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Design and Capability Analysis of a Solar-Powered Conveyor for Water Hyacinth Removal: A Case Study at Kumphawapi Flood Gate

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Abstract

Water hyacinth is a fast-growing invasive plant that disrupts water management in tropical regions. This study presents the design and capability analysis of a solar-powered conveyor system for large-scale water hyacinth removal, demonstrated at the Wiang Kham Sluice Gate, Kumphawapi District, Udon Thani, Thailand. The prototype incorporates conveyor belts, picker wheels, and a photovoltaic power supply sized for off-grid operation. Motor drive requirements were calculated from friction, load, and torque data, while process capability indices (Cp) were applied to assess the stability of motor efficiency and removal rate. Experimental results indicated that a 1.5 kW motor was sufficient for both conveyor and picker wheel assemblies, maintaining efficiency above 76%. The machine achieved an average removal capacity of 60 t/h with Cp = 1.17, demonstrating acceptable yet further-optimizable process stability, suggesting potential for performance refinement through parameter adjustment. Economic analysis indicated that the proposed system has an estimated operating cost of around USD 2,700 per 58 ha per cycle, corresponding to a 3–6× cost reduction compared with conventional methods. These findings highlight the feasibility of integrating renewable energy with mechanical design for sustainable aquatic weed management.

Keywords: Water Hyacinth, Process Capability, Machinery Design, Conveyor System

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1. Introduction

The government currently has a policy for managing water hyacinth, including activities to maintain cleanliness and eliminate aquatic weeds, dredging canals, rivers, and drainage channels, particularly in densely populated areas. This persistent problem has prevented effective water use. Furthermore, canals and rivers are becoming shallow due to the accumulation of water hyacinth, water lettuce, duckweed, and various types of waste. This results in insufficient drainage during the rainy season, leading to flooding in the area, causing damage to communities and homes along the canals [1]. Furthermore, it has damaged the scenic beauty of riverbanks and impacted local livelihoods [2].

Water hyacinth is an invasive species that has infested Thailand's ecosystems [3]. It spreads rapidly. In one month, a single water hyacinth can multiply into as many as 1,000 plants [4]. Even if the water dries up and the plant dies, its seeds can survive for up to 15 years. Once the seed receives sufficient water, it will sprout new plants. This has become a serious and national problem, requiring the government to spend a significant amount of money on water hyacinth eradication. This problem is not limited to Thailand but is also present in over 50 countries worldwide [5].

Contemporary management strategies encompass human extraction, mechanized harvesting, herbicide treatment, and biological control. Each technique, meanwhile, exhibits significant disadvantages. Manual collection is cost-effective regarding equipment but requires significant work and is inefficient in high biomass scenarios [6]. Mechanical harvesters enhance efficiency but incur substantial capital and maintenance expenses and are inappropriate for shallow or narrow streams [5]. Herbicides offer swift suppression but may jeopardize water quality and ecosystem integrity [7]. Biological management is ecologically sustainable; however, it progresses slowly in achieving substantial reductions and is contingent upon species-specific limitations [7]. Moreover, the disposal of collected biomass poses challenges: inadequate management or valorization of decomposing plant material can emit greenhouse gases, resulting in further environmental and economic liabilities [8]. This expenditure underscores the necessity for integrated strategies that amalgamate the advantages of current methodologies, reduce energy expenditure, and augment the value or secure disposal of harvested biomass.

To solve these issues, this work proposes the design and development of a semi-automatic water hyacinth eradication device powered by solar energy. The prototype features a conveyor-belt system built from corrosion-resistant steel to carry biomass from the sea surface to the bank. The belt is supported by rollers and fitted with drainage channels to minimize water weight prior to release. Power requirements were derived from plant load, belt velocity, friction, and

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torque, with motor specifications set to withstand peak loads and integrate an acceptable safety factor. The structure was intended for ease of assembly, transport, and maintenance. Solar photovoltaic panels and batteries were sized according to the machine's daily energy need and the region's solar irradiance, enabling off-grid operation and alignment with clean energy and green technology principles [9].

Following construction, the prototype conducted performance testing and process capability evaluation (C_p) to measure operational stability and consistency. Key performance parameters included conveyance rate, biomass loss, and mean electricity usage. Economic analysis contrasted investment and operating expenses with those of standard removal procedures [6]. Unit cost and payback time calculations were undertaken to establish the financial sustainability and potential scalability of the system for community or agency-level implementation.

2. Theoretical Background and Literature Review

This section discusses the theoretical foundations and research for designing and assessing a solar-powered conveyor system for water hyacinth management. It covers literature reviews on equipment design [10,11], energy efficiency [12,13], and process capability [14,15].

2.1 Motor Power Calculation in Belt Conveyors

Accurate estimation of the motor drive power is essential for designing conveyor belt systems that operate efficiently and reliably [16,17].

The total power requirement is obtained by summing the components needed to overcome belt friction, to transport the material horizontally, to lift the load vertically, and to supply any auxiliary devices [18].

$$P = P_1 + P_2 + P_3 + P_t \qquad (1)$$

Where:

P = total required drive power (kW)
P_1 = horizontal power without load (kW)
P_2 = horizontal power under load (kW)
P_3 = vertical lifting power under load (kW)
P_t = power of auxiliary equipment (kW)
       Component Power Formulas

2.1.1 Horizontal power (no load)

$$P_1 = [f(\ell + \ell_0) \cdot W \cdot v] / 6120 \qquad (2)$$

2.1.2 Horizontal power – with load

$$P_2 = [f(\ell + \ell_0) \cdot Qt] / 367 \text{ or}$$
$$[f(\ell + \ell_0) \cdot Wm \cdot v] / 6120 \qquad (3)$$

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2.1.3 Vertical lifting power

$$P_3 = [H \cdot Qt] / 367 \text{ or}$$
$$[H \cdot Wm \cdot v] / 6120 \qquad (4)$$

Auxiliary Calculations

2.1.4 Total weight of moving parts

$$W = (Wc / pc) + (Wr / pr) + 2W_1 \qquad (5)$$

2.1.5 Horizontal power – with load

$$H = \ell \cdot \tan(\alpha) \qquad (6)$$

2.1.6 Vertical lifting power

$$Wm = Qt / (0.06 \cdot v) \qquad (7)$$

Where:

- f = Coefficient of friction of carrying rollers
- ℓ = Horizontal length of the conveyor (m)
- ℓ_0 = Equivalent length for return side or tensioning (m)
- H = Vertical lift (m)
- v = Belt speed (m/min)
- W = Weight of moving parts (kg/m)
- Wm = Weight of conveyed material per metre of belt (kg/m)
- Qt = Capacity of material conveyed (ton/hr)
- Pt = Power for auxiliary equipment (kW)

Employing such techniques allows researchers to establish the ideal motor rating, pick an appropriate safety factor, and analyze energy consumption for conveyor systems used in water hyacinth removal or other bulk-handling applications.

2.2 Photovoltaic (PV) System sizing calculations

The sizing of a photovoltaic system is crucial for its energy generation to meet the load demand of an electromechanical device, based on daily energy consumption, solar irradiance, and system losses [19].

2.2.1 Effective Output of a PV Module

$$P_{module,eff} = (P_{rate}/1000) \times EF \qquad (8)$$

2.2.2 Total Array Capacity and Number of Modules

$$P_{array} = P_{module,eff} \times N \qquad (9)$$

2.2.3 Daily Energy Production

$$E_{pv,day} = P_{array} \times PSH \qquad (10)$$

Where:

- P_{rate} = Rated peak power of a single PV module (Wp)
- EF = Energy yield derating facto
- P_{array} = Total effective array power (kW)
- N = Number of PV modules
- PSH = Peak Sun Hours (h/day)

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2.3 Motor Power Calculation for the Picker Wheel Assembly

The picker wheel assembly is crucial for lifting water hyacinth onto a conveyor system as shown in Figure 1, requiring accurate torque estimation for reliability and ensuring smooth operation under varying load conditions.
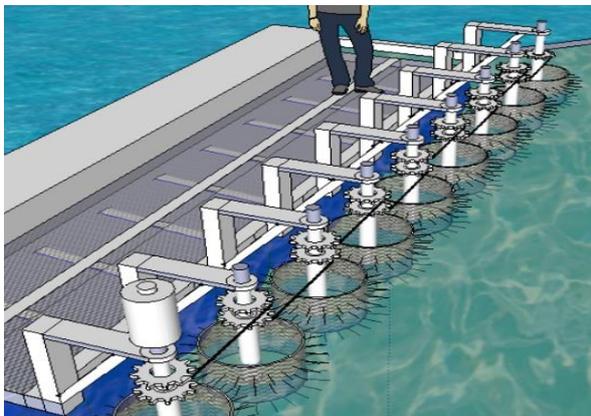
Figure 1. Picker wheel and accelerator drive of the water-hyacinth conveyor belt.

The motor power required to drive the picker wheel assembly was determined based on the torque generated by the combined weight of the wheel structure and the harvested water hyacinth [20,21]. The mechanical power (P) was calculated using the standard relationship:

$$P = (2 \times \pi \times N \times T) / 60 \qquad (11)$$

The torque necessary to rotate a single wheel was obtained from:

$$T = W \times g \times r \qquad (12)$$

Where:

P = the motor power (W)

N = the rotational speed (rpm)

T = the torque (Nm)

W = the total mass of the wheel (kg)

g = the acceleration due to gravity (9.81 m/s^2)

r = the wheel radius (m)

In literature review the effective eradication of invasive aquatic plants requires not only practical harvesting equipment but also a good theoretical basis and a thorough evaluation of the effectiveness of the process. Previous research on water hyacinth (Eichhornia crassipes) control has shown that harvesting equipment must consider mechanical design principles [21], proper material selection, and operational factors to ensure durability and efficiency. Successful systems must account for the plant's high biomass density, buoyancy, and fluctuating moisture content while being versatile for use in shallow or narrow streams. Researchers have proposed several alternatives, including lightweight but corrosion-resistant designs, improved delivery mechanisms, and energy-efficient power sources to ensure sustainable operation. Building on these findings, this study investigates a semi-automated, solar-powered conveyor system that enables continuous removal of water hyacinths as shown in Figure 2, reduces energy requirements for operation, and addresses environmental concerns.

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Another important component covered in the literature is the investigation of process stability using process capacity analysis [22]. In modern manufacturing and machine performance research, quality outcomes are determined by 3 phases: design, production, and inspection. Product specifications are set during design, production ensures these standards are met, and inspection verifies compliance. Process capacity analysis, often expressed by indices such as C_p or C_{pk} [23, 24], evaluates the variability of a process in relation to its design tolerances. This approach provides insight into the consistency and adequacy of operational systems. Applying process capability methods to water hyacinth removal machines provides an objective framework for analyzing throughput, accuracy, and energy efficiency under typical working conditions, while providing guidance for revising design parameters and maintenance procedures.
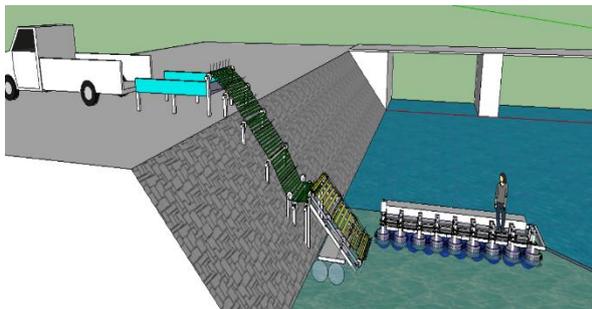
Figure 2. Water hyacinth removal concept using a trapping system with conveyor floats and conveyor belts.

3. Result

3.1 Machinery Design

The conveyor was designed to transport water hyacinth at a belt speed of 60 m/min. A friction coefficient of 0.035 was assumed for the belt and rollers. The average material weight per meter of belt was taken as 75 kg/m, giving a volumetric capacity of approximately 14.4 ton/h.

3.1.1 Stainless Steel Conveyor (Length = 3 m, Width = 1.5 m)

The total weight of the moving parts (excluding material) was calculated as:

$$W = (8/1) + (6/1) + 2 \times (10 \times 1.5) = 44 \text{ kg/m}$$

Vertical lift from the conveyor incline:

$$H = \ell \times \tan(\alpha) = 3 \times \tan(21°) \approx 1.1516 \text{ m}$$

Power components:

$$
\begin{aligned}
P_1 &= (0.035 \times (3+3) \times 44 \times 60)/6120 \\
&= 0.0906 \text{ kW} \\
P_2 &= (0.035 \times (3+3) \times 75 \times 60)/6120 \\
&= 0.1544 \text{ kW} \\
P_3 &= (1.1516 \times 75 \times 60)/6120 \\
&= 0.8468 \text{ kW}
\end{aligned}
$$

Total required power:

$$P_{total} = P_1 + P_2 + P_3 = 1.0918 \text{ kW}$$

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Considering the motor efficiency (η=76.54%):

$$P_{rated} = 1.0918/0.7654 = 1.426 \text{ kW}$$

3.1.2 UPVC Conveyor (Length = 10 m, Width = 1 m)

Weight of moving parts (excluding material, Figure 3):

$$W = (8/1) + (6/1) + 2 \times (5 \times 1.0) = 44 \text{ kg/m}$$

Vertical lift from the conveyor incline:

$$H = \ell \times \tan(\alpha) = 10 \times \tan(21°) \approx 3.8386 \text{ m}$$

Power components:

$$P_1 = (0.035 \times (10+10) \times 24 \times 20)/6120$$
$$= 0.0549 \text{ kW}$$
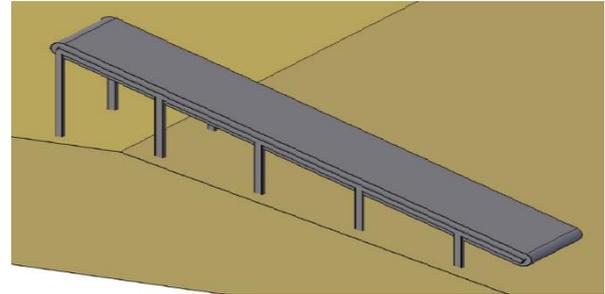$$P_2 = (0.035 \times (10+10) \times 50 \times 20)/6120$$
$$= 0.1144 \text{ kW}$$
$$P_3 = (3.8386 \times 50 \times 20)/6120$$
$$= 0.6272 \text{ kW}$$

Total required power:

$$P_{total} = P_1+P_2+P_3 = 0.7965 \text{ kW}$$

Considering the motor efficiency (η=76.54%):

$$P_{rated} = 0.7965/0.7654 = 1.046 \text{ kW}$$

Figure 3. Belt set with width 1.5 m, length 10 m, made from UPVC material.

Both calculations indicate that a 1.5 kW drive motor is appropriate for stainless steel and UPVC conveyors. The selected rating provides sufficient margin for transient loads, prevents over-temperature, and enhances the motor's operational lifespan. Furthermore, running below the rated power improves efficiency and tolerance to shock loads or accidental overloads.

3.1.3 Picker Wheel

The weight of one wheel was calculated from its components: a 1-mm stainless-steel plate (7.72 kg), a 1-inch stainless-steel tube (0.71 kg), and a 4-inch stainless-steel shaft (5.01 kg), giving 13.43 kg. Including the biomass mass of approximately 25 kg, the total load per wheel was:

$$T_{wheel}= (13.43+25) \times (9.81) \times (0.5)$$
$$\approx 188.5 \text{ Nm}$$

For a set of 12 wheels, the overall torque was:

$$T_{total} = 188.5 \times 12 = 2262 \text{ Nm}$$

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Motor Power Requirement Using a nominal rotational speed of N=4 rpm, the corresponding motor power was:

$$P = (2 \times \pi \times 4 \times 2262)/60 = 0.947 \text{ kW}$$

Considering the motor efficiency (η=76.54%):

$$P_{rated} = 0.947/0.7654 = 1.24 \text{ kW}$$

A 1.5 kW motor was chosen for its reserve capacity, ensuring adequate temperature even under rated load conditions.

3.1.4 Motor Efficiency Test Results

The efficiency of the drive motor was evaluated to verify its suitability for continuous operation in the water hyacinth removal system.
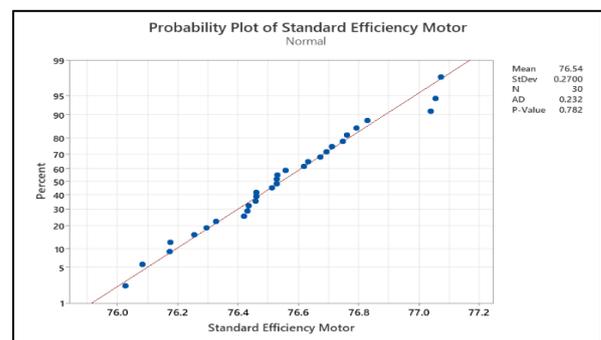

Figure 4. The motor efficiency test.

Tests were conducted under representative loading conditions, with input power and shaft output measured to determine overall performance as shown in Figure 4.
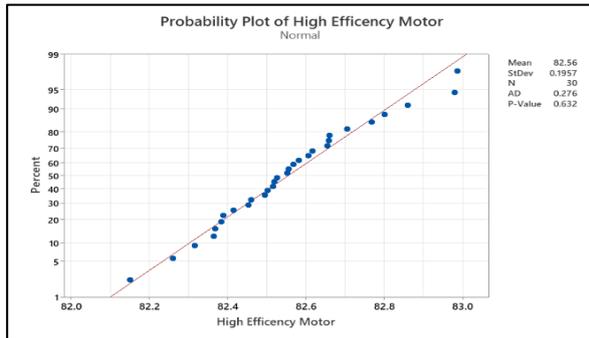
The results indicated that the standard-efficiency motor delivered an average efficiency of 76.54%, while a high-efficiency model of the same power rating achieved an average of 82.56%. These findings confirm that both options meet the operational requirements of the conveyor and picker wheel assemblies.

In Figure 5, the normality test results of the motor efficiency data, the P-value, was found to be greater than 0.05, indicating that the data did not deviate significantly from a normal distribution. Therefore, the efficiency measurements can be regarded as normally distributed, and subsequent statistical analyses, such as the calculation of mean efficiency and process capability indices, can be appropriately applied.

(a)

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(b)

Figure 5. Normality Test for (a) Standard Efficiency Motor (b) High Efficiency Motor.

3.1.5 The Photovoltaic (PV) System

The sizing of a photovoltaic system is crucial for its energy generation to meet the load demand of an electromechanical device, based on daily energy consumption, solar irradiance, and system losses. The design data, the PV system specifications include a rated module power of 645 W, an energy yield derating factor of 0.70, a peak sun hour value of 5.23 h/day, and a required load power of approximately 5 kW.

Effective power per module:

$$P_{module,eff} = (645\ W/1{,}000) \times 0.7$$
$$= 0.4515\ kW$$

Number of modules:
$$N = 5/0.4515 = 12\ modules$$

Select 12 modules, giving:

$$P_{array} = 12 \times 0.4515 = 4.515\ kW$$

Daily energy:

$$E_{pv,day} = 4.515 \times 5.23 = 23.6\ kWh/day$$

This capacity satisfies the energy requirements of the 1.5 kW conveyor motor with adequate margin.

3.2 Process Capability

Performance testing of the solar-powered conveyor prototype was conducted at Kumphawapi Flood Gate. Each test was performed under similar ambient conditions (temperature 31–34 °C, humidity 65–70 %) using naturally floating water hyacinth with an average biomass density of about 80 kg/m².

The machine operated continuously for 10 minutes per run, and the collected biomass was drained for 2 minutes before weighing with a 0.1 kg-precision digital scale. The throughput rate (Q = m/t) was computed and converted to tons per hour (t/h). Thirty repetitions n = 30 (Table 1) were performed to ensure measurement consistency and reproducibility.

The throughput data were analyzed using Minitab 21. Normality was verified by the Anderson–Darling test. The specification limits were set at USL = 67 t/h and LSL = 53 t/h, symmetrically centered around the design target of 60 t/h. Since the process mean was located at the center of the tolerance range, only the process capability index (Cp) was calculated as

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$$Cp = (USL\text{-}LSL)/6\sigma$$

$$(13)$$

Bootstrapped 95 % confidence intervals were generated to evaluate statistical stability. A $C_p \geq 1.33$ was considered indicative of adequate process capability.

Following the performance testing of the water hyacinth removal process, the process tolerance limits were set at 60 ± 0.4764 t/h. Process capability research done in Minitab produced a capacity index of C_p =1.17 (Figure 6). Although this number may be provisionally acceptable for a recently built process, it shows large variability and stays below the typically recommended requirement of $C_p \geq$ 1.33. Further variance-reduction measures are advised to boost capability.

Table 1. The machine achieved a removal capacity.

Run	Capacity (t/h)			Standard deviation (t/h)		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
1	60.4	59.8	60.7	0.67	0.33	1.17
2	59.3	60.1	58.9	0.95	0.15	1.02
3	60.5	61.2	59.7	0.33	0.83	0.5
4	60.8	59.6	60.2	0.4	0.67	0.2
5	61.3	60.9	60.5	1.1	0.85	0.6
6	59.5	60	59.2	0.75	0.45	0.6
7	60.1	60.3	59.7	0.5	0.8	0.3
8	60.6	60	60.8	0.33	0.17	0.58
9	59.4	58.9	60.1	1.05	0.75	0.55
10	60.7	61.0	60.2	0.45	0.6	0.35
11	60.5	60.8	59.9	0.38	0.52	0.42
12	60.3	59.8	60.1	0.3	0.65	0.55
13	60.0	59.7	60.2	0.62	0.48	0.4
14	59.8	60.6	59.9	1.0	0.7	0.9
15	61.2	60.4	60.1	0.45	0.33	0.67
16	60.5	60.2	59.6	0.3	0.4	0.55

Table 1. The machine achieved a removal capacity (con).

Run	Capacity (t/h)			Standard deviation (t/h)		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
17	60.7	60.9	60.1	0.25	0.5	0.35
18	59.6	60.3	60.0	0.55	0.45	0.28
19	60.4	59.8	59.9	0.33	0.22	0.48
20	60.2	59.7	60.5	0.4	0.65	0.5
21	60.0	60.3	59.5	0.58	0.47	0.37
22	60.5	60.8	60.2	0.72	0.53	0.48
23	60.3	59.9	60	0.5	0.44	0.36
24	60.1	60.2	59.8	0.35	0.55	0.25
25	60.6	60.4	60.3	0.65	0.7	0.6
26	60.2	59.6	60.0	0.28	0.4	0.38
27	59.9	60.1	59.7	0.33	0.45	0.29
28	60.4	60.2	60.6	0.6	0.42	0.47
29	60.5	60.8	60.3	0.38	0.55	0.4
30	59.8	60.0	60.4	0.41	0.49	0.31
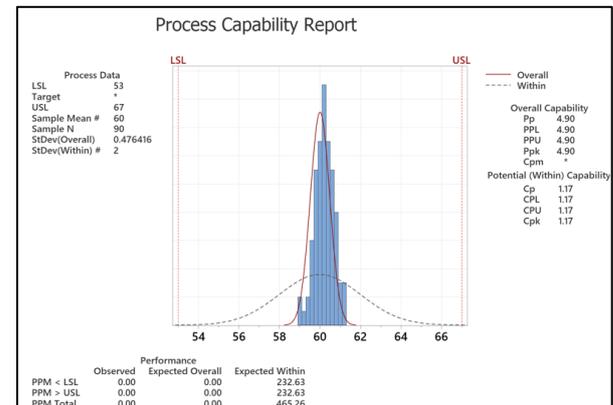
Figure 6: Process capability of water hyacinth removal process.

3.3 Economic Analysis

The survey encompassed 58 ha (360 rai) of water surface, which contained an estimated 28,800 tons of water hyacinth (about 80 tons). Table 2 offers a cost comparison between known water hyacinth control technologies, namely a small-scale

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collecting boat and a typical motorized harvester, and the suggested prototype system. The results suggest that the proposed innovation delivers the lowest operational cost, at an estimated operating cost of around USD 2,700 per 58 ha per cycle, corresponding to a 3–6× cost reduction compared with conventional methods.

These findings imply that the solar-powered conveyor-based removal equipment offers a highly cost-effective alternative for large-scale water hyacinth management, particularly in rivers with similar biomass density and access restrictions.

Table 2: Comparison of economic data

Item	Small-Scale Collection Boat	Mechanical Harvester Set	Proposed Prototype
1. Removal capacity (t/h)	10	50	60
2. Total cost of 58 ha per cycle (USD)	8,091	17,633	2,700

4. Discussion

The prototype successfully operated with a mean throughput of 60 t/h (n = 30), corresponding with the design aim. All throughput data were converted to tons per hour (t/h) to ensure unit consistency across analyses. The torque values for the picker wheels were collected from direct measurements of 12 wheels, each sustaining roughly 25 kg of wet biomass under field moisture conditions (≈ 75 % water content).

The observed torque–speed (T–rpm) profile verified sufficient driving margin for stable operation at 4 rpm, needing ≈ 1.2 kW of mechanical power.

The photovoltaic subsystem, rated at 4.52 kW, was designed to supply the 1.5 kW motor load in intermittent operation mode, where the conveyor and picker assemblies' function alternately rather than simultaneously. The 12-module array, paired with a 48 V – 200 Ah battery bank, supplied > 4 hours of backup on cloudy days, assuring enough energy availability during low irradiance periods.

Process capability analysis yielded C_p = 1.17, reflecting moderate variability within the tolerance range of 60 ± 7 t/h. Since the process was centered, C_{pk} ≈ C_p. The standard deviation (σ) produced from capability analysis was then used to construct 95 % confidence intervals (CI) for operational costs. The total cost of USD 2,700 ± 190 per 58 ha per cycle represents a 3–6× cost reduction compared to conventional mechanical or manual removal systems, confirming the statistical and economic feasibility of the design.

5. Conclusion

This research successfully designed, built, and tested a solar-powered conveyor machine for water hyacinth removal. Calculations of motor power, photovoltaic sizing, and picker wheel torque were consistent with field measurements, ensuring

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that a 1.5 kW motor provides adequate capacity and thermal margin. The process capability index confirmed acceptable stability for biomass removal, while economic evaluation highlighted significant cost savings compared with conventional technologies.

Future work should focus on refining process parameters to reduce variability, improving durability of structural components under continuous load, and exploring valorization of harvested biomass.

6. Acknowledgments

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