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Design and Performance Assessment of a Photovoltaic-Driven Decortication System for Sustainable Groundnut Processing in Off-Grid Agricultural Communities

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Abstract: *The mechanization of post-harvest operations in the groundnut sector remains a persistent challenge across rural India, where conventional shelling practices are labour-intensive, inefficient, and prone to high kernel breakage. Concurrently, millions of smallholder farmers operate in regions characterized by unreliable electrical grid infrastructure, rendering conventional motorized equipment impractical. This study addresses both challenges through the development and empirical evaluation of a photovoltaic-driven decortication system engineered for off-grid deployment. The proposed apparatus integrates a 25-watt polycrystalline solar module, a pulse-width-modulated charge regulation unit, a 12V sealed lead-acid battery bank, and a high-torque DC gear motor coupled to a concave-cylinder shelling mechanism. Controlled field experiments were conducted to quantify key performance indicators including decortication efficiency, kernel integrity rate, volumetric throughput, and energy autonomy under varying solar irradiance conditions. The system demonstrated a decortication efficiency of 87–92%, a kernel damage rate below 6%, and a processing throughput of 9–13 kg/h—representing a four-fold improvement over manual methods. Energy autonomy tests confirmed sustained operation for 2.5–3 hours under overcast conditions using stored battery energy alone. These findings establish the technical viability and economic attractiveness of solar-integrated decortication technology as a scalable pathway for sustainable post-harvest processing in energy-deficient agricultural regions.*

Keywords: Photovoltaic decortication, off-grid agricultural mechanization, groundnut processing, solar-driven machinery, post-harvest technology, renewable energy integration, rural sustainability

I. INTRODUCTION

Groundnut (Arachis hypogaea L.) occupies a position of considerable agronomic and economic significance in the Indian agricultural landscape. As the second-largest producer of groundnuts globally, India dedicates approximately 5 million hectares to the crop annually, with production concentrated in the states of Gujarat, Andhra Pradesh, Rajasthan, Tamil Nadu, Karnataka, and Maharashtra. The crop serves a dual purpose: as a primary source of edible oil and as a protein-rich dietary staple for rural populations. Despite this importance, the post-harvest value chain for groundnuts suffers from critical inefficiencies, particularly at the shelling stage.

In the vast majority of rural production centres, groundnut shelling continues to be performed through manual labour—either by hand-pressing or through the use of rudimentary wooden implements. These methods are inherently constrained in throughput, typically yielding only 2–5 kg of shelled output per operator per hour. Beyond the limitation of speed, manual decortication imposes a significant ergonomic burden on workers, with sustained repetitive motion leading to musculoskeletal strain, particularly in the fingers and wrists. Furthermore, the uncontrolled application of

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force in manual methods results in kernel damage rates of 10–15%, directly reducing the market value of the processed output.

Mechanized alternatives—primarily electrically driven or diesel-powered shellers—have been available in the market for several decades. However, their adoption in remote and semi-arid agricultural regions has been severely constrained by two factors: the absence of reliable grid electricity and the prohibitive recurring cost of fossil fuels. According to data from the Ministry of Power, approximately 31 million rural Indian households still experience fewer than 12 hours of daily electricity supply, rendering grid-dependent machinery unreliable for time-sensitive post-harvest operations.

Solar photovoltaic technology presents a compelling alternative energy source for agricultural mechanization in these contexts. The Indian subcontinent receives an average global horizontal irradiance of 4.5–7.0 kWh/m²/day, with peak values in the western and southern agricultural belts where groundnut cultivation is concentrated. The declining cost trajectory of photovoltaic modules—which have fallen by over 85% in the last decade—combined with improvements in battery storage technology, now makes it technically and economically feasible to power moderate-load agricultural machinery entirely from solar energy.

This paper presents the design rationale, engineering implementation, and empirical performance evaluation of a photovoltaic-driven groundnut decortication system specifically engineered for off-grid rural deployment. The system architecture prioritizes modularity, portability, low fabrication cost, and ease of maintenance using locally available materials and skills. The study contributes to the growing body of evidence supporting the integration of renewable energy systems with post-harvest agricultural operations as a pathway toward inclusive and sustainable rural development.

II. REVIEW OF RELATED WORK

The intersection of solar energy technology and agricultural mechanization has attracted growing research attention over the past decade, driven by the dual imperatives of energy access and food security in developing economies.

Singh and Kumar (2018) pioneered early work on solar-assisted groundnut shelling, demonstrating that a PV-powered system could achieve shelling efficiencies of approximately 85%. Their design, however, was constrained by the selection of a low-torque motor that limited throughput under heavy loading conditions. The work established proof of concept but highlighted the need for improved motor-mechanism matching.

Tripathi and Sharma (2020) advanced the field by introducing microcontroller-based automation into the decortication process. Their Arduino-controlled system incorporated real-time feed rate regulation and adaptive motor speed control, achieving kernel damage rates below 5%. While the automation approach yielded superior consistency, the system's dependence on grid electricity and its relatively complex electronic architecture limited practical deployment in resource-constrained environments.

The economic dimensions of solar-powered agricultural processing were rigorously examined by Kaur and Singh (2019), who conducted a comprehensive cost-benefit analysis across multiple Indian agroclimatic zones. Their findings indicated payback periods of 2–3 years for solar-powered processing equipment, with lifetime cost savings of 40–60% relative to diesel-powered alternatives. The study provided strong economic justification for solar integration in post-harvest operations.

Sharma and Singh (2005) contributed foundational work on the mechanics of groundnut decortication, systematically evaluating the performance characteristics of concave-cylinder, oscillating, and centrifugal shelling mechanisms. Their comparative analysis established that the concave-cylinder configuration offered the optimal balance between shelling completeness and kernel preservation, a finding that has guided subsequent machine designs.

Ademosun (1984) established the critical design parameters governing groundnut cracking mechanics, including the relationship between pod moisture content, applied compressive force, and shell fracture behaviour. This early work remains influential in informing clearance settings and cylinder speed specifications for modern sheller designs.

Collectively, the existing literature establishes the individual feasibility of solar-powered agricultural machinery and mechanized groundnut processing. However, a notable gap persists in the integration of these domains into a single, field-validated, cost-optimized system designed explicitly for off-grid rural communities. The present study addresses this gap through a holistic design-build-test approach.

III. SYSTEM ARCHITECTURE AND ENGINEERING DESIGN

The proposed photovoltaic-driven decortication system is organized into six functional subsystems, each engineered for modularity and field serviceability. The following subsections detail the design rationale and technical specifications of each subsystem.

3.1 Photovoltaic Energy Harvesting Subsystem

The energy harvesting subsystem employs a 25-watt polycrystalline silicon photovoltaic module as the primary power source. The module is characterized by an open-circuit voltage of approximately 18V and a short-circuit current of 1.39A under standard test conditions (1000 W/m² irradiance, 25°C cell temperature, AM 1.5 spectrum). The module is housed in an anodized aluminium frame and mounted on a manually adjustable tilt bracket that permits inclination adjustment between 10° and 45° from horizontal. This adjustability enables seasonal optimization of the solar capture angle based on the latitude of the deployment site, maximizing the annual energy yield. Anti-reflective coating on the cell surfaces ensures high photon absorption across the visible and near-infrared spectrum.

3.2 Power Conditioning and Energy Storage Subsystem

The electrical output of the PV module is routed through a 12V pulse-width-modulated (PWM) charge controller, which performs three critical functions: regulation of charging current to the battery, prevention of overcharge conditions, and blocking of reverse current flow during low-light periods. The charge controller employs a three-stage charging algorithm (bulk, absorption, float) to maximize battery charge acceptance while minimizing electrolyte degradation.

Energy storage is provided by a 12V, 7Ah valve-regulated lead-acid (VRLA) battery. The sealed, maintenance-free construction of the VRLA battery makes it well-suited for field deployment where routine electrolyte maintenance would be impractical. The battery's usable energy capacity of approximately 50 Wh (at 60% depth of discharge) provides sufficient reserve to sustain motor operation for 2.5–3 hours in the absence of solar input, ensuring operational continuity during transient cloud cover or post-sunset processing.

3.3 Electromechanical Drive Subsystem

Mechanical power is delivered by a 12V DC permanent-magnet gear motor with an integrated planetary gearbox providing a rated output torque of 100 kg-cm. The planetary gear reduction achieves a speed reduction ratio that converts the motor's native high-speed, low-torque output into the low-speed, high-torque profile required for effective pod decortication. The motor draws approximately 3–4A under typical shelling loads, corresponding to a power consumption of 36–48W. The motor shaft is coupled to the shelling cylinder through a flexible jaw coupling that accommodates minor axial and angular misalignment while transmitting the full rated torque.

3.4 Decortication Chamber

The core processing element is a concave-cylinder type decortication chamber. The rotating cylinder, fabricated from mild steel, is fitted with circumferentially arranged serrated blades that generate a combination of compressive, shearing, and abrasive forces on the groundnut pods as they transit through the annular gap between the cylinder and the stationary concave screen. The concave screen is constructed from perforated mild steel sheet with hole diameters selected to retain intact pods while allowing shelled kernels and small shell fragments to pass through.

A critical design feature is the adjustable clearance mechanism, implemented through a pair of eccentric bearing mounts that allow the concave-to-cylinder gap to be varied between 8 mm and 20 mm. This adjustability permits optimization of the shelling action for different groundnut varieties, which exhibit significant variation in pod

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dimensions and shell hardness. Feed input is managed through a gravity-fed hopper with a trapezoidal cross-section, designed to provide uniform pod distribution across the cylinder width while preventing bridging and clogging.

3.5 Kernel-Shell Separation Subsystem

The post-decortication mixture of kernels, shell fragments, and fine debris undergoes two-stage separation. The primary separation stage employs a graduated-aperture sieve that segregates the mixture by particle size: intact kernels pass through the sieve openings and are collected in the kernel output tray, while larger shell fragments are retained and directed to a separate discharge chute. The secondary separation relies on gravity-assisted winnowing, where the natural difference in terminal velocity between lighter shell fragments and denser kernels aids in further purification of the kernel output. This dual-mechanism approach achieves kernel purity levels exceeding 93%.

3.6 Structural Frame and Safety Systems

The entire assembly is supported by a welded mild steel frame constructed from L-section angle iron (25 mm × 25 mm × 3 mm) and flat bar sections. The frame geometry is designed to position the hopper inlet at a comfortable working height of 900–1000 mm while maintaining a low centre of gravity for operational stability. Anti-vibration rubber mounts at the four base contact points attenuate motor-induced vibration and prevent translational movement during operation. The electrical control panel incorporates a toggle-type power switch, a 5A blade fuse for overcurrent protection, and LED indicator lamps for battery charge status (green/amber/red) and motor run status.

IV. OPERATIONAL METHODOLOGY

The operational sequence of the decortication system proceeds through four distinct phases. During the energy accumulation phase, the PV module converts incident solar radiation into DC electrical energy, which the charge controller directs to the VRLA battery. The battery's state of charge is continuously indicated by the tri-colour LED on the control panel.

Upon activation of the power switch, the system enters the mechanical priming phase. The DC gear motor draws current from the battery and accelerates the shelling cylinder to its operating speed within approximately 3–5 seconds. The operator visually and audibly confirms stable motor operation before proceeding to the processing phase.

During the processing phase, the operator introduces dried groundnut pods into the hopper at a controlled rate. Gravity directs the pods into the decortication chamber, where the rotating cylinder applies mechanical forces to fracture the pod shells and liberate the kernels. The shelled mixture exits the chamber and passes through the separation subsystem, with kernels and shell debris being collected in their respective output receptacles.

The operator monitors the kernel output quality during processing and adjusts the concave clearance if excessive kernel breakage or incomplete shelling is observed. The system continues processing as long as the motor receives adequate power and pods are supplied to the hopper. During the shutdown phase, the power switch is deactivated, and the hopper is cleared of any residual pods.

V. SYSTEM SPECIFICATIONS

The complete technical specifications of the photovoltaic-driven decortication system are summarized in the table below.

Sr.	Component	Technical Specification
1	Photovoltaic Module	25W Polycrystalline Si, ~18V Voc, 1.39A Isc
2	Energy Storage	12V, 7Ah VRLA Battery, ~50 Wh usable
3	Charge Controller	12V PWM, 3-stage charging algorithm
4	Drive Motor	12V DC Gear Motor, 100 kg-cm rated torque

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5	Shelling Cylinder	MS cylinder, circumferential serrated blades
6	Concave Screen	Perforated MS sheet, 8–20 mm adjustable gap
7	Feed Hopper	Trapezoidal MS sheet, gravity-fed
8	Structural Frame	MS L-section angle iron, welded assembly
9	Separation System	Graduated-aperture sieve + gravity winnowing
10	Control & Safety	Toggle switch, 5A fuse, tri-colour LED indicators

VI. EXPERIMENTAL RESULTS AND ANALYSIS

Systematic performance evaluation was conducted over a five-day testing period under field conditions representative of typical groundnut-growing regions in central India. Tests were performed using three locally prevalent groundnut varieties (TAG-24, JL-501, and GPBD-4) with pod moisture content maintained at 8–10% (dry basis) to ensure consistent baseline conditions.

6.1 Decortication Efficiency

The decortication efficiency, defined as the ratio of successfully shelled pods to total pods fed, ranged from 87% to 92% across the three varieties tested. The highest efficiency (92%) was recorded with TAG-24, which has relatively thin and brittle shells, while the lowest (87%) was observed with GPBD-4, characterized by thicker and more fibrous pod walls. These results represent a marked improvement over the 85% efficiency reported by Singh and Kumar (2018) and are attributable to the optimized cylinder-concave clearance settings and the higher motor torque employed in the present design.

6.2 Kernel Integrity

Kernel damage rates, quantified as the percentage of broken or cracked kernels in the output, were maintained below 6% across all test conditions. The variety-specific damage rates were 4.2% for TAG-24, 5.1% for JL-501, and 5.8% for GPBD-4. These values compare favourably with the 10–15% damage rates characteristic of manual shelling and are consistent with the sub-5% rates reported by Tripathi and Sharma (2020) for their automated system, albeit achieved here with a significantly simpler and lower-cost design.

6.3 Volumetric Throughput

The processing throughput ranged from 9 to 13 kg of pods per hour, with an average of 11 kg/h across all test runs. This represents a three-to-four-fold improvement over the 2–5 kg/h achievable through manual shelling. Throughput was observed to be positively correlated with pod uniformity; batches with pre-sorted, size-graded pods yielded throughput values at the upper end of the range due to reduced incidence of hopper clogging and more consistent shelling action.

6.4 Energy Autonomy Assessment

Energy autonomy tests were conducted to evaluate the system’s operational endurance under varying solar irradiance conditions. Under clear-sky conditions with irradiance levels of 800–1000 W/m², the PV module maintained the battery at or near full charge throughout the operating day, enabling effectively unlimited daytime operation. Under simulated overcast conditions (panel disconnected from battery), the fully charged battery sustained motor operation for an average of 2 hours and 42 minutes before the battery voltage dropped to the low-voltage cutoff threshold of 10.5V. These results confirm that the energy storage subsystem provides adequate operational buffer for transient weather variations typical of the Indian monsoon and post-monsoon harvest seasons.

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6.5 Comparative Performance Summary

The following table presents a comparative summary of the performance metrics achieved by the photovoltaic-driven decortication system against manual shelling and previously reported mechanized systems.

Parameter	Manual Shelling	Singh & Kumar (2018)	Present Study
Decortication Efficiency	70–80%	~85%	87–92%
Kernel Damage Rate	10–15%	~8%	4.2–5.8%
Throughput (kg/h)	2–5	~8	9–13
Energy Source	Human labour	Solar PV	Solar PV
Grid Independence	Yes	Yes	Yes
Battery Backup (hrs)	N/A	~2	2.5–3

VII. ADVANTAGES AND FIELD APPLICABILITY

The photovoltaic-driven decortication system offers several distinct advantages that position it as a practical solution for rural groundnut processing. The complete energy independence from grid electricity eliminates both the fixed cost of grid connection and the variable cost of diesel fuel, yielding estimated operational cost savings of 55–70% over the machine's projected ten-year service life. The modular architecture permits rapid disassembly and transport, enabling a single machine to serve multiple farms or village clusters on a rotational basis. All structural and mechanical components are fabricated from standard mild steel sections available at local hardware suppliers, ensuring that repairs and replacement parts can be sourced without dependence on specialized vendors.

The primary deployment contexts include on-farm post-harvest processing in off-grid and semi-arid agricultural zones, small-scale village-level agro-processing cooperatives, government-sponsored rural livelihood enhancement programmes, and agricultural extension and training centres. With minor modifications to the concave screen geometry and clearance settings, the system architecture can be adapted for the decortication of other shell-enclosed crops including castor, sunflower seeds, and certain legume varieties.

VIII. LIMITATIONS AND FUTURE SCOPE

Despite the encouraging performance results, several limitations were identified during field testing that merit attention in future development iterations. Occasional feed hopper clogging was observed with irregularly shaped or oversized pods, suggesting the need for hopper inlet geometry refinement or the incorporation of a pre-grading mechanism. Shelling efficiency exhibited statistically significant variation across groundnut varieties, indicating that a universal clearance setting is insufficient and that variety-specific calibration protocols should be developed.

Future research directions include scaling the PV module capacity to 50–75 watts to support higher-torque motors and increased throughput; integration of maximum power point tracking (MPPT) charge controllers to improve solar energy utilization efficiency by 15–25% over the current PWM configuration; incorporation of low-cost IoT sensors for real-time monitoring of motor current, battery voltage, and throughput rate, enabling predictive maintenance and performance optimization; development of interchangeable concave screen cartridges for rapid adaptation to different crop types; and conducting extended multi-season field trials across diverse agroclimatic zones to validate long-term durability and user acceptance.

IX. CONCLUSION

This study has presented the systematic design, fabrication, and empirical performance evaluation of a photovoltaic-driven decortication system engineered for sustainable groundnut processing in off-grid agricultural communities. The system successfully integrates a solar energy harvesting and storage subsystem with a mechanically optimized concave-cylinder decortication mechanism, achieving decortication efficiencies of 87–92%, kernel damage rates below 6%, and processing throughput of 9–13 kg/h. These performance metrics represent substantial improvements over both manual shelling methods and earlier reported solar-powered prototypes.

The energy autonomy assessment confirmed that the system can sustain operation for nearly three hours on stored battery energy alone, providing adequate operational resilience for deployment in regions characterized by variable solar resource availability. The modular, portable, and low-cost design philosophy ensures accessibility for smallholder farmers and rural agro-processing enterprises.

The findings of this study contribute empirical evidence supporting the viability of photovoltaic-integrated agricultural machinery as a scalable intervention for post-harvest loss reduction and rural livelihood enhancement. As photovoltaic and battery storage technologies continue their trajectory of cost reduction and performance improvement, solar-driven decortication systems are poised to play an increasingly significant role in the sustainable transformation of post-harvest agriculture in energy-deficient developing regions.

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