

Development and performance evaluation of a low-cost, dual-mode suction device for emergency medical care

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Abstract

There is a persistent lack of reliable suction capability for emergency airway management in rural Nigerian health facilities, where unstable grid power, high equipment costs and limited maintenance capacity frequently render conventional electric suction units unavailable or non-functional. Against this backdrop, a dual-mode medical suction device was developed from locally sourced materials in line with ISO 10079-1 standard. The system integrates a solar-powered electric mode with a manual backup mode in a single, portable unit. A 10 W, 12 V photovoltaic panel charges a 12.6 V, 5 Ah lithium-ion battery pack that supplies a 12 V DC diaphragm pump. An ESP32 microcontroller provides closed-loop electronic pressure control via pulse-width modulation, with real-time pressure feedback from an MPX5100DP differential pressure sensor displayed on an OLED screen. The manual mode employs a hand-operated pump connected to the same 2 L collection canister through a T-valve, enabling seamless switching between power modes without disconnecting the patient circuit. All components are housed wooden box of sides 27 cm each for structural rigidity, low cost and ease of local fabrication. The total fabrication cost was estimated at N141,860, a 40–70% reduction in the price of commercial electric suction units.

Keywords: Dual-mode operation; Emergency medical equipment; Medical suction device; Rural healthcare; Solar powered medical equipment

1. Introduction

Medical suction devices are mechanical or electromechanical instruments used to remove unwanted biological fluids or debris from the airway, surgical field or body cavities using vacuum technology [1,2]. In airway management, these devices are essential for clearing blood, vomitus and secretions to prevent obstruction, hypoxia and aspiration, especially in emergency and critical care [3]. Effective suctioning has been identified as a critical component of airway clearance, and inadequate suction capacity contributes to inefficient patient management and increased mortality in low-resource settings [4,5]. Clinically, suction systems operate by generating negative pressure relative to the atmosphere to enable fluid flow from the patient through tubing into a collection canister. Contemporary devices incorporate additional safety and usability features, such as pressure gauges, bacterial filters, overflow protection and adjustable regulators to ensure safe operation across different patient populations [6].

Suction systems may be broadly categorised as centralised wall suction, portable electrically powered devices and manual devices, with each category suited to particular clinical environments [7]. Central vacuum systems are permanently installed in hospitals and use pipeline networks to distribute suction from a central pump to wall outlets, providing high, consistent negative pressure but remaining immobile and entirely dependent on a reliable mains supply

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[8]. Their infrastructural and power requirements make them unsuitable for rural facilities where grid access is limited or absent.

Portable electrically powered suction devices have been developed to address mobility and access challenges, particularly in operating theatres, wards without pipeline suction, ambulances and pre-hospital care [9]. Ibitoye et al. [6] designed and fabricated an inexpensive portable suction device using a Thomas compressor–vacuum pump (Model 2107V, 220 V, 50 Hz, 1.3 A), a 2.5 L glass suction canister, bacterial filter, negative-pressure gauge and continuous pressure regulator housed in a galvanized iron compartment, targeting low, medium and high pressures of about 70, 90–100 and 120 mmHg suitable for infants and elderly patients. Their cost analysis indicated a material cost of approximately USD 63.5, and electrical safety tests using a Fluke ESA620 analyser recorded leakage currents of 0.1 μ A AC and 0.0 μ A DC and mains voltages around 228 V, 50 Hz, demonstrating compliance with IEC 60601-1 limits and safe clinical deployment. Joseph et al. [10] designed and constructed a low-cost suction machine for Lagos State primary healthcare needs using locally available components and a 220 - 240 V AC motor with provision for battery connection, emphasising affordability, ease of fabrication and suitability for primary health-care centres. Although such devices improve availability and reduce cost relative to imported equipment, they depend essentially on electricity and may become unusable during outages that frequently occur in low-resource settings.

Manual suction devices, including hand-operated, bulb and foot-operated mechanisms, provide an alternative where electricity is unavailable or unreliable [11,12]. Dawud & Abagaro (2025) developed a low-cost single foot-operated mechanical suction machine using a piston–cylinder assembly, a trash-bag diaphragm, a spring of stiffness about 3.5 kN/m and simple check valves fabricated from local materials, all mounted on a compact frame suitable for rural health centres and home care. Commercial foot-operated machines such as the Avishkar system, marketed for operating theatres and ambulances, similarly provide hands-free suction without electricity but are rarely documented with detailed suction performance data in peer-reviewed literature [13]. These trade-offs underline the need for suction devices that combine the convenience of powered operation with the reliability of manual backup in a single unit.

The design and performance of medical suction devices are guided by international standards that specify pressure ranges, flow rates and safety requirements. ISO 10079-1, which addresses electrically powered suction equipment, recommends occluded suction pressures in the range of about 80–150 mmHg for adults and 80–100 mmHg for neonates and paediatrics, and stipulates minimum free-air flow rates, typically 15–30 L/min for airway suction, to ensure rapid clearance [14]. The American Association for Respiratory Care (AARC) clinical practice guideline on endotracheal suctioning similarly recommends limiting occluded suction pressures to safe ranges for different age groups to minimise mucosal trauma and other adverse effects [3].

Nigeria's healthcare system, especially in rural and peri-urban communities, is severely constrained by unreliable electricity supply. National grid generation frequently falls below demand, leaving many primary and secondary facilities with intermittent power or no connection at all, and forcing dependence on petrol or diesel generators [15]. Fuel costs, maintenance burdens, noise, and emissions limit sustained generator use in low-budget facilities, while small solar installations are often undersized and primarily dedicated to lighting and vaccine refrigeration rather than powering medical devices [16].

These power-supply challenges directly affect the availability and reliability of electrically powered medical suction devices. Specific attempts have been made to apply solar power to suction and pumping applications. Adekoya et al. [17] reported the design, modelling, and fabrication of a portable solar-powered suction pump that uses a PV array, a battery bank and a locally sourced pump to provide continuous suction for industrial and auto clinic applications, demonstrating that appropriately sized solar and storage subsystems can sustain suction loads without direct mains power. Nevertheless, published reports of solar-powered suction devices specifically designed for emergency airway management in low-income rural healthcare settings remain scarce, and the integration of solar power with other redundancy modes has received limited attention. The broader literature on portable solar dual-storage systems suggests that combining different energy sources and storage elements can markedly improve reliability. Yet, these strategies have not been systematically applied to medical suction devices for rural emergency care. This gap indicates an opportunity for dual-mode suction systems that deliberately integrate electric (solar–battery) and manual modes while ensuring that failure in one mode does not affect the other.

2. Materials and methods

2.1. Design Specifications

The design specifications for the dual-mode suction device were established based on medical suction standards, power availability constraints in rural Nigerian healthcare settings, and cost limitations appropriate for resource-limited facilities. Table 1 presents the key design specifications that guided the device development. The rationale for the design specification involves the 27 cm cubic dimensions, which accommodate the 27 cm canister height vertically while providing adequate top surface area (27 × 27 cm) for mounting the 36 × 24 cm solar panel. The cubic form provides structural stability for the total system weight of 5-6 kg. The pressure range targets adult airway suction per ISO 10079-1 recommendations (80-120 mmHg). Also, the rationale of the design specification shown in Table 3.1b uses the 12V system voltage as the standard for solar components to ensure component availability. The 3S2P battery configuration provides approximately 4-5 hours of runtime. The 10 W solar panel provides adequate daily charging capacity for intermittent use patterns typical in rural healthcare. The ESP32 microcontroller provides sufficient capability for analogue-to-digital conversion, PWM generation, and I2C communication. A 3S2P lithium-ion battery configuration supplies a nominal 12.6 V compatible with 12 V system components while delivering a capacity of 5 Ah. A battery management system (BMS) module ensures safe lithium-ion operation through overcharge, over-discharge, and cell-balancing protection.

A 12 V DC diaphragm pump was selected for its moderate power consumption (0.8 A typical) and adequate vacuum pressure generation. The enclosure was constructed from plywood to provide structural rigidity, cost-effectiveness, and ease of local repair using basic woodworking tools. A commercial manual suction unit was adopted to ensure reliability and medical-grade performance. Real-time vacuum pressure measurement is achieved using the MPX5100DP pressure sensor with ±2.5 % accuracy. Most components were sourced locally, with electronics obtained from vendors in Lagos and Ibadan, solar equipment from Lagos suppliers, and medical components from medical distributors. The overall procurement process spanned approximately 2–3 weeks. Manual mode included as backup, not primary operation mode. This comparison informed the selection of solar-electric primary mode with manual backup, addressing both reliability (manual backup) and usability (solar-electric primary) requirements for rural healthcare settings. Table 2 presents a comparison of diverse design approaches considered and their limitations.

Table 1 System design specification

Parameter	Specification	Unit	Rational
Physical and mechanical parameters			
Overall dimensions	27 × 27 × 27	cm	Compact size
Target weight	<8	kg	Lightweight and mobility
Enclosure material	1.5 cm thick plywood		Availability and low-cost
Collection canister capacity	2	l	Similar studies (Ibitoye et al. 2023)
Patient interface tubing length	8	mm	
Suction pressure	70 – 120 (electric mode) 80 – 120 (manual mode)	mmHg	ISO 10079-1
Electrical and power parameters			
System operating voltage	12	V DC	
Solar panel power	10	W	Based on system sizing
Solar panel voltage	12	V	To meet the operating voltage
Battery configuration	3S2P (6 cells)		Manufacturer specification
Battery nominal voltage	12.6	V	Manufacturer specification
Battery capacity	5	Ah	System sizing
Battery energy storage	63	Wh	System sizing

Diaphragm pump voltage	12	V DC	
Diaphragm pump current	0.8	A	
Pressure control method	PWM via potentiometer		
Display type	OLED, 0.96 inch		
Microcontroller	Arduino Nano (Atmega 328P)		

Table 2 Comparison of Design Alternatives

Design Approach	Specification	Critical Limitation	Selected?
AC-Powered only	Simple, lowest cost	Grid Dependent	No
Battery-electric only	Portable	Requires grid charging	No
Solar plus battery	Grid independent	Moderate cost	Yes
Collection canister capacity	Always functional	Labour Intensive	No
Dual-mode (this works)	Reliable and convenient	Highest complexity	Yes

2.2. Engineering Design and 3D Models of the Dual-Mode Medical Suction Device

Also, the dual-mode medical suction device was meticulously modelled to capture both functional and structural requirements using SolidWorks as the main design platform, as shown in Figure 1. The software's adaptability enabled optimisation of component placement, structural stability, and ease of assembly, thereby producing a small, useful design, as shown in Figure 1, appropriate for both manual and electric modes of operation. The suction pump housing, collection canister, solar panel, tubing interfaces, power and control compartment, and supporting enclosure were all included in the design process.

2.3. System Description

The dual-mode suction device integrates multiple subsystems to provide reliable airway suction capability through either solar-powered electric operation or manual backup.

2.4. Power System

A 10-watt polycrystalline solar panel serves as the primary energy source, generating sufficient energy under Nigerian sunlight conditions to operate the device and recharge the battery. Six lithium-ion cells configured in a 3S2P arrangement provide 12.6V nominal voltage and 5Ah capacity, storing 63 watt-hours. The BMS module protects the battery by preventing overcharging, over-discharging, and provides overcurrent protection while balancing charge. An LM2596 buck converter regulates variable battery voltage to a stable 12V for the pump and 5V for logic circuits.

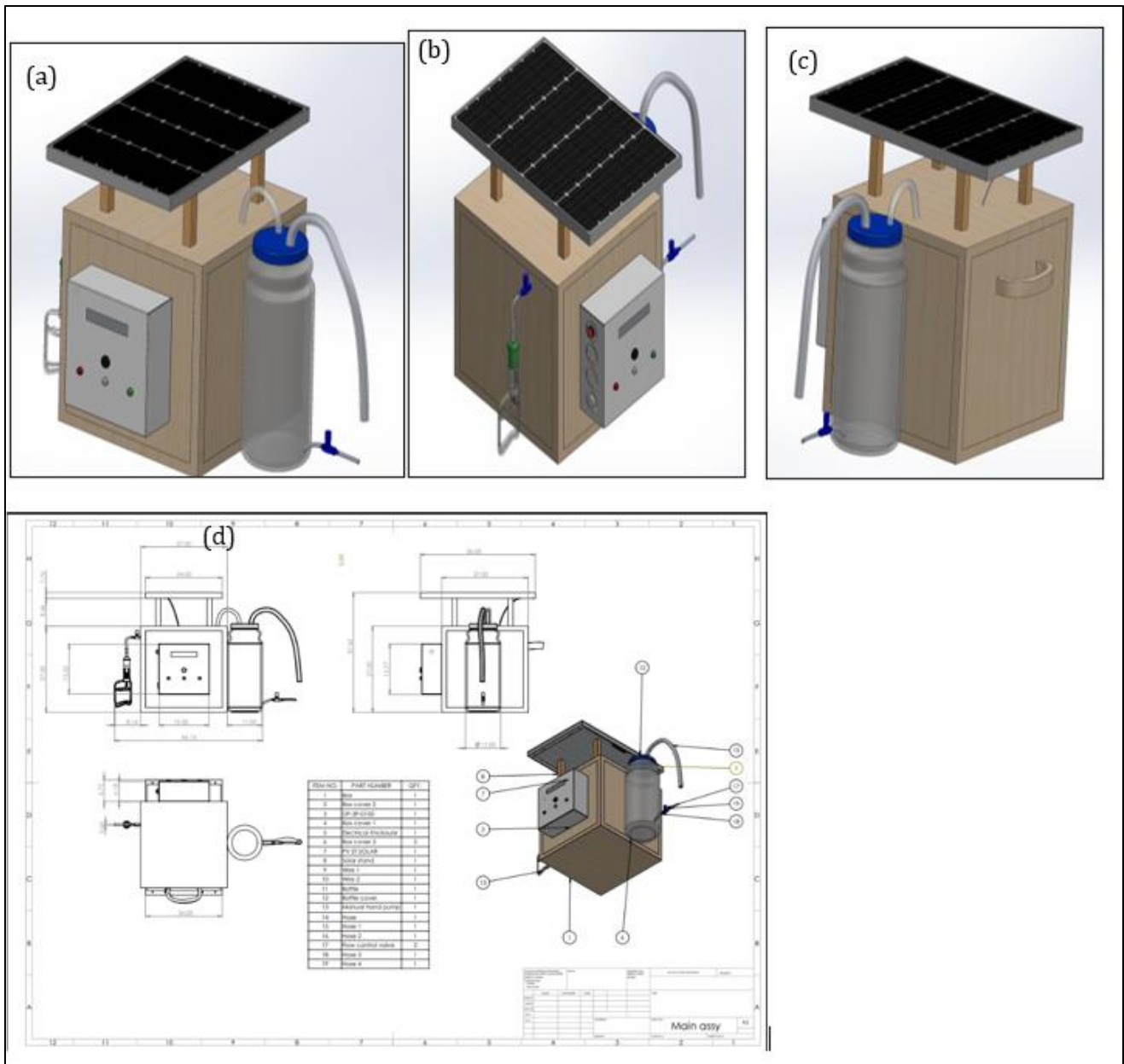


Figure 1 Engineering drawing of the Dual-Mode Medical Suction Device showing (a) Isometric front-right view (b) Isometric front-left view (c) Isometric back-right view (d) 2D orthographic views

2.5. Electric Suction Mode

The 12V DC diaphragm pump operates at 0.8A typical current with a maximum pressure capability of 6000 mmHg. The user adjusts a potentiometer, which the Arduino Nano (Atmega328P) reads via ADC and converts to a PWM signal controlling pump speed through a motor driver module. The MPX5100DP pressure sensor continuously measures vacuum. The Arduino Nano (Atmega328P) microcontroller reads sensor voltage and converts to mmHg, displaying real-time pressure on the OLED display, which shows operating mode, pressure, and battery status. LED indicators and a piezoelectric buzzer provide status feedback.

2.6. Manual Suction Mode

The pistol-grip manual suction device generates a vacuum through trigger actuation. One-way check valves maintain a vacuum between pump strokes, achieving 80-120 mmHg. The manual mode serves as a backup for emergencies. Both electric and manual vacuum sources connect to the collection canister through a T-tube connector.

A flow control tap integrated into the patient tubing serves dual purposes. It facilitates system priming by allowing pressure buildup during initial pump operation and provides clinical flow rate adjustment. The tap is essential for optimal pump performance, particularly when operating against gravity. A drain tap mounted at the canister base allows convenient fluid disposal without removing the lid, reducing spill risk and simplifying handling of infectious materials. The major components of the manual suction mode setup are shown in Figure 2.

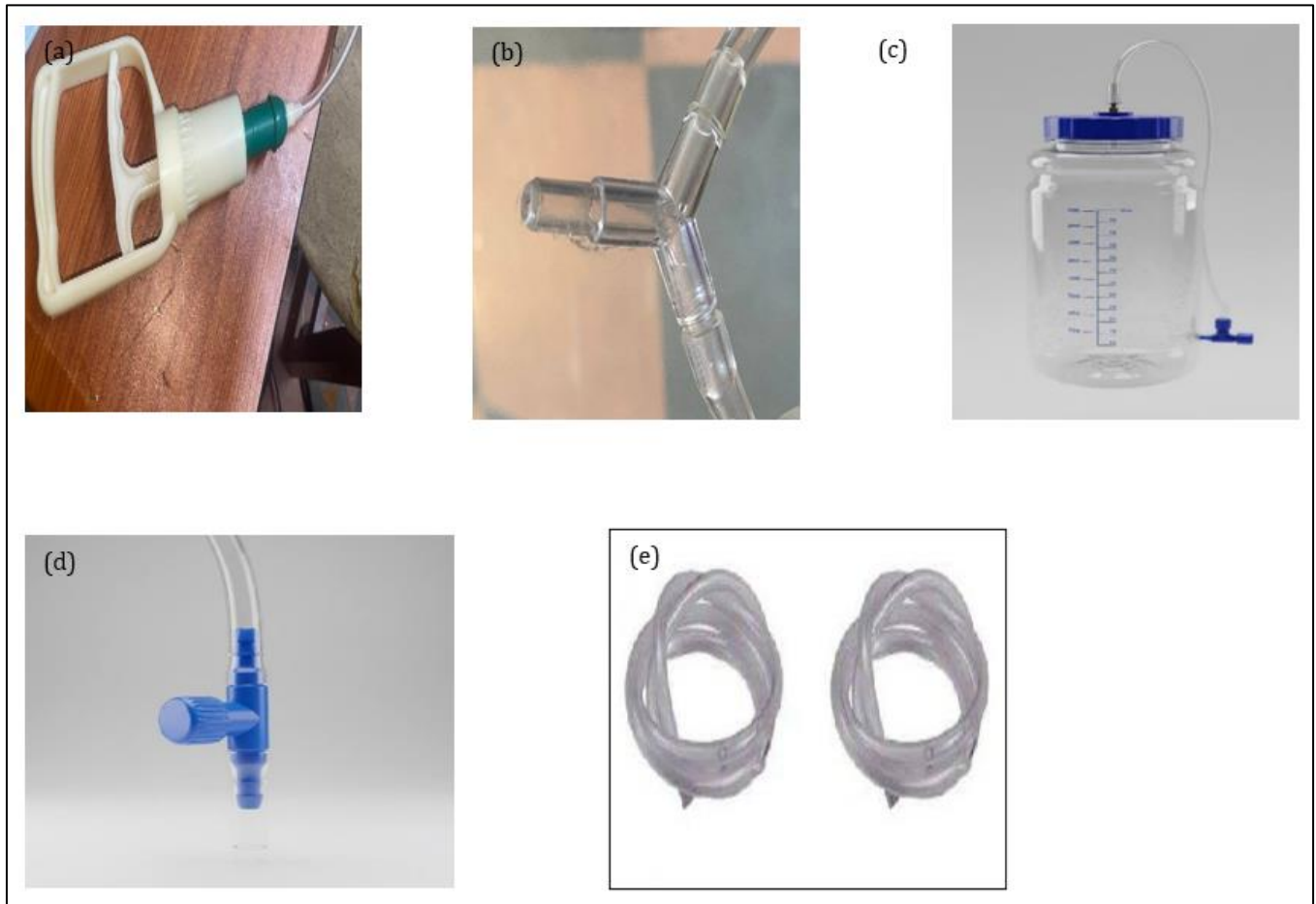


Figure 2 Manual Mode and Collection Components (a) Manual Pump, (b) T-Valve, (c) Canister with drain tap at base, (d) Flow control tap, (e) Tubing

2.7. Control System

The Arduino Nano (Atmega328P) microcontroller manages all electronic functions, including ADC reading, PWM generation, I2C communication, battery voltage monitoring, and alarm logic, as shown in Figure 3. The control loop executes at approximately 10 Hz, continuously reading potentiometer position, mapping to desired pressure, reading actual pressure, generating PWM to achieve the target, monitoring battery voltage, updating display, and activating alarms if needed. The control panel mounts on the front face with an OLED display centred at the top, a potentiometer knob on the right, a power button on the left, and LED indicators flanking the display.

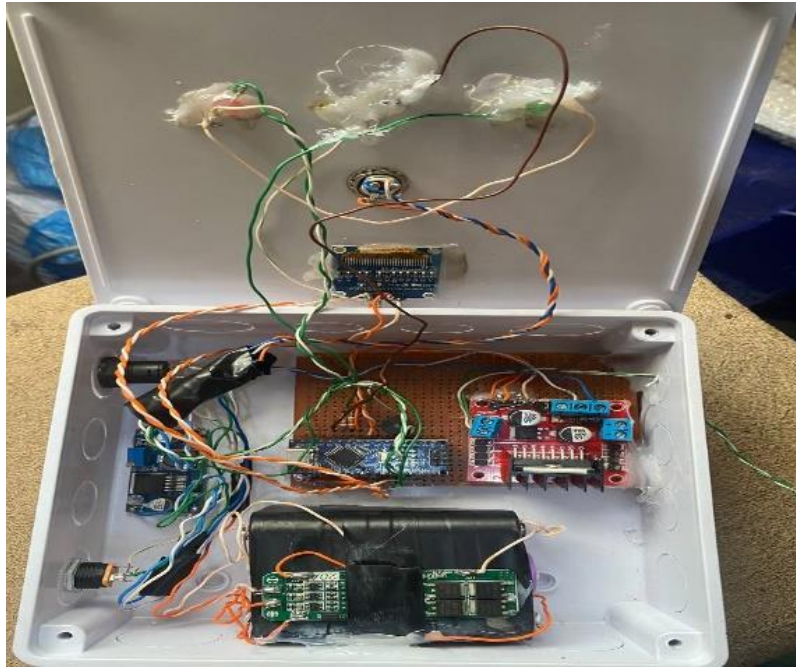


Figure 3 Control panel assembly

2.8. Structural components

The wooden enclosure as shown in Figure 4 provides structural support while remaining cost-effective and locally repairable. Plywood was selected for load-bearing capacity, light weight, low cost, ease of fabrication with basic tools, and repairability by local carpenters, which is critical for long-term sustainability in rural settings.



Figure 4 Structural Component

2.9. Design Calculations

Design calculations were performed to validate component sizing and predict system performance. These calculations ensured the battery capacity, solar panel output, and power consumption were properly matched for reliable operation in rural healthcare settings. The following subsections present key calculations for battery runtime, solar charging requirements, and power consumption analysis.

2.10. Battery Capacity and Runtime

The battery system was designed to provide sufficient runtime for intermittent daily use in rural healthcare settings. Based on typical emergency airway suction demand of 2–5 minutes per patient and 5–10 procedures per day, a minimum continuous runtime of 4 hours was selected as the design target.

A 3S2P lithium-ion battery pack using 18650 cells (3.7 V, 2500 mAh each) was adopted, delivering a fully charged voltage of 12.6 V and a total capacity of 5 Ah. Lithium-ion chemistry was chosen over lead-acid alternatives due to its higher energy density (approximately 150 Wh/kg compared to 30–50 Wh/kg), longer cycle life (over 500 cycles), and lower weight, which are critical for portable medical devices.

2.11. System Power Budget

The estimated system power consumption was determined from component specifications:

- Diaphragm pump (medium setting): $12\text{ V} \times 0.8\text{ A} = 9.6\text{ W}$
- Control electronics (microcontroller, display, sensors, and driver): approximately 2 W
- Total estimated power consumption: approximately 12 W (1.0 A at 12 V)

2.12. Given Parameters:

Total system current: approximately 1.0A at 12V

- Battery capacity: 5Ah
- Battery energy: 63Wh

2.13. Runtime Calculation

Theoretical runtime calculated using:

$$t = \frac{c}{I} \quad (1)$$

Where:

t = runtime (hours)

c = battery capacity (Ah)

I = current (A)

Theoretical runtime, $t = \frac{5\text{Ah}}{1\text{A}} = 5\text{ hours}$ (theoretical)

Accounting for system efficiency losses (battery discharge efficiency, power conversion losses, pump inefficiency), a combined efficiency factor of 0.8 is applied:

Practical runtime = 5 hours $\times$ 0.8 = 4 hours

This provides adequate operational time for daily use with overnight or solar recharge.

Solar Panel Sizing and Charging Time

2.13.1. Given Parameters:

Battery capacity: 63Wh

Solar panel: 10W at 12V

System efficiency: 0.7

Effective Power:

$$P_{\text{effective}} = P_{\text{rated}} \times \eta_{\text{system}} \quad (2)$$

Where $P_{\text{effective}}$ = effective charging power (W), P_{rated} = rated panel power (W), η_{system} = system efficiency (0.7)

Effective power = 10 W × 0.70 = 7 W

2.13.2. Charging Time

$$t_{charge} = \frac{E_{battery}}{P_{effective}} \quad (3)$$

Where t_{charge} = charging time (hours), $E_{battery}$ = battery energy (Wh)

Charging time = $\frac{63Wh}{7W} = 9 \text{ hours}$

2.13.3. Daily Energy Balance

$$E_{daily} = P_{effective} \times t_{sun} \quad (4)$$

Where E_{daily} = daily energy harvested (Wh), t_{sun} = peak sun hours

Daily energy harvested = 7W × 5 hours = 35Wh

Daily consumption (1 hour) = 12W × 1 hour = 12Wh

Net daily energy = **+23Wh**

2.14. Power Consumption Analysis

2.14.1. Electric Mode:

Diaphragm pump: 9.6 W

Electronics: ~2 W

Total: 11-12 W

2.14.2. Standby Mode:

Electronics only: 0.6 W

Standby runtime: 100 hours

2.15. Fabrication Process

2.15.1. Component Procurement and Enclosure Construction

Components were sourced from Nigerian suppliers: electronics from Lagos/Ibadan, solar equipment from Lagos, and medical devices from medical suppliers. Plywood sheets were cut into six 27×27 cm panels, edges sanded, holes drilled for control panel cutout, tubing, and wiring. Panels assembled with screws and glue, corner braces added, one panel removable for maintenance.

2.15.2. Electrical and Mechanical Integration

Battery pack constructed in a 3S2P configuration, connected to BMS. Power distribution established on the Vero board. Arduino Nano (Atmega328P) installed, all sensors and interface components wired. Motor driver and pump wired with PWM control. Firmware programmed implementing ADC reading, PWM generation, I2C communication, pressure calculation, and control logic.

Diaphragm pump mounted with vibration isolation, manual device positioned, T-valve and flow control tap installed, connecting pump outputs to the collection system. Drain tap installed at canister base. All hoses connected and leak-tested. Control panel components installed and secured. Solar panel mounted on top, all wiring organised.

2.15.3. Initial Functional Testing

Power-on test procedures verified system initialisation requirements and display function expectations. Electric mode test protocols confirmed pump activation sequences, pressure sensor response requirements, and vacuum generation targets. The design incorporated the flow control tap to facilitate priming by allowing pressure buildup. Manual mode test procedures confirmed hand pump vacuum generation requirements and check valve function specifications. Mode switching verification protocols ensured clean transitions. Solar charging verification procedures confirmed panel connection requirements and expected battery voltage increase patterns.

3. Results and Discussions

3.1. Final Prototype Specifications

The fabricated prototype achieved the specifications presented in Table 3. Figure 5 shows the fabrication stage and the completed dual-mode suction device as fabricated. The completed prototype demonstrates successful integration of all subsystems within the 27×27×27 cm wooden enclosure. The front panel displays the OLED screen, potentiometer knob, power button, and LED indicators as designed. The solar panel is securely mounted on the top surface. The total weight of 5.85 kg confirms lightweight portability for clinical settings.

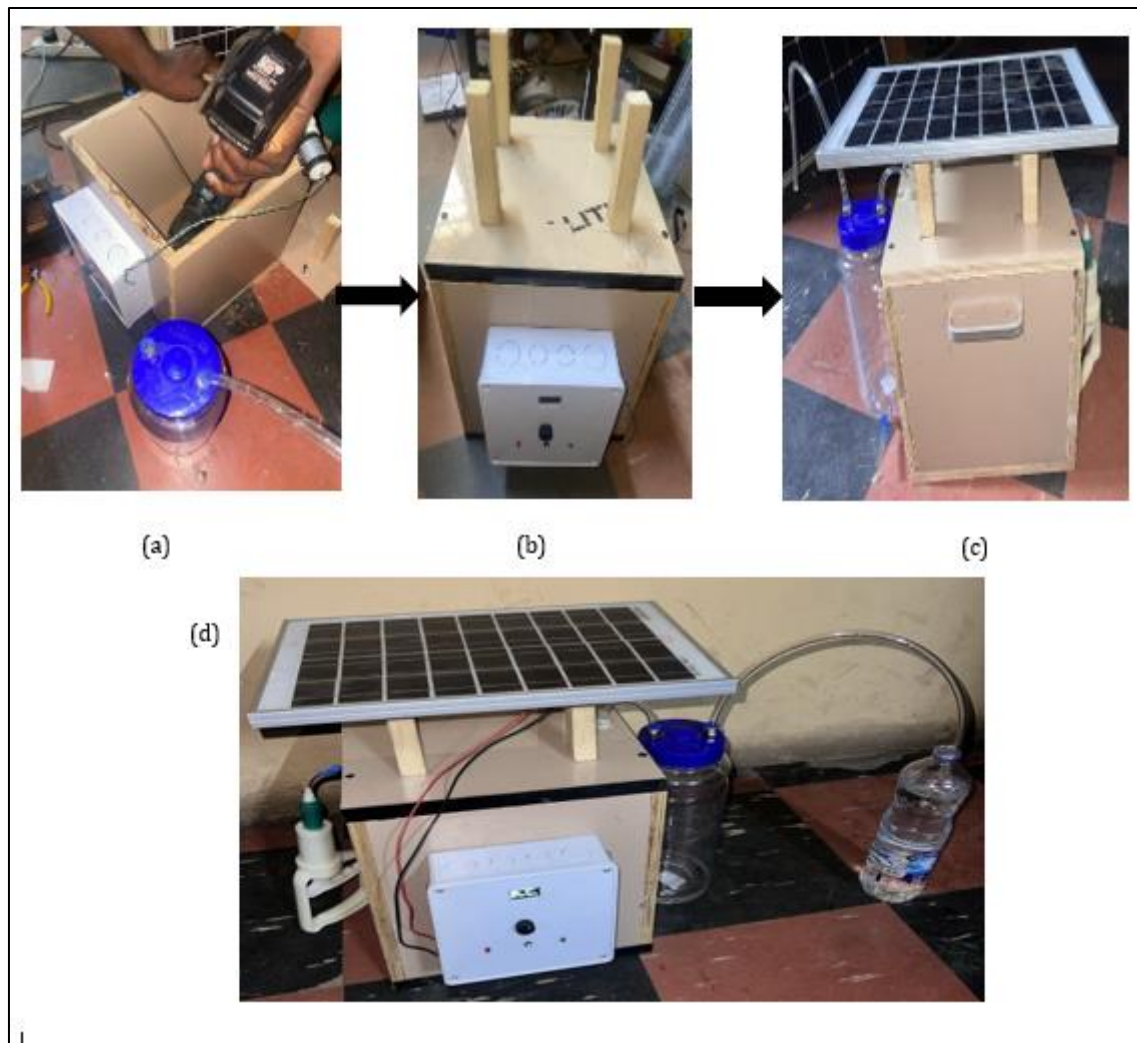


Figure 5 Prototyping Stage and Final Prototype Structure (a) Prototyping Stage, (b) Wooden Structure with only Control Panel, (c) Back view of Final Prototype, (d) Final Prototype Complete Structure

Table 3 Final Prototype Specifications

Parameter	Specification	Unit
Overall dimension (L x W x H)	27 x 27 x 27	Cm
Total weight (with battery)	5.85	Kg
Battery configuration	3S2P / 5Ah	-
Solar panel	10W, 12V	-
Suction pressure range (electric)	72-118	mmHg
Max pressure (manual)	95	mmHg
Flow rate (medium setting)	3.8	L/min
Battery runtime (medium setting)	4.2	hours

3.2. Performance Testing Results

This section presents the experimental results from performance testing of the dual-mode suction device. All tests were conducted under controlled conditions using a fully charged battery to ensure consistency and repeatability. Results are presented in tabular form with a brief analysis linking measured performance to clinical requirements and applicable medical device standards. Evaluated parameters include suction pressure, flow rate, power consumption, and mode-specific performance.

Performance testing measured suction pressure at three settings and flow rate at the medium setting. Testing was conducted at room temperature ($\sim 25^{\circ}\text{C}$) with a fully charged battery (12.6V). Flow rate at the medium setting was determined by measuring the time required to remove a known volume of water. Using a graduated cylinder filled with 1000 mL, the device was activated, and the time was recorded until the cylinder was empty. Flow rate was calculated using:

$$Q = \frac{V}{t} \quad (5)$$

Where:

Q = flow rate (L/min)

V = volume removed (L)

t = time elapsed (min)

For example, at medium setting, removing 1.0 L in 15.8 seconds yields:

$$Q = \frac{1.0\text{L}}{(15.8/60)\text{ min}} = 3.8 \text{ L/min}$$

Flow rates at low and high settings were estimated using the turbulent flow relationship ($Q \propto \sqrt{\Delta P}$) scaled from the measured medium setting value. Reynolds number analysis indicated a turbulent flow regime ($\text{Re} \approx 10,000$) in the 8 mm diameter tubing of the system at typical flow velocities.

Using this relationship and the measured medium setting as a reference:

$$\text{Low: } Q = 3.8 \times \sqrt{(72/91)} = 3.4 \text{ L/min}$$

$$\text{High: } Q = 3.8 \times \sqrt{(118/91)} = 4.3 \text{ L/min}$$

Power consumption was calculated from measured voltage and current:

$$P = V \times I \quad (6)$$

Where:

P = power (W)

V = voltage (V)

I = current (A)

3.3. Analysis

Measured pressures of 72-118 mmHg (electric) and 95 mmHg (manual) meet ISO 10079-1 recommendations for adult airway suction (80-120 mmHg). Flow rate of 3.8 L/min falls within the typical range for portable suction devices (2-10 L/min) and is adequate for emergency airway clearance. Pressure sensor displayed readings within ± 2 mmHg of the external gauge, confirming $\pm 2.5\%$ sensor accuracy specification.

The flow control tap proved essential for optimal pump operation. Initial testing revealed the diaphragm pump required back-pressure buildup to overcome system resistance and gravity effects, particularly when drawing fluid from below the pump level. Partially closing the tap during priming enabled the pump to establish an adequate vacuum, after which the tap could be opened for clinical flow rates. This refinement enhances both device functionality and clinical utility. A summary of the measured performance parameters is presented in Table 4, while the graphical representation of performance vs PWM and battery discharge are shown in Figure 9.

Table 4 Measured Performance Parameters

Setting	Pressure (mmHg)	Current (A)	Power (W)	Flow Rate (L/min)
Low	72	0.62	7.4	3.4*
Medium	91	0.81	9.7	3.8
High	118	1.05	12.6	4.3*
Manual	95	-	-	4.1

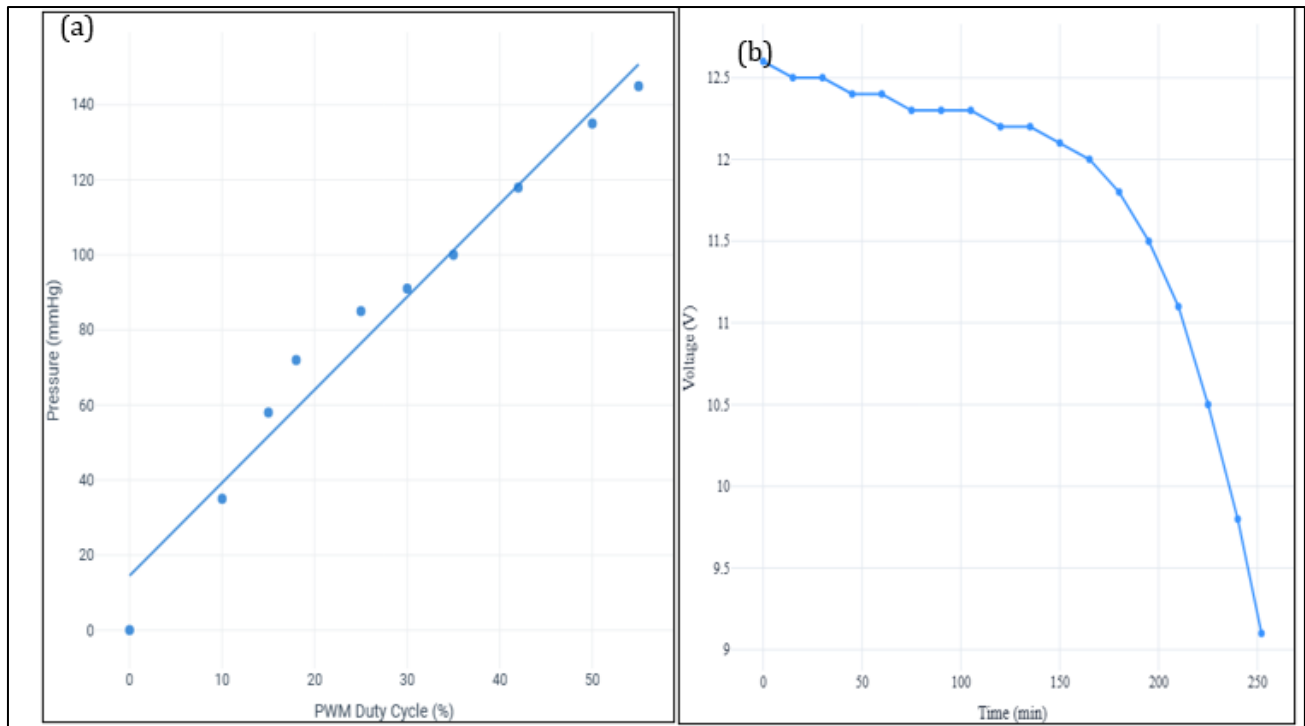


Figure 9 Performance analysis a) Pressure Vs. PWM Graph b) Battery discharge curve

3.4. Electrical Performance

Battery runtime testing at medium setting demonstrated 4.2 hours of continuous operation before BMS shutdown at 9.1 V, slightly exceeding the calculated 4-hour runtime (Section 3.4.1). This runtime is substantially longer than many commercial portable suction units that typically provide about 45–90 minutes of operation on a full charge (e.g. Laerdal LSU $\approx$ 45 min, SSCOR and UNICEF-spec units $\approx$ 45–90 min) and is comparable to higher-end systems such as the Gomco OptiVac and SAM e.p.s units, which report approximately 2–3 hours at maximum vacuum and up to 11 hours at low settings. Voltage under load measured 12.4 V at medium setting, representing only a 0.2 V drop from the 12.6 V open-circuit voltage, indicating good battery and wiring performance under typical operating conditions. Current draw ranged from 0.62 A to 1.05 A across settings, corresponding to 7–13 W power consumption; this is within the range expected for low-flow portable suction devices and easily satisfies ISO 10079-1 minimum requirements for battery-powered suction equipment, which specify at least 20 minutes of operation at 40 kPa vacuum and 2 L/min free-air flow on a fully charged battery. Details of the battery performance are displayed in Table 5.

Table 5 Battery Performance

Parameter	Measured Value	Unit
Battery runtime (medium, continuous)	4.2	Hours
Voltage at start	12.6	V
Voltage at shutdown	9.1	V
Average current draw (medium)	0.81	A

3.5. Cost Analysis

The device was fabricated for N142,360, achieving 40-70% cost reduction compared to commercial electric suction units (N200,000-350,000). Cost breakdown by subsystem is presented in Table 6.

Table 6 Cost Summary

Subsystem	Cost (N)	Percentage (%)
Mechanical and suction components	53,300	37.4
Power system (solar, battery, BMS)	38,000	26.7
Control electronics	32,790	23.0
Structural (wooden enclosure)	10,000	7.0
Miscellaneous	8,270	5.8
TOTAL	142,360 (\$105)	100

For rural healthcare facilities with annual equipment budgets of N500,000-1,000,000, the device consumes 14-28% of the budget compared to 20-70% for commercial electric units.

4. Discussions

4.1. Performance Relative to Standards

The measured performance complies with ISO 10079-1 requirements for medical suction devices. Pressure outputs of 72–118 mmHg (electric mode) and 95 mmHg (manual mode) fall within the recommended range for adult airway clearance (80–120 mmHg). The measured flow rate of 3.8 L/min lies within the typical range for portable suction devices (2–10 L/min) and is sufficient for emergency airway management.

The pressure sensor accuracy of ± 2 mmHg ($\pm 2.5\%$ of reading) satisfies medical device precision requirements. The dual-mode configuration ensures continued operation during power outages, directly supporting the device's intended use in resource-limited environments.

4.2. Comparison with Similar Work

The University of Ilorin electric suction device developed by Ibitoye et al. (2023) achieved pressure outputs of 70, 90 and 120 mmHg at a fabrication cost of about N30,000– N40,000 (\$26 – 85); however, it operates solely on AC mains power, restricting use to locations with reliable electricity. In contrast, the present device, fabricated at a cost of N142,360 (\$105), prioritizes solar-powered operation with integrated manual backup, significantly improving reliability in off-grid rural settings.

Commercial battery-powered suction units available in Nigeria (N300,000–500,000) still depend on grid electricity for charging. The proposed solar-powered system eliminates this dependency. The 10 W solar panel provides sufficient daily energy recovery under typical Nigerian solar conditions (≈ 5 peak sun hours), enabling sustainable off-grid operation.

4.3. Deployment Considerations

Deployment considerations include usability, environmental durability, and maintenance sustainability. The simple user interface, which comprises a potentiometer, power button, OLED display, and LED indicators, supports rapid operation during emergencies by healthcare workers with varying technical skill levels. Dual-mode operation provides redundancy without complex switching procedures. The wooden enclosure offers cost-effectiveness and local repairability but requires moisture-resistant sealing for long-term durability in humid tropical environments to prevent warping or structural degradation. Sustainability depends on the local availability of consumables, including patient tubing, canister seals, and replacement batteries (estimated lifespan of 2–3 years). The use of standard 18650 lithium-ion cells and commonly available electronic components supports maintainability.

5. Conclusions

The study has demonstrated that a reliable, low-cost, and power-independent medical suction device can be developed using locally available components. The prototype meets ISO 10079-1 suction standards at a fabrication cost of

N142,360, offering substantial savings over commercial alternatives while ensuring operational reliability through dual-mode redundancy.

Although further refinement, field validation, and regulatory approval are required, the prototype establishes a strong proof of concept. The context-sensitive design approach adopted highlights the potential of appropriate engineering solutions to improve emergency healthcare delivery in rural and underserved communities. The prototype will also serve as a reference framework for future low-cost medical device development in resource-limited settings.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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