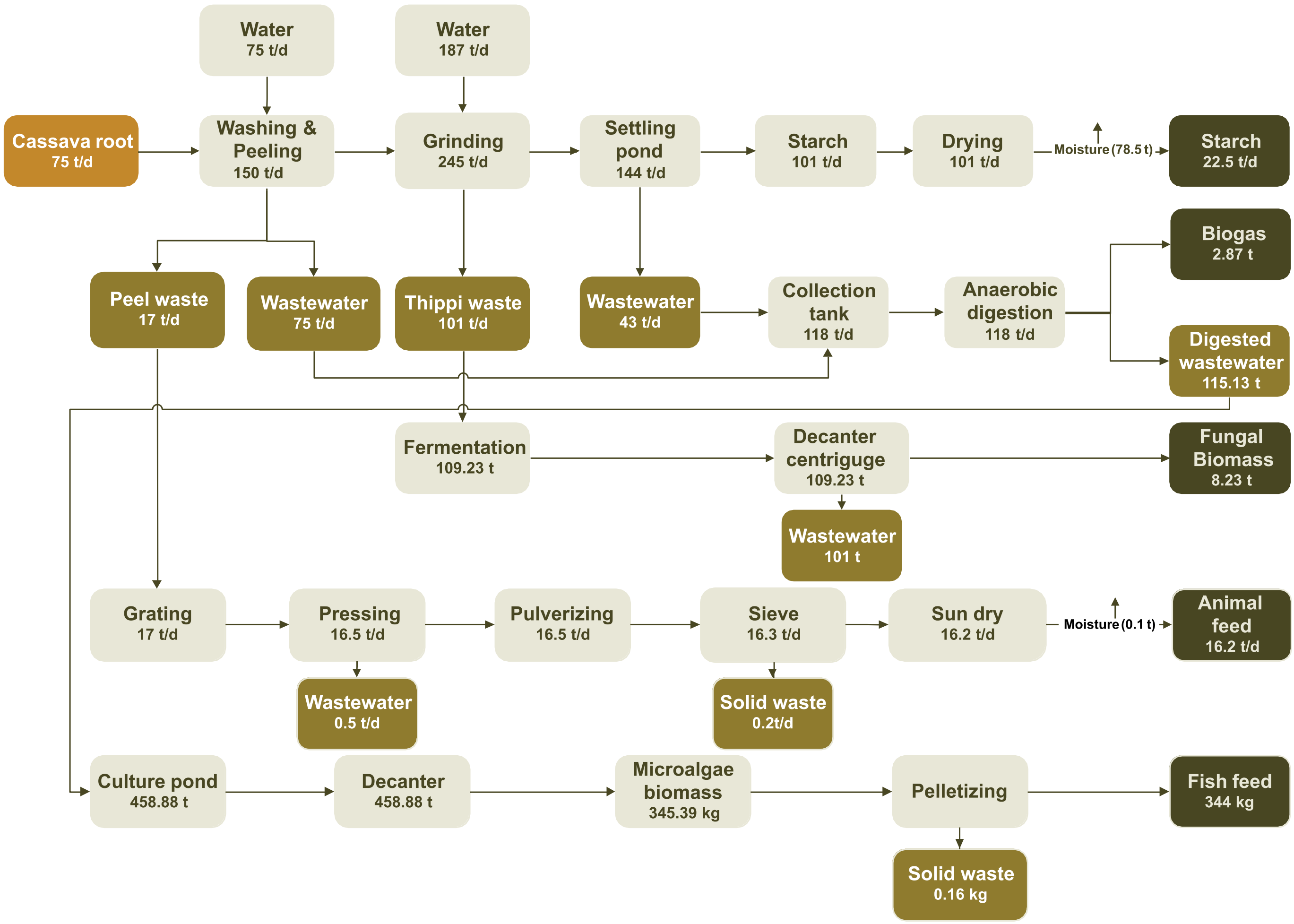

Fig. S5. Unit operations involved in Scenario 4.

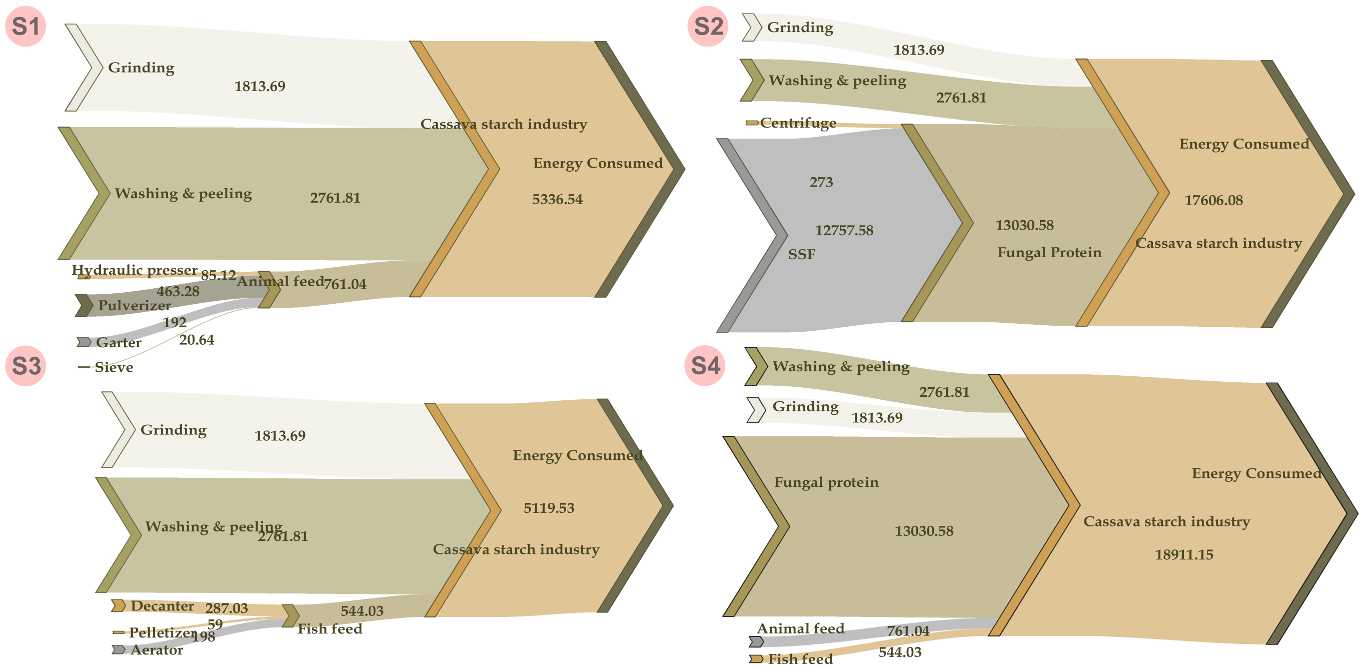

Fig. S6. Energy consumption in all the scenarios (kWh).

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Tables

Table S1.
Literature analysis for CO_2 avoidance.

Animal feed	GWP	per t	Ref.
Milled dairy feed	0.62 kg CO_2/kg feed	620	Adom et al. (2013)
Milled dairy feed	0.93 kg CO_2/kg feed	930	
AF from food waste	1064.6 kg CO_{2eq}/135 kg	7890	Alsaleh and Aleisa (2023)
Wheat feed	0.577 kg CO_2/kg feed	580	Styles et al. (2015)
Marginal wheat feed	1.38 kg CO_2/kg feed	1380	
Fish feed			
Extruded	1333.9 kg CO_2/t	1333.9	Wang et al. (2022)
Pelleted	1071.1 kg CO_2/t	1071.1	
Fish feed	1400 kg CO_2/t	1400	Rustad (2016)
	924.14 kg CO_2/t	924.14	Kallitsis et al. (2020)
Mycoprotein			
Mycoprotein	5.55–6.15 kg CO_{2eq} per kg	5850	Souza Filho et al. (2019)
	1.14 kg CO_{2eq} per kg	1140	Microbiology Society (2018)
	0.8 kg CO_{2eq} per kg	800	Derbyshire and Finnigan (2021)

Table S2.
Raw material costs and Selling prices of the products.

Raw material	Cost (USD)	Ref.
Cassava root	78/t	IndiaMart (2024)
Water	0.144/t	Time of India (2020)
Electricity	0.08/kWh	Statista (2024)
Labor cost	2.13 USD/per person	India-briefing (2024)
Products	**Selling price (USD/t)**	**Ref.**
Starch	0.624	IndiaMart (2024)
Animal feed	108	IndiaMart (2024)
Fungal protein	3983	Bulkan et al. (2020)
Fish feed	34680	IndiaMart (2024)

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Table S3.
The cost of equipment for different scenarios investigated in the present study.

Scenario	Equipment	Cost (USD)	Ref.
BAU	Cassava starch processer	150,000	Cassavastarchmachine.com (2024)
	Wastewater treatment unit	3,894	Padi and Chimphango (2020)
	Total	**153,894**	
	Salvage cost	38,474	
	Depreciation cost/yr	11,542	
S1	Animal feed unit	3,400	IITA (2024)
	Total	**157,294**	
	Salvage cost	39,323	
	Depreciation cost	11,797	
S2	Fermenter	9,100	IndiaMart (2024)
	Decanter	2,993	IndiaMart (2024)
	Total	**165,987**	
	Salvage cost	41,497	
	Depreciation cost	12,449	
S3	Pelletizer	2,993	TradeIndia (2024)
	Aerator	611	EASYPETS (2024)
	Total	**157,498**	
	Salvage cost	39,375	
	Depreciation cost	11,812	
S4	**All (Total)**	**172,991**	
	Salvage cost	43,248	
	Depreciation cost	12,974	

Table S4.
The cost of labour for different scenarios investigated in the present study.

All scenarios	Labour cost (USD)	Ref.
10 labours	1,780	India-briefing (2024)
Per annum (300 d)	534,000	

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Table S5.
Raw materials cost analysis for different scenarios investigated in the present study.

Scenario	Raw material	Cost (USD)
BAU	Cassava root	5,850
	Water	37.73
	Electricity	170.32
	Total	**6,058**
	per annum (300 d)	1,817,415
S1	Cassava root	5,850
	Water	37.73
	Electricity	227.76
	Total	**6,116**
	per annum (300 d)	1,834,648
S2	Cassava root	5,850
	Water	37.73
	Electricity	1,153.87
	Total	**7,041.59**
	per annum (300 d)	2,112,480
S3	Cassava root	5,850
	Water	37.73
	Electricity	211.38
	Total	**6,099.11**
	per annum (300 d)	1,829,733
S4	Cassava root	5,850
	Water	37.73
	Electricity	1,252.38
	Total	**7,140.11**
	per annum (300 d)	2,142,032

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Table S6.
Operational cost analysis for different scenarios investigated in the present study.

Scenario	Cost split up	Cost (USD)
BAU	Equipment cost	153,894
	Raw material cost	1,817,415
	Labour cost	534,000
	Total	**2,505,309**
S1	Equipment cost	157,294
	Raw material cost	1,834,648
	Labour cost	534,000
	Total	**2,525,942**
S2	Equipment cost	165,987
	Raw material cost	2,112,480
	Labour cost	534,000
	Total	**2,812,467**
S3	Equipment cost	157,498
	Raw material cost	1,829,733
	Labour cost	534,000
	Total	**2,521,231**
S4	Equipment cost	172,991
	Raw material cost	2,142,032
	Labour cost	534,000
	Total	**2,849,023**

Table S7.
Profitability analysis for different scenarios investigated in the present study.

Profitability analysis		
BAU		
Starch	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	7.19
	Selling price (USD/kg) total flow	0.624
Animal feed	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	7.19
	Selling price (USD/kg) total flow	0.108
	Revenue (USD/yr) final product	4,941,014
	Annual operating cost (USD)	2,505,309
	Gross profit (revenue-annual operating cost)	2,435,706
	Tax (22%)	535,855
	Net profit (USD)	**1,911,393**

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Table S7.
continued.

Profitability analysis		
S1		
Starch	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	7.34
	Selling price (USD/kg) total flow	0.624
Animal feed	Revenue stream flowrate (kg/yr product) total flow	11,610,000
	Production cost (USD/kg product) final product	47.63
	Selling price (USD/kg) total flow	0.108
	Revenue (USD/yr) final product	5,465,935
	Annual operating cost (USD)	2,525,942
	Gross profit (revenue-annual operating cost)	2,939,993
	Tax (22%)	646,798
	Net profit (USD)	**2,304,991**
S2		
Starch	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	7.76
	Selling price (USD/kg) total flow	0.624
Mycelium	Revenue stream flowrate (kg product /yr) total flow	2,469,000
	Production cost (USD/kg product) final product	21.24
	Selling price (USD/kg) total flow	3.98
	Revenue (USD/yr) final product	9,219,033
	Annual operating cost (USD)	2,812,467
	Gross profit (revenue-annual operating cost)	6,406,567
	Tax (22%)	1,409,445
	Net profit (USD)	**5,009,571**
S3		
Starch	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	7.35
	Selling price (USD/kg) total flow	0.624
Animal feed	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	7.35
	Selling price (USD/kg) total flow	0.108
Fish feed	Revenue stream flowrate (kg product/yr) total flow	103,200
	Production cost (USD/kg product) final product	480.74
	Selling price (USD/kg) total flow	34.68

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Table S7.
continued.

Profitability analysis		
	Revenue (USD/yr) final product	13,603,731
	Annual operating cost (USD)	2,521,231
	Gross profit (revenue-annual operating cost)	11,082,499
	Tax (22%)	2,438,149
	Net profit (USD)	**8,656,162**
S4		
Starch	Revenue stream flowrate (kg product/yr) total flow	6,750,000
	Production cost (USD/kg product) final product	8.08
	Selling price (USD/kg) total flow	0.624
Animal feed	Revenue stream flowrate (kg product /yr) total flow	4,860,000
	Production cost (USD/kg product) final product	11.22
	Selling price (USD/kg) total flow	0.108
Mycelium	Revenue stream flowrate (kg product /yr) total flow	2,469,000
	Production cost (USD/kg product) final product	22.10
	Selling price (USD/kg) total flow	3.98
Fish feed	Revenue stream flowrate (kg product/yr) total flow	103,200
	Production cost (USD/kg product) final product	528.81
	Selling price (USD/kg) total flow	34.68
	Revenue (USD/yr) final product	14,182,809
	Annual operating cost (USD)	2,849,023
	Gross profit (revenue-annual operating cost)	11,333,787
	Tax (22%)	2,493,433
	Net profit (USD)	**8,853,328**

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Table S8.
Multi-criteria decision-making (MCDM) performance score.

Varying the cost of raw material cassava root				
Scenarios	**-20%**	**-10%**	**20%**	**10%**
BAU	0.179	0.179	0.179	0.179
S1	0.193	0.193	0.193	0.193
S2	0.154	0.154	0.154	0.155
S3	0.191	0.191	0.191	0.191
S4	0.281	0.281	0.283	0.282
Varying the cost of electricity				
Scenarios	**-20%**	**-10%**	**20%**	**10%**
BAU	0.179	0.179	0.179	0.179
S1	0.193	0.193	0.193	0.193
S2	0.154	0.154	0.154	0.154
S3	0.192	0.192	0.192	0.192
S4	0.282	0.282	0.282	0.282
Varying the selling price of starch				
Scenarios	**-20%**	**-10%**	**20%**	**10%**
BAU	0.179	0.179	0.183	0.179
S1	0.193	0.193	0.196	0.193
S2	0.155	0.155	0.151	0.154
S3	0.191	0.191	0.193	0.191
S4	0.281	0.282	0.277	0.281

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