International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 3, September 2026, pp. 1351~1365
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i3.pp1351-1365

Design development and techno-economic assessment of a solar-powered three-row chickpea leaf nipping and collecting machine for sustainable farming

Prashant Kadi[1,2], Basanagouda Ronad[2]
[1]Department of Electrical and Electronics Engineering, BLDEA's V. P. Dr. P. G. Halakatti College of Engineering and Technology, (Affiliated to Visvesvaraya Technological University), Vijayapura, India
[2]Department of Electrical and Electronics Engineering, Basaveshwar Engineering College, (Affiliated to Visvesvaraya Technological University), Bagalkote, India

Article Info

Article history:

Received Nov 17, 2025
Revised Jun 20, 2026
Accepted Aug 15, 2026

Keywords:

Agricultural mechanization
BLDC motor
Chickpea crop
Payback period
Solar-powered machine

ABSTRACT

Agricultural mechanization enhances productivity and reduces manual labour in labour-intensive regions. Chickpea, a major pulse crop in India, is widely cultivated in semi-arid regions of North Karnataka, particularly in Vijayapura district. In 2024, 500,000 hectares of pigeonpea and 1.9 million hectares of chickpea were sown in this region. In chickpea, leaf nipping is a vital agronomic practice that encourages branching and improves yields. However, this practice is done manually, making it highly labour-intensive, time-consuming, and less feasible for small-scale farmers. To address these challenges, the current research focuses on the design, development, and techno-economic evaluation of a solar-powered, three-row leaf-nipping and collecting machine. This machine is equipped with a 150 W solar PV system, six 15 W BLDC motors, and an adjustable cutter-head assembly for efficient operation. A techno-economic analysis was conducted to evaluate cutting force, torque, power consumption, and battery discharge characteristics, as well as the payback period, cost savings, and improvements in farm income. Field trials conducted on a 9-acre farm in Vijayapura, receiving an average annual solar irradiation of approximately 1950 kWh/m², demonstrated 350–400 kg of leaf collection and a 25–30% increase in crop productivity. The machine provides a cost-effective, eco-friendly, and scalable solution for small and medium-scale farmers.

Corresponding Author:

Prashant Kadi
Department of Electrical and Electronics Engineering
BLDEA's V. P. Dr. P. G. Halakatti College of Engineering and Technology
(Affiliated to Visvesvaraya Technological University)
Vijayapura, Karnataka, India
Email: ee.prashantkadi@bldeacet.ac.in

1. INTRODUCTION

Agriculture is the backbone of the Indian economy, contributing approximately 18% to the national GDP and employing nearly 58% of the rural workforce. With the increasing labor shortage, rising wages, and declining farm profitability, there is a growing need to mechanize agricultural operations. In India, where agriculture is predominantly labor-intensive and a major source of livelihood, mechanization has gained increasing importance to address challenges such as labor shortages, low productivity, and the need for sustainable farming. The various farm operations in agriculture include planting, spraying, weeding, and harvesting. Automating these processes with farm machinery helps to achieve sustainability goals by reducing fossil fuel demand and lowering greenhouse gas emissions.

Agricultural mechanization is essential for improving farm efficiency, reducing human drudgery, and enhancing agricultural productivity. Recently, the integration of renewable energy technologies into agricultural systems has attracted significant attention due to the need for sustainable and eco-friendly farming practices. Agrivoltaic systems, which integrate agricultural production with photovoltaic energy generation, have demonstrated advantages, including improved crop yields, more efficient water use, and enhanced rural electrification [1]. In particular, solar photovoltaic (PV) applications have been widely explored for irrigation, drying, greenhouse operations, and small-scale mechanization on farms [2].

However, the continued use of diesel-powered agricultural machinery contributes to environmental pollution and increases operational costs, posing challenges to achieving India's net-zero emission targets by 2070 [3]. In this context, adopting renewable-energy-driven farm machinery is essential. Chickpea is a major pulse crop cultivated extensively in semi-arid regions such as North Karnataka. Chickpea leaf nipping is a critical agronomic practice in chickpea cultivation, typically performed at 30 to 40 days after sowing (DAS), where the apical bud of the plant is removed to suppress vertical growth and promote lateral branching. This physiological response increases the number of productive branches, enhances pod formation, and improves overall crop yield. Previous studies have reported yield improvements of approximately 20–30% due to timely nipping. However, this operation is predominantly performed manually, making it labour-intensive and inefficient, particularly on large-scale farms. Therefore, there is a need for a sustainable, cost-effective, and crop-specific mechanized solution. The integration of solar-powered agricultural machinery offers a viable strategy to improve operational efficiency, decrease reliance on fossil fuels, and increase farm income [4]. A recent study demonstrates that combining artificial intelligence (AI) with solar-powered systems can further enhance energy efficiency and decision-making in precision farming. AI-based optimization has been shown to increase solar energy utilization by up to 25% and reduce carbon emissions by nearly 30% [5]. To encourage farmers to adopt electric agricultural machinery, there is a need for the Common Agricultural Policy (CAP), which provides incentives for farmers [6].

2. LITERATURE SURVEY

This section explores the findings from the literature survey in the field of farm machinery. Renewable energy sources can be harnessed to power different agricultural machines. These machines can be used for tasks such as irrigation, planting, and harvesting using modern renewable technologies [7].

Lanjekar *et al.* [8] developed a techno-economic analysis and life cycle assessment of a solar-powered farm rickshaw designed for Indian road conditions. The increasing role of autonomous, renewable energy-powered electric vehicles (EVs) in agriculture is noteworthy. These vehicles have the potential to enhance automation, improve energy efficiency, and promote sustainability through on-site green energy generation [9].

The performance analysis of grid-connected solar PV systems for family farm loads indicates that the system generates 117.06 MWh per year. This output covers 40% of the farm's energy needs and achieves a renewable fraction (RF) of 49%. Furthermore, the system significantly reduces environmental impact by cutting emissions of CO_2 by 56.34%, SO_2 by 56.52%, and NO_x by 56.45%, thereby promoting sustainable energy use in Algerian farms [10].

Das *et al.* [11] developed an electric mini tractor features a 3 kW BLDC motor designed for mild ploughing operations. It has been developed and tested under various conditions and is powered by a 60 V, 100 Ah lead-acid battery pack, allowing for operation lasting 5 to 6 hours. A 1.2 kW portable solar charging station has been developed for charging an electric power tiller, primarily used for land cultivation. The key findings from research publications are shown in Table 1.

Based on the literature and field surveys conducted in these regions, large-scale farmers use internal combustion engine (ICE) agricultural machinery for various operations. The integration of solar power into agricultural machinery remains in its early stages. Significant research is needed to enable the adoption of electric vehicles in the agricultural sector.

2.1. Novelty in the research

The literature survey, supported by field visits in North Karnataka, India, highlights critical research and development gaps in agricultural mechanization and renewable energy integration. These findings emphasize the importance of addressing technological limitations in the sector. There is a need for crop-specific agricultural machines or e-agri vehicles for operations such as nipping in chickpea and pigeon pea cultivation.

Chickpea is a short-height crop, making manual nipping of leaves difficult and labor-intensive, leading to significant drudgery for farmers. This study presents a solar-powered three-row chickpea nipping machine that simultaneously nips three rows of chickpea while reducing energy consumption. The proposed machine also integrates a leaf-collection mechanism, enabling farmers to collect chickpea leaves during nipping. These leaves can be sold as a vegetable, thereby providing an additional source of income for farmers while improving operational efficiency and sustainability.

Table 1. Literature survey

Authors	Highlights of the paper	Methodology employed	Relevance to work
Chauhan and Mittal [12]	Solar-powered farm e-vehicle with 60 V $LiFePO_4$ battery for cargo [12].	PV array + battery pack powering DC motor, tested on farm terrain.	Useful design insights for multi-functional, load-carrying e-agri vehicles.
Moshayedi *et al.* [13]	Analyzed the role of robotics in corn farming, covering planting, weeding, harvesting, monitoring, and soil sampling. Emphasized efficiency, precision, and sustainability through autonomous systems with advanced sensors [13].	The paper presents a comprehensive literature review and classification of agricultural robots, detailing their platforms, sensors, navigation, and control systems. It also provides practical applications with case studies.	Provides strategic insights for crop-specific mechanization design and renewable integration for autonomous e-agri vehicles.
Lanjekar *et al.* [8]	Designed a 450 W solar-powered farm rickshaw for transporting farm produce and labor. The payload capacity of this rickshaw is 300 kg.	Equipped with three 150 W polycrystalline solar modules, a 48 V 30 Ah Li-ion battery, a BLDC motor, and an MPPT charge controller.	Demonstrates a viable solar-powered transport solution in the agriculture field.
Sagor *et al.* [14]	Designed and implemented a solar PV-operated electric power tiller with a portable solar charging station to replace diesel-based tillers [14]	Theoretical design and MATLAB/Simulink simulation for powertrain, torque and energy calculations, solidworks modeling for structural design and experimental validation of performance parameters.	Provides technical insights for solar-powered, motor-driven agricultural machines, supporting the e-agri vehicle design, torque calculation, and energy estimation.
Singh *et al.* [15]	Proposed “KisaanMitra” autonomous solar seed-sowing e-agri vehicle with smart control [15].	Dual-axis solar tracker, embedded system for precision sowing.	Demonstrates the use of solar-powered e-agri robotics for the autonomous seed sowing process.
Chand *et al.* [16]	Solar-powered smart farming robot with computer vision and MPPT controller [16].	Image processing + embedded control + solar array with MPPT	Integration of autonomy, renewables, and IoT in small-scale e-agri robotics
Scolaro *et al.* [17]	Review on electrification of agricultural machinery, including trends, types and future road maps [17].	Summarized data from field surveys, case studies and technology readiness levels.	Provides a comprehensive review of electrified machinery and serves as a foundation for techno-economic analysis.
Gorjian *et al.* [4]	Review of modern solar-powered agricultural machinery with a focus on climate-smart and autonomous systems [4].	Review and analysis of PV applications, battery technologies, and global case studies.	Strong overview on solar PV integration into electric agri-machines; aligns with the solar charging focus.
Vogt *et al.* [18]	Electric tractor system for small-scale family farming to replace diesel-based systems [18].	Simulation and testing of a modular electric drive and energy storage system with solar integration.	Highlights energy savings and emission reductions for small family-run farms.
Chadalavada *et al.* [19]	Developed a solar-powered semi-automated multipurpose agricultural machine for sowing, spraying, grass cutting and surface leveling. Aimed to increase farm productivity and reduce labor dependency through renewable energy integration [19].	Integrated a 12 V, 7 Ah battery charged by a 20 W solar panel, powering DC motors for seed sowing, water spraying and grass cutting. Included Bluetooth interface.	Demonstrates a modular, low-cost solar-based farm tool for multiple operations.
Melo *et al.* [20]	Developed a 9 kW electric propulsion system for tractors suitable for low-power farm operations [20].	Design, prototyping, and performance analysis of an electric powertrain for tractors.	Offers scalable electric drivetrain options for low-horsepower tractors applicable to Indian conditions.
D. Yallappa *et al.* [21]	Developed and evaluated a solar-powered agricultural sprayer with multi-purpose applications for sustainable farming [21].	Design of a PV-powered DC motor pump system, field testing for flow rate, pressure, and spraying efficiency evaluation of multi-purpose usability in irrigation.	Shows integration of PV for multi-utility agricultural equipment; aligns with renewable-powered auxiliary systems for e-agri machinery.

3. METHOD

The approach for the design and performance evaluation of the chickpea nipping machine is shown in Figure 1. It begins with field data collection and farmer feedback to understand the challenges of manual nipping, which highlights the need for mechanization. This is followed by an evaluation of technical parameters, including cutting force, torque requirement, and power consumption. Based on these, system specifications and design are carried out for the nipping machine. This machine undergoes performance testing under different sunlight and crop conditions, leading to the collection of field results such as leaf collection efficiency and crop yield improvement. Finally, an economic analysis evaluates cost savings and payback period, ensuring feasibility for small and medium-scale chickpea farmers.

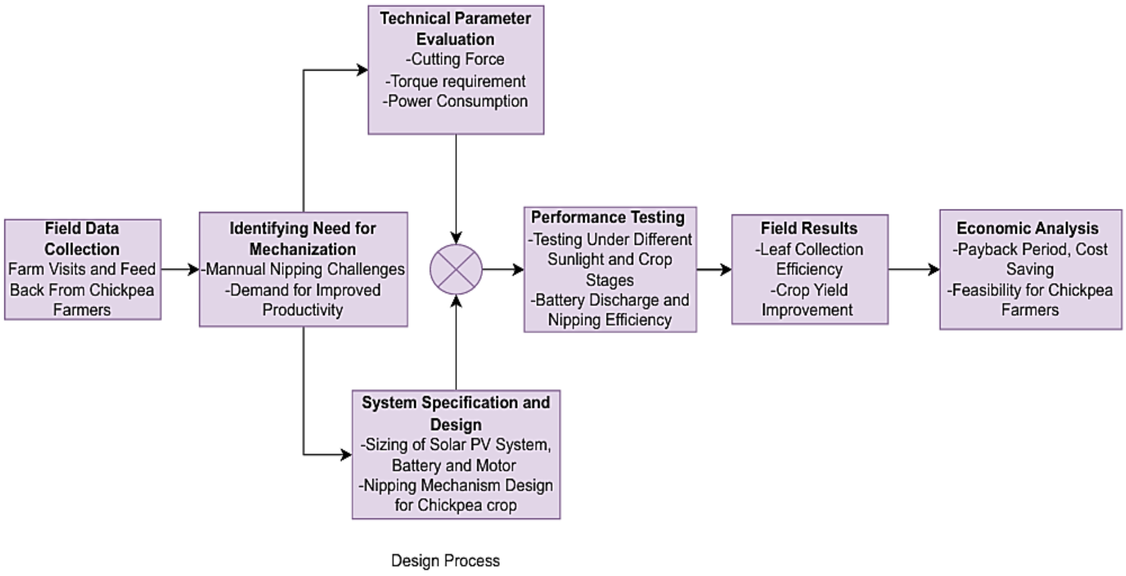

Figure 1. Research flow for the design and performance evaluation of a solar-powered chickpea leaf nipping machine

3.1. Availability of solar energy for the considered location

Vijayapura, located in North Karnataka at 16.49 °N, 75.43 °E, and 593 m, India, benefits from a substantial amount of solar energy, making it a promising region for solar-powered agricultural applications. Vijayapura receives global solar radiation ranging from 5.1 to 6.4 kWh/m² during summer, 3.5 to 5.3 kWh/m² during monsoon, and 3.8 to 5.9 kWh/m² during winter, as shown in Figure 2. Figure 3 shows temperature variations across different months.

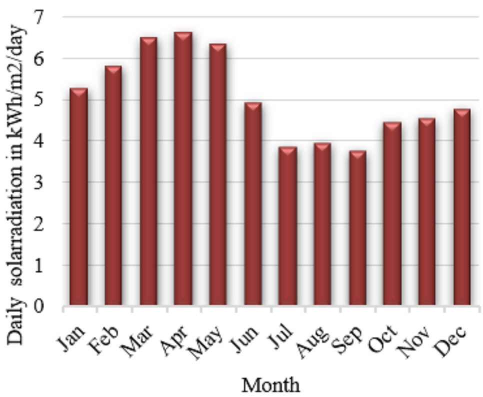

Figure 2. Characteristics of solar potential at the considered location

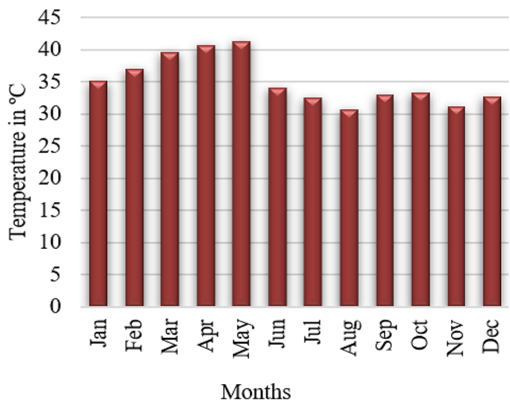

Figure 3. Temperature in °C at the considered location

3.2. Design and development of a three-row nipping machine for the chickpea crop

The design and analysis of the nipping machine is carried out in Basaveshwar Engineering College, Bagalkote, India. This work is conducted in association with Krishitaranga Farmtech LLP. The collaboration takes place in Vijayapura.

3.3. Principle of operation

The machine is equipped with crop-cutting blades, a BLDC motor with a speed control unit, a solar panel, and a battery. Figure 4 shows the architecture of the nipping machine. This machine uses six BLDC motors, which are powered by a 150 W solar PV module and a lithium-ion battery. The model integrates three independently height-adjustable cutter head assemblies, each equipped with two 15 W BLDC motors rotating in opposite directions to perform the nipping action. These cutter heads are strategically spaced to cover three chickpea rows simultaneously, thereby maximizing field coverage and reducing operational time. The adjustable cutter head assembly allows for precise trimming of overgrown chickpea branches.

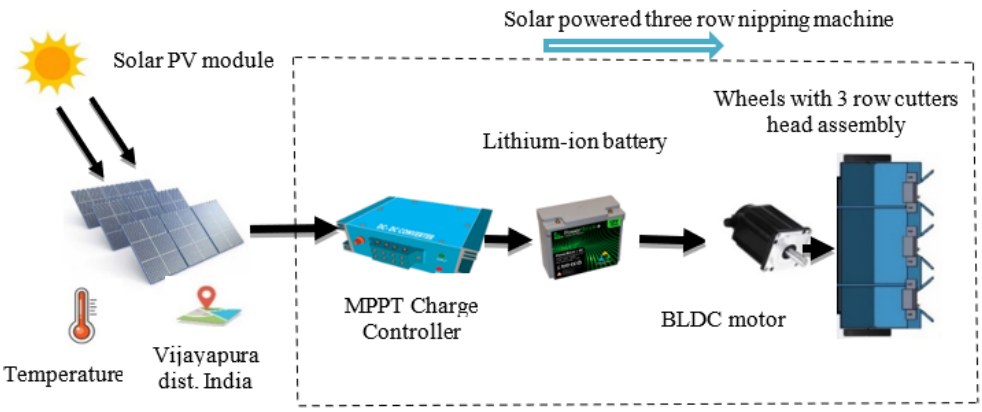

Figure 4. Architecture of the three-row solar-powered nipping machine for chickpea crops

3.4. Cutting force, torque, and battery sizing for a chickpea nipping mechanism

The mechanical design of the nipping mechanism is based on the crop's physical characteristics. It also considers the system's powertrain requirements. Cutting force for the nipping operation depends on stem geometry, material properties, cutting speed, and cutting depth.

3.4.1. Cutting force estimation

The average stem diameter of chickpea plants ranges between 3 mm to 6 mm [22]. The cutting force required for green gram crops ranges from 4 to 8N, with significant variation depending on stem moisture content and diameter [23]. The cutting force F_C required for effective stem or leaf nipping is estimated using (1).

$$F_C = \frac{\sigma_{C\times} \times A_C}{\eta} \tag{1}$$

σ_c is the specific cutting resistance or shear strength of the chickpea stem, typically ranging from 0.5 to 1 MPa (Megapascal) [24]. A_C is the cross-sectional area of the stem in m^2 which varies from 4.91×10^{-6} to 9.62×10^{-6} m^2. η is the mechanical efficiency of the cutting mechanism (typically 0.75 to 0.80).

The moisture content of chickpea varieties commonly cultivated in the North Karnataka region, namely JG-11, BGD-103, and JAKI-9218, was determined using the standard oven-dry method [25]. For agricultural machinery studies, moisture content is typically expressed on a wet basis (MC_{wb}) and is calculated using (2).

$$(Moisture\ Content\ \%)_{Wb} = \left(\frac{W_w - W_d}{W_w}\right) \times 100 \tag{2}$$

W_w (wet weight) is the mass of fresh chickpea stem samples measured immediately after harvesting in the field. W_d (Dry Weight) is the mass of the same samples after being dried in an oven (typically at 60 °C for 52 hours) until the weight becomes constant.

3.4.2. Torque requirement

The torque required by the cutting blade for successful operation is calculated. The calculation is performed using (3).

$$T_r = F_C \times r \quad (3)$$

Where T_r is the required torque in Nm, F_C is the cutting force in N, and r is the blade radius in m, which is taken as 0.03 m for this design.

Using the above parameters, the calculated torque per blade is approximately 0.264 Nm. To meet this requirement, a 15 W BLDC motor at 600 RPM is selected. The required torque output from all six motors used in the three-cutter head assembly ranges from 1.4 to 1.6 Nm. This setup ensures redundancy and operational reliability, even under varying crop densities.

3.4.3. Battery sizing for field operation

The energy storage system is dimensioned to meet the total power consumption during a typical nipping operation lasting between 3 to 4 hours. The required battery capacity is calculated using (4) [26].

$$Capacity\ of\ the\ battery(Ah) = \frac{\alpha \times P_T \times t}{V \times \eta_B \times (DoD)_{max}} \quad (4)$$

V is the battery voltage, and α is the speed control factor, assumed to be 0.8. The operating time t is considered between 3 to 4 hours, while $(DoD)_{max}$ is the maximum depth of discharge, taken as 80% for lithium-ion batteries, and ηB is the efficiency of the battery, typically around 90%. P_T represents the total rated power of all motors.

Using the above parameters, a 12 V, 20 Ah lithium-ion battery is selected, which is sufficient to support the complete operation cycle. Real-time battery current is measured using a current sensor and SOC is determined using (5).

$$SOC_{(t)} = SOC_{(t_0)} - \frac{1}{C_h}\int_{t_0}^{t} I(t)dt \quad (5)$$

SOC (t_o) is the initial state of charge at time t_o, SOC (t) is the state of charge at time t, C_h is the battery capacity in Ah, I(t) is the current draw over time and $\int I(t)dt$ is the total Ah consumed so far.

SOC is essential for monitoring energy availability and ensuring the efficient operation of electric agricultural machinery in off-grid applications. Figure 5 shows the typical voltage profile of a 12V lithium-ion battery. The profile illustrates how the battery discharges from a fully charged to a fully depleted state.

3.4.4. Solar photovoltaic (PV) sizing

The solar PV system for charging the battery-powered chickpea nipping machine is sized based on the machine's energy consumption profile, local solar insolation data and system efficiency parameters. The total energy consumption for the nipping operation over a 6 to 7 hour field session is estimated to be in the range of 600 to 650 Wh. For calculation purposes, the daily energy load E_L is determined by (6).

$$E_L = P_T \times t_{on} \quad (6)$$

t_{on} is the daily operational time.
Considering losses in battery charging and the charge controller, the effective energy required from the PV system, E_{PV}, is determined by (7).

$$E_{PV} = \frac{E_L}{\eta_{(bc)}} \quad (7)$$

η_{bc} is the combined efficiency of battery charging and the charge controller and is determined by (8).

$$\eta_{(bc)} = \eta_b \times \eta_c \quad (8)$$

The overall efficiency considered for the system design is 90 to 95%. To account for real-world losses such as temperature effects, dust, panel mismatches and wiring inefficiencies, a derating factor (safety margin) of 25% is applied. The required specific power output from the PV panel P_{sp} is determined using (9).

$$P_{sp} = \frac{E_L \times (1+S_f)}{t_{sunshine} \times \eta_{(bc)}} \quad (9)$$

S_f is the derating factor (25%), $t_{sunshine}$ is the average effective sunshine hours.

A solar panel of 150 W to 160 W is sufficient to meet the daily energy demand of the machine [10]. The maximum solar radiation available on a solar PV module placed on the nipping machine is given by (10).

$$P_{module} = P_0 \times (\cos(\delta) \times \cos(\Psi) \times \sin(\omega) + \sin(\delta) \times \sin(\Psi)) \times \cos(\beta) \quad (10)$$

P_{module} is the maximum incident radiation on the PV module in W/m^2, P_0 is the solar constant measured in watts per square meter δ is the declination angle measured in degrees, Ψ is the latitude of the considered location in degrees, ω is the hour angle measured in degrees, and β is the tilt angle of the PV module measured from the reference axis in degrees.

The declination angle (δ) is the angle between the sun's apparent position in the sky and the Earth's equatorial plane and is given by (11).

$$\delta = 23.45 \times \sin\left[360 \times \frac{284+n}{365}\right] \quad (11)$$

n is the day of the year; the declination angle varies throughout the year due to the Earth's tilt and orbit around the sun [27].

The instantaneous value of the PV module power output is calculated. The calculation is performed using (12).

$$\mathrm{P_{mh}(t) = \eta_m(t)\eta_d A_m G_{t\beta}(t)} \quad (12)$$

A_m is the module surface area (m^2), $G_{t\beta}$ is the hourly solar radiation on the PV module surface, η_d is the loss due to dust and dirt, and η_m(t) is the instantaneous value of module efficiency at instant t. The variation of PV output power with different solar radiation is shown in Figure 6.

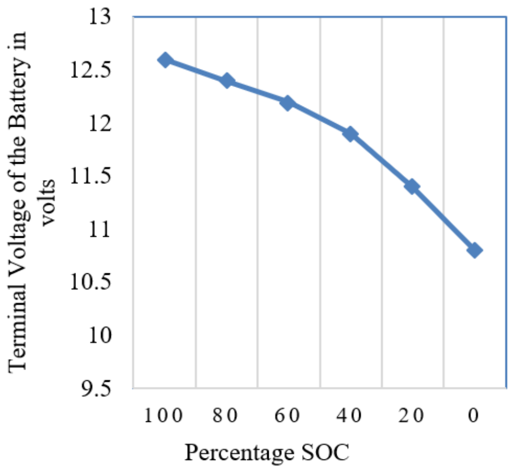

Figure 5. SOC vs. terminal voltage of the battery

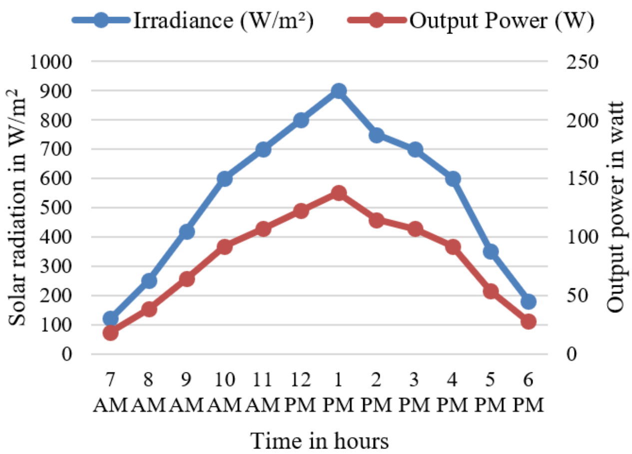

Figure 6. Electrical output of the solar panel over different solar radiation incident on the tilted surface of the panel

3.4.5. MPPT charge controller

The maximum power point tracking (MPPT) solar charge controller regulates the charging and discharging of the battery and prevents the backward flow of power to the PV module. It is expressed in terms of the current and voltage rating and is calculated by (13).

$$MPPT\ charge\ controller\ rating = \frac{Solar\ power\ (W) \times S_f}{Battery\ Voltage(V)} \quad (13)$$

The complete specifications of the three-row solar-powered nipping machine for chickpea crop are shown in Tables 2 and 3.

Table 2. Specification of the solar-powered 3-row leaf-nipping machine for chickpea crop

S.L.	Particulars	Technical specification
1	Name of the equipment	Solar-powered 3-row leaf-nipping machine for chickpea crop
2	Source of power	Solar energy
	Solar panel	
	Solar panel type	Monocrystalline
	Model	OJAS 12100
	PV module dimensions (L×W×T)	1474 mm × 660 mm × 40 mm
	PV module weight	12 Kg
3	Number of PV modules	01
	Rated maximum power (P_{ma})	150 W ± 3% 8.13 A
	Method of mounting	Fixed
	Battery	
	Type of battery	Lithium ion
	Voltage rating V	12 V
4	Current capacity Ah	20 Ah
	Fully charged voltage level	13.2 V
	Discharged voltage level	11.5 V
	Battery weight	3.5 kg
5	Solar charge controller	
	MPPT with speed control circuit	12 V
	Current	10 A
6	BLDC (Brushless DC) motor	
	No. of motors	06
	Capacity of each motor	15 W
	Speed requirement	800 to 900 RPM
	Voltage rating	12 V
	Current rating	
	No. of teeth on shaft	--
7	Wheel unit	
	Type of wheel	Metal wheel
	No. of wheel	02
	Type of material	MS steel
	Dimension	4 spoke 13inch wheel with bearings
	Method of fixing	Axle mounting
8	Handle	
	Material	MS steel
	Dimension(L×W)	990.6 mm × 304.8 mm
	Method of fixing	Socket type fixing with a nut and bolt
9	Blades	
	Number of blades	18
	Material of blades	Carbon steel
	Dimension of the blade	58.42 × 9.2 × 0.38 mm
	Direction of rotation	9 blades rotate in a clockwise and the remaining 9 blades rotate in an anticlockwise direction
	Method of fixing	Screw fixing

Table 3. Overall dimensions of the equipment with the cutter head assembly

S.L.	Particulars	Technical specification
1	Cutter head assembly	
	Type	Blade mounting wheel
	Number	03
	Material	MS steel
	Distance between cutter heads	406.4 mm
	Method of operation	3 Motors rotate in clockwise and the remaining 3 rotate in an anticlockwise direction
	Size of holes for mounting the cutter head assembly	12.7 mm
	Method of operation	Each row has 2 motors with a fixed cutter head assembly; hence, for three rows, 6 motors and 6 cutter heads are used.
2	Foliage collector	
	Type of material	MS V box
	Dimension(L×W)	1,257.3 × 330.2 mm
	Method of fixing	Nut Bolts
3	Overall dimensions of the machine	
	Length×Width × Height	2260.6 × 1371.6 × 1066.8 mm
	Ground clearance	101.6 mm
	Weight of the machine	65 Kg

4. PERFORMANCE TESTING OF THE MACHINE

The 3D model of the developed machine, shown in Figure 7, is designed to optimize leaf nipping, enhance leaf collection efficiency, and ensure adaptability to varying crop heights in the field. Field performance testing of the machine is conducted at Hittinahalli research farm, Vijayapura District, Karnataka, as shown in Figure 8. The cutting force required for the chickpea crop at different growth stages (30–45 DAS) evaluated for the JG-11 variety is shown in Table 4.

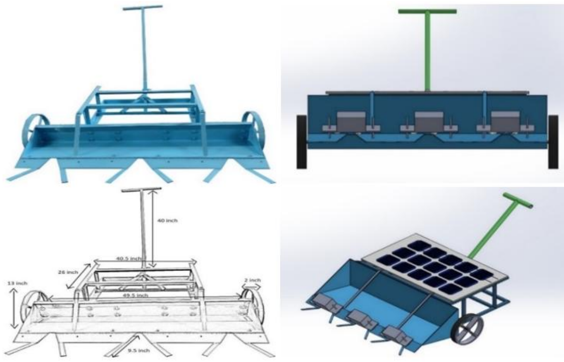

Figure 7. Developed 3D model in the solid edge software

Figure 8. Performance testing of the machine at Hittinahalli research farm, Vijayapura Dist.

Table 4. Statistical evaluation of cutting force variation with moisture content in JG-11 chickpea (apical region, 30–45 DAS)

Stage (DAS)	Moisture content (%)	Stem diameter (mm)	Cross-sectional area (m²)	Shear strength (MPa)	Theoretical force (with η=0.7)	Experimental cutting force (N)
30 DAS	55–65 (high)	2.5	4.91×10^{-6}	0.4	2.80 N	2.5 to 5
40 DAS	45–55 (moderate)	3.0	7.07×10^{-6}	0.6	6.06 N	6 to 12
45 DAS	25–35 (low)	3.5	9.62×10^{-6}	0.9	12.37 N	12 to 15

The sensitivity analysis demonstrated that the crop maturity stage affects the cutting force requirement. As the crop progressed from 30 DAS to 45 DAS, stem diameter increased from 2.5 mm to 3.5 mm, and moisture content decreased from 55–65% to 25–35%. Consequently, the experimental cutting force increased from approximately 2.5–5 N to 12–15 N. The machine performance was assessed under two distinct operating modes: i) Battery-only mode – the machine operated solely using the onboard battery without solar input and ii) Solar-assisted mode – the machine operated with simultaneous solar PV input during daylight hours.

For each trial, parameters such as operating time, energy consumption, area covered and leaf collection quantity were recorded. The average values from the three trials were used for analysis, which are shown in Table 5. With an average irradiance of 800 to 850 W/m² and a panel area of 0.973 m² (150 W panel), the effective solar energy contribution is estimated at 600 to 700 Wh/day. The experiments were carried out to analyze the performance of the machine under different solar radiation. Solar radiation is measured using the PMA2144 class II pyranometer, and battery voltage and discharge currents are measured using a digital multimeter.

Table 6 provides a comparative analysis of a gasoline-operated nipping machine with a solar-powered nipping machine, which indicates that the solar-powered nipping machine provides substantial economic and environmental benefits compared to the gasoline-operated model. The gasoline-powered machine runs on petrol/diesel and consumes approximately 750 ml per acre, resulting in daily CO_2 emissions of about 10-11 kg. On the other hand, the solar-powered nipping machine uses a renewable energy source, has almost no fuel costs, and produces no on-site emissions.

Field performance of the nipping machine was tested at three locations, with each experiment repeated three times under similar conditions to ensure reliability. Key parameters such as operating time, area coverage, leaves collected, and solar irradiance were recorded. Data analysis used mean, standard deviation (SD), and coefficient of variation (CV), as shown in Table 7.

Table 5. Performance results under different operating modes

Parameter	Battery-only mode	Solar-assisted mode
Energy source	Battery only	Battery + Solar PV
Battery capacity	12 V, 20 Ah	12 V, 20 Ah
Solar input energy (Wh)	0	600
Total energy available (Wh)	240	840
Average operating time (h)	2.5 to 3	9–9.5
Average power consumption (W)	65–70	65–70
Area covered per day (acres)	Around 3 acres	9 acres
Leaf collection (kg/day)	120–150	350–400
Operator requirement	1	1
Mode suitability	Short-duration operation	Full-day operation

Table 6. Comparative analysis of a gasoline-operated nipping machine with a solar-powered nipping machine

Parameter	Gasoline-operated nipping machine	Solar-powered nipping machine
Power source	Petrol/Diesel	Renewable energy
Energy storage	Fuel tank	Battery
Energy cost	₹100/litre	₹6/Unit of electricity*
Fuel consumption per acre of land	750 ml	Negligible
CO_2 Emission/day	Approximately 10 to 11kg	Zero
Operating time required	6–7 hours/day	9–10 hours/day
Leaves collected	No provision for leaves collection in the machine	Approximately 350-400 kg of leaves can be collected
Daily operating cost, including labour and fuel	₹1,100 to 1,200	₹600
Annual maintenance	High (engine servicing)	Low (electrical system)
Emissions	CO_2, NOx emissions	Zero on-field emissions
Net income increases	₹6,000–7,000	₹11,500 to 12,000
Payback period	2 seasons	1 cropping season
Environmental impact	High	Very low (eco-friendly)

Table 7. Statistical analysis of the solar nipping machine across different locations

Parameter	Vijayapura (Mean ± SD)	Bagalkote (Mean ± SD)	Kalaburagi (Mean ± SD)	Overall mean ± SD	CV (%)
Soil type	Black cotton soil	Red loamy soil	Mixed dryland soil	--	---
Crop stage (DAS)	35 ± 1	36 ± 1	34 ± 1	35 ± 1	2.85
Solar irradiance (W/m²)	820 ± 15	790 ± 20	850 ± 18	820 ± 25	3.05
Operating time (h/acre)	1.00 ± 0.05	1.10 ± 0.06	1.05 ± 0.04	1.05 ± 0.05	4.76
Area covered (acres/h)	1.00 ± 0.04	0.91 ± 0.05	0.95 ± 0.03	0.95 ± 0.04	4.21
Leaves collected (kg/acre)	45 ± 2	42 ± 2	44 ± 1.5	43.7 ± 2.0	4.57

5. CASH FLOW ANALYSIS OF THE MACHINE

Cash flow analysis for a machine is a financial tool used to assess its viability, profitability, and return on investment throughout its operational life. This analysis tracks all inflows, such as savings and revenues, and outflows, including costs and expenses, on an annual basis. By doing so, it allows for accurate calculations of net cash flow, payback period, and overall profitability. This analysis is especially important for small and medium-scale farmers as it helps them determine how quickly they can recover their investment in the machine.

5.1. Net cash flow (NCF)

Net cash flow is the difference between total income (benefits) generated from the machine and the total operational and maintenance costs (including depreciation, repair, and interest) in a year. It is calculated by (14).

$$NCF = \text{Total Revenue or Savings} - \text{Total Expenses} \tag{14}$$

5.2. Present value of cash flow (PV)

The present value of future net cash flows is the value today of an amount of money to be received in the future, discounted using a given interest rate (r) calculated by (15) [28].

$$PV = \frac{NCF}{(1+r)^t} \tag{15}$$

5.3. Net present value (NPV)

NPV is the sum of all discounted net cash flows over the machine's life minus the initial investment [29]. It determines whether the machine is economically viable. It is calculated by (16).

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{NCF_t}{(1+r)^t} - C_0 \tag{16}$$

6. RESULTS AND DISCUSSION

From Figure 6, the peak output from the PV panel occurs between 12:00 pm and 2:00 pm. According to Table 4, the cutting force required for chickpea leaf nipping varies from 2.80 N to 12.37 N with an increase in stem diameter. The cutting force decreases linearly with increasing moisture content due to reduced shear strength of hydrated plant tissues, as shown in Figure 9. The performance of the machine is evaluated under two operating modes, without solar panel support and with solar panel support. In battery-only mode, the machine operated on a 20 Ah battery with 240 Wh of available energy. This provided about 3 hours of runtime, covering 2.5-3 acres of chickpea fields. Under solar-assisted operation, a 150 W solar panel supplied an extra 600 to 650 Wh. This increased the total energy and extended the runtime, allowing the machine to cover up to 9 acres of farmland in a single day. The machine completed nipping operations over 9 acres in approximately 9 hours with zero fuel consumption, whereas the gasoline-operated machine requires 7 hours and consumes nearly 7 litres of petrol, as shown in Table 6. The machine is evaluated under different soil conditions, including black cotton, red loamy, and mixed dryland soils, demonstrating its adaptability and reliable performance across diverse field environments. These results show that solar integration enhances both the operational duration and the field coverage capacity of the machine, making it a more efficient and sustainable solution for chickpea cultivation.

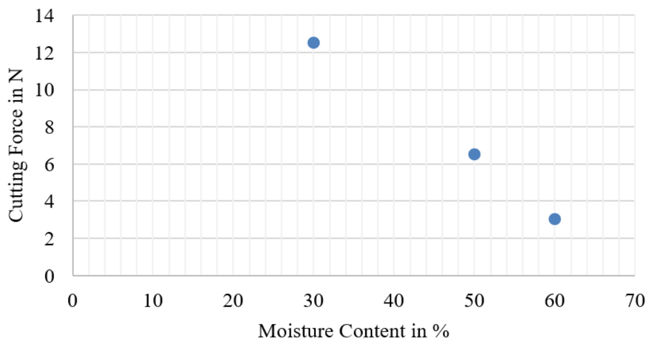

Figure 9. Effect of moisture content on cutting force for JG-11 chickpea crop variety

6.1. Techno- economic analysis and payback period

The techno-economic analysis and payback period of the machine were evaluated using field performance trials and a cost analysis, as shown in Table 8. The machine underwent testing and received approval from the Farm Machinery Testing Centre (FMTC) in Vijayapura, ensuring that it meets all operational and safety standards. The annual depreciation and maintenance costs for the developed machine are estimated using the straight-line method. Table 9 presents an economic analysis comparing the manual nipping operation of chickpea crops with the mechanized nipping operation across 9 acres of land. By utilizing the machine, farmers can save ₹6,000 in labour costs. The cash flow analysis of the machine is shown in Table 10. The initial investment required for fabricating the machine is ₹28,000, with a detailed cost breakdown presented in Table 11. The lifecycle cost analysis estimated a total cost of ₹55,000 to 60,000 over the six-year service life, with battery replacement accounting for approximately 19.3% of the overall cost.

C is the initial cost of the machine, S is the salvage value of the machine (Estimated residual value after 6 years), L is the life of the machine, R is the rate of interest (2%), F_R is the failure rate of the machine (2%) and Mr is the maintenance rate of the machine (2%). Based on the field test, the machine can gather approximately 360-400 kg of leaves. The collected leaves have a market value of 120 Rs/kg and are nutritious enough to be used as a vegetable. This provides additional revenue for chickpea farmers. In contrast, the manual nipping process requires multiple workers and can only cover 1.5 to 2 acres per day.

Table 8. Techno- economic analysis and payback period of the developed nipping machine for chickpea crops

Parameters	Formula	Cost
Total investment on the machine- ₹28,000 (includes PV module, BLDC motors, fabrication, cutter head assembly)		
Annual depreciation cost (D)	C-S/L Straight-line depreciation	₹3835
Annual interest (I)	C*R*L/2L	₹700
Annual repair and maintenance cost	$R_{mc} = (C \times F_r) + (C \times M_r)$	₹1120
Total cost of the battery with MPPT charge controller is		₹11800
Annual repair and maintenance cost of the battery	$R_{mc} = (C \times F_r) + (C \times M_r)$	₹450
Total annual operating cost of the machine		₹2270

Table 9. Economic analysis of the manual nipping process and a three-row solar-powered nipping machine for 9 acres of agricultural land

Parameters		Manual nipping operation of the chickpea crop	With the use of a three-row solar-powered nipping machine
Analysis carried out in 9 acres of chickpea crop land	Requirement of labours	8 to 10 labours are required	One labour is sufficient
	Labour cost	₹600/person	
	Time required for the nipping operation	16 h	9 h
	Collected leaves after the nipping operation	350 Kg	400 Kg
Market value of the collected leaves after the nipping process is ₹120/Kg	Income increase		₹11,400 (31%)
	Payback period	$P = \frac{Initial\ investment\ on\ the\ machine}{(Total\ labour\ cost\ saving \times Market\ Value\ of\ the\ leaves)}$	Less than one year (one cropping season)
	Benefit-to-cost ratio	$BC_{ratio} = \frac{Total\ benefits\ of\ the\ machine}{Total\ cost\ of\ investment\ on\ the\ machine}$	8.8
	Total labour cost saving	$= \text{Cost for one} \frac{\text{labour}}{\text{day}} \times \text{Numbers of labours required for 9 acres of land}$	₹6000

Table 10. Cash flow analysis of the nipping machine with certain assumptions

S. L.	Particulars	Three-row nipping machine
1	Life of the machine	06 years
2	Interest rate	2%
3	Depreciation rate of the machine	10%
4	Annual repair and maintenance cost of the machine	10% of the development cost of the machine
5	Total developed cost of the machine	₹28,000

Table 11. Development cost of the machine

S. L.	Parameters	Cost
1	Solar panel	₹5,400
2	Lithium-ion battery	₹8,000
3	MPPT charge controller	₹3,800
4	BLDC motors	₹3,300
5	Fabrication cost, including cutter head assembly	₹7,500
6	Total cost	₹28,000

6.2. Payback period

The payback period refers to the amount of time it takes for a farmer to recover the initial investment made in the machine through savings in labour costs and additional income from the sale of collected chickpea leaves. An initial investment of ₹28,000 for the machine is offset by estimated seasonal savings and earnings of ₹45,000 to ₹50,000, which include reduced labour costs and revenue from leaf sales. Consequently, the payback period is less than one cropping season. Following this period, all subsequent economic gains directly contribute to increased farmer profit.

6.3. Effect of nipping process on growth and yield of chickpea

The impact of various nipping stages on chickpea crop performance was assessed at ICAR-Krishi Vigyan Kendra (KVK), Hittinhalli Farm, in collaboration with Krishitaranga Farm Tech LLP, to determine crop yield and an economic evaluation, as shown in Table 12. Nipping at both 30 and 40 DAS resulted in the highest seed yield of 22.38 q/ha and the highest number of branches per plant (12.04). Despite a slightly increased cultivation cost for this dual-stage nipping, the net return was ₹53,250/ha, which was marginally lower than the net return from nipping at 35 DAS. The 35 DAS treatment produced a seed yield of 21.86 q/ha and the highest net return of ₹55,400/ha, indicating its superior economic viability. Nipping at 45 DAS yielded moderate results, whereas the control (no nipping) had the lowest seed yield of 12.36 q/ha and profitability. These findings emphasize the essential role of nipping in optimizing yield and enhancing economic returns in chickpea production.

Table 12. Effect of nipping process on growth and yield of chickpea crop

Nipping stage	No. of branches/plant	Grains/pod	100-Grain weight (g)	Seed yield (q/ha)	Cost of cultivation (₹/ha)	Net return (₹/ha)
No nipping (control)	8.64	1.30	16.86	12.36	₹21,128	₹45,114
Nipping at 35 DAS	11.58	1.50	22.16	21.86	₹24,388	₹55,400
Nipping at 45 DAS	10.26	1.50	22.45	17.64	₹24,396	₹39,990
Nipping at 30 and 40 DAS	12.04	1.50	22.45	22.38	₹26,396	₹53,250

7. CONCLUSION

This study presents a solar-powered nipping machine designed for chickpea crops. The machine handles three rows of chickpea crop at a time and offers a sustainable, cost-effective alternative to manual nipping. Performance tests carried out at three locations in North Karnataka, India, showed that one worker using the machine can nip 9 acres in a single day, collecting about 350-400 kg of chickpea leaves. In contrast, manual nipping requires 8 to 10 workers and 16 to 18 operating hours to cover 9 acres of chickpea, with a daily capacity of only 1.5 to 3 acres. Petrol or diesel machines use 750 ml of fuel per acre and cost ₹1,120 per day to operate. Opposite rotation of the motors in each cutter head assembly improves foliage collection, making the system more energy-efficient and sustainable for agricultural operations. Chickpea leaf nipping boosts yields by promoting better nodulation and branching. The best results were obtained when nipping was performed at 30 DAS, followed by a second round at 40 DAS. Plots that were nipped consistently performed better than those that were not, showing clear agronomic and economic benefits of timely nipping in chickpea cultivation. The analysis shows that the developed machine saves ₹6,000 per season in labour and raises farmers' income by 20-25%. Furthermore, the market value of the collected chickpea leaves, priced at ₹120 per kg, provides an additional revenue stream. The initial investment of ₹28,000 can be recouped within a single season. Utilising locally available solar energy, the system reduces reliance on fossil fuels, supports rural electrification and farm-level energy independence, and contributes to sustainable energy use in agriculture. The developed architecture can also be extended to other crop-specific mechanization systems, thereby promoting distributed renewable energy adoption in rural farming communities.

The study concludes that integrating solar-powered mechanization in chickpea farming not only enhances operational efficiency and farm profitability but also contributes to sustainable agriculture and climate resilience. The machine's affordability, quick payback period, and environmental benefits position it as a scalable solution for small and medium-sized farms in semi-arid regions of India. Furthermore, future advancements can focus on integrating IoT-based monitoring and control systems to enable precision agricultural operations, real-time performance tracking, and intelligent decision-making. Effective power management strategies also enhance future profits.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Girish Badragond, an innovator in the agricultural field and founder of Krishitaranga Farm Tech LLP, a start-up industry, Karnataka, India, and ICAR-Krishi Vigyan Kendra and the Farm Machinery Testing Center, Hittinahalli Farm, Vijayapura, Karnataka, India, for their valuable support in facilitating field testing and for approving the developed machinery for use by local farmers.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Prashant Kadi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	
Basanagouda Ronad		✓			✓	✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that there is no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [PK], upon reasonable request.

REFERENCES

[1] A. Bathaei and D. Štreimikienė, "Renewable energy and sustainable agriculture: review of indicators," *Sustainability*, vol. 15, no. 19, p. 14307, Sep. 2023, doi: 10.3390/su151914307.

[2] S. Gorjian, S. Minaei, L. MalehMirchegini, M. Trommsdorff, and R. R. Shamshiri, "Applications of solar PV systems in agricultural automation and robotics," in *Photovoltaic Solar Energy Conversion*, Elsevier, 2020, pp. 191–235. doi: 10.1016/B978-0-12-819610-6.00007-7.

[3] A. Farokhi Soofi, S. D. Manshadi, and A. Saucedo, "Farm electrification: a road-map to decarbonize the agriculture sector," *The Electricity Journal*, vol. 35, no. 2, p. 107076, Mar. 2022, doi: 10.1016/j.tej.2022.107076.

[4] S. Gorjian, H. Ebadi, M. Trommsdorff, H. Sharon, M. Demant, and S. Schindele, "The advent of modern solar-powered electric agricultural machinery: a solution for sustainable farm operations," *Journal of Cleaner Production*, vol. 292, p. 126030, Apr. 2021, doi: 10.1016/j.jclepro.2021.126030.

[5] M. Padhiary, K. Kumar, and A. Sheikh, "AI-driven innovations in precision agriculture," 2025, pp. 37–70. doi: 10.4018/979-8-3373-1434-1.ch002.

[6] G. V. Lombardi and R. Berni, "Renewable energy in agriculture: farmers willingness-to-pay for a photovoltaic electric farm tractor," *Journal of Cleaner Production*, vol. 313, p. 127520, Sep. 2021, doi: 10.1016/j.jclepro.2021.127520.

[7] S. Gorjian, R. Singh, A. Shukla, and A. R. Mazhar, "On-farm applications of solar PV systems," in *Photovoltaic Solar Energy Conversion*, Elsevier, 2020, pp. 147–190. doi: 10.1016/B978-0-12-819610-6.00006-5.

[8] P. R. Lanjekar, M. S. Dulawat, J. Makavana, and P. M. Chauhan, "Solar-powered farm rickshaw for agricultural transport," *Energy Nexus*, vol. 9, p. 100181, Mar. 2023, doi: 10.1016/j.nexus.2023.100181.

[9] A. Ghobadpour, L. Boulon, H. Mousazadeh, A. S. Malvajerdi, and S. Rafiee, "State of the art of autonomous agricultural off-road vehicles driven by renewable energy systems," *Energy Procedia*, vol. 162, pp. 4–13, 2019, doi: 10.1016/j.egypro.2019.04.002.

[10] H. Maammeur, A. Hamidat, L. Loukarfi, M. Missoum, K. Abdeladim, and T. Nacer, "Performance investigation of grid-connected PV systems for family farms: case study of north-west of Algeria," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1208–1220, Oct. 2017, doi: 10.1016/j.rser.2017.05.004.

[11] A. Das, Y. Jain, M. R. B. Agrewale, Y. K. Bhateshvar, and K. Vora, "Design of a concept electric mini tractor," in *2019 IEEE Transportation Electrification Conference, ITEC-India 2019*, 2019, doi: 10.1109/ITEC-India48457.2019.ITECIndia2019-134.

[12] S. Chauhan and L. Mittal, "Solar-powered agricultural vehicles: advancing sustainable farming in India," *The Indian Journal of Agricultural Sciences*, vol. 95, no. 2, pp. 233–236, Feb. 2025, doi: 10.56093/ijas.v95i2.157126.

[13] A. J. Moshayedi, A. S. Khan, K. Geng, J. Hu, and A. Kolahdooz, "Advancing agricultural practices: analyzing the role of robotics in corn farming," *International Journal of Engineering*, vol. 38, no. 7, pp. 1517–1532, 2025, doi: 10.5829/ije.2025.38.07a.07.

[14] A. R. Sagor, T. M. Mridul, M. M. H. Bhuiyan, F. A. Mridha, M. R. Hazari, and M. A. Rahman, "Design and implementation of solar PV operated e-power tiller," in *2023 3rd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST)*, IEEE, Jan. 2023, pp. 368–373, doi: 10.1109/ICREST57604.2023.10070045.

[15] G. Singh, A. Sharma, A. Mittal, and A. Kumar, "KisaanMitra: an autonomous farm vehicle with dual-axis solar tracking," *Lecture Notes in Mechanical Engineering*, pp. 391–399, 2021, doi: 10.1007/978-981-15-9956-9_41.

[16] A. A. Chand *et al.*, "Design and analysis of photovoltaic powered battery-operated computer vision-based multi-purpose smart farming robot," *Agronomy*, vol. 11, no. 3, 2021, doi: 10.3390/agronomy11030530.

[17] E. Scolaro, M. Beligoj, M. P. Estevez, L. Alberti, M. Renzi, and M. Mattetti, "Electrification of agricultural machinery: a review," *IEEE Access*, vol. 9, pp. 164520–164541, 2021, doi: 10.1109/ACCESS.2021.3135037.

[18] H. H. Vogt *et al.*, "Electric tractor system for family farming: increased autonomy and economic feasibility for an energy transition," *Journal of Energy Storage*, vol. 40, 2021, doi: 10.1016/j.est.2021.102744.

[19] H. Chadalavada, N. B. Kumar, P. S. Srujan, O. L. Narayana, and C. N. Kumar, "Solar powered semi-automated mutlipurpose agriculture machine," *Materials Today: Proceedings*, vol. 46, pp. 3469–3473, 2021, doi: 10.1016/j.matpr.2020.11.864.

[20] R. R. Melo, F. L. M. Antunes, S. Daher, H. H. Vogt, D. Albiero, and F. L. Tofoli, "Conception of an electric propulsion system for a 9 kW electric tractor suitable for family farming," *IET Electric Power Applications*, vol. 13, no. 12, pp. 1993–2004, 2019, doi: 10.1049/iet-epa.2019.0353.

[21] D. Yallappa, V. Palled, M. Veerangouda, and Sushilendra, "Development and evaluation of solar powered sprayer with multi-purpose applications," in *2016 IEEE Global Humanitarian Technology Conference (GHTC)*, IEEE, Oct. 2016, pp. 1–6, doi: 10.1109/GHTC.2016.7857252.

[22] F. G. Pekitkan, A. Sessiz, and R. Esgici, "Effects of blades types on shear force and energy requirement of paddy stem," *International Journal of Agriculture Environment and Food Sciences*, vol. 4, no. 3, pp. 376–383, 2020, doi: 10.31015/jaefs.2020.3.18.

[23] S. Kumar *et al.*, "Effect of stem diameter, cutting speed and moisture content on cutting torque for green gram harvesting," *International Journal of Bio-resource and Stress Management*, vol. 14, no. 8, pp. 1127–1132, 2023, doi: 10.23910/1.2023.3593b.

[24] N. K. Telangi, M. Din, K. N. Agarwal, M. Kumar, M. Kumar, and D. Singh, "Effects of moisture content and stem diameter on mechanical properties of chickpea plants for harvester development," *Legume Research*, vol. 48, no. 7, pp. 1239–1245, 2025, doi: 10.18805/LR-5092.

[25] T. N. Aruna *et al.*, "Static and dynamic cutting forces in coriander crop harvesting: engineering insights for harvester optimization," *Smart Agricultural Technology*, vol. 10, p. 100772, Mar. 2025, doi: 10.1016/j.atech.2025.100772.

[26] H. Borhanazad, S. Mekhilef, V. G. Ganapathy, M. Modiri-Delshad, and A. Mirtaheri, "Optimization of micro-grid system using mopso," *Renewable Energy*, vol. 71, pp. 295–306, Nov. 2014, doi: 10.1016/j.renene.2014.05.006.

[27] M. S. Khan, M. A. M. Ramli, H. F. Sindi, T. Hidayat, and H. R. E. H. Bouchekara, "Estimation of solar radiation on a PV panel surface with an optimal tilt angle using electric charged particles optimization," *Electronics*, vol. 11, no. 13, p. 2056, Jun. 2022, doi: 10.3390/electronics11132056.

[28] R. Esfilar, M. Bagheri, and B. Golestani, "Technoeconomic feasibility review of hybrid waste to energy system in the campus: a case study for the University of Victoria," *Renewable and Sustainable Energy Reviews*, vol. 146, p. 111190, Aug. 2021, doi: 10.1016/j.rser.2021.111190.

[29] A. Al Wahedi and Y. Bicer, "Techno-economic optimization of novel stand-alone renewables-based electric vehicle charging stations in Qatar," *Energy*, vol. 243, p. 123008, Mar. 2022, doi: 10.1016/j.energy.2021.123008.

BIOGRAPHIES OF AUTHORS

Prashant Kadi is working as an assistant professor in the Electrical and Electronics Engineering Department in BLDEA's V. P. Dr. P. G. Halakatti College of Engineering and Technology, Vijayapura, India. He received a master's in Microelectronics and control systems from Visvesvaraya Technological University, Belagavi, Karnataka, India. His areas of research are applications of renewable energy sources in the agricultural field. He can be contacted at email: ee.prashantkadi@bldeacet.ac.in.

Basanagouda Ronad is working as an associate professor in the Electrical and Electronics Engineering Department at Basaveshwar Engineering College, Bagalkote, Karnataka, India, and specializes in wind-solar hybrid energy systems, energy conservation and audit, SPV-based irrigation systems, and power system studies. He received a Ph.D. from Jain University, Bangalore. His research areas are SPV-powered DC irrigation pumps in the agricultural field. He can be contacted at email: basugouda.ronad@gmail.com.