Solar-Powered Heavy-Duty Multipurpose Farming Equipment for Efficient, Sustainable Agricultural Operations

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Abstract. The aim of the current research is to create heavy-duty, multipurpose machinery for agriculture primarily runs using solar electricity for efficient, sustainable farming methods. Heavy-duty machinery for agriculture that runs on solar electricity has enormous societal, economic, along with environmental advantages. The solar-powered large-scale multipurpose farming equipment presents notable qualitative advantages in energy efficiency, operational cost, and pollution reduction when compared to traditional diesel-powered agricultural machinery. An average diesel tractor uses 4–6 litres of fuel per hour, which means it emits 10–15 kg of CO_2 per hour. In contrast, an electric system that runs on solar power produces no direct emissions while in operation. In accordance with the fuel price and load, diesel-based operations may spend between Rs. 300 and Rs. 500 per hour on gasoline; in contrast, solar-powered systems can save up to 70–90% on operational costs, primarily covering maintenance as well as battery replacement. Additionally, energy efficiency increases significantly because electric drive trains are 85–90% more efficient than internal combustion engines, which are only 30–40% efficient. Additionally, operator comfort is increased by lowering noise levels from 90–100 dB in conventional machinery to 60–70 dB in electric systems The suggested solar-powered equipment has a clear practical benefit over current baseline systems, as it can reduce overall lifecycle costs by 30 to 40% over an operational lifecycle of 8 to 10 years while improving sustainability and independence from power sources.

Keywords: Solar-Powered farming, multipurpose farming equipment, Heavy-Duty, sustainable farming

1 Introduction

Heavy-duty, versatile agricultural equipment that runs on renewable energy offers an environmentally friendly alternative to agricultural mechanization. It effectively uses sustainable solar energy to carry out required tasks in the field. This technique reduces the demand for conventional fuel-powered machinery. Both diesel along with petrol-powered agricultural machinery has high operating costs. They emit greenhouse

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gases and are contributing towards ecological degradation. These devices are expensive, particularly for medium- and small-sized farms, due to the need for frequent maintenance along with variability in fuel prices. It have been particularly for small and medium-sized farmers. Solar-powered farming equipment circumvents these limitations. It uses electric drive systems that work in conjunction with PV (photovoltaic) cells to generate and consume renewable energy. The chosen strategy can reduce operational costs as well as the release of greenhouse gases. Additionally, it improves environmental sustainability and reliability of the systems. Numerous agricultural tasks are made easier by the equipment. Most of the field operations that can be performed on the same platform included ploughing, seeding, and pesticide spraying. Its adaptability increases output along with reduces the requirement for many pieces of equipment. Therefore, solar-powered multipurpose farming equipment offers a useful and sustainable substitute for contemporary agriculture [1–4].

Numerous operational difficulties confront modern agriculture. Rising fuel prices and labour shortages are common problems for farmers. There are still a few effective and reasonably priced tools available, especially for small-scale farmers. It takes a lot of work and time to do tasks like manual weeding and pesticide spraying. These activities lower overall farm productivity and raise production expenses. During the busiest farming seasons, the issue gets worse. This research proposes a solar-powered heavy-duty multipurpose farming equipment to address these issues. The device combines soil weeding tasks with water or pesticide spraying capabilities. It uses a single, small mechanism to accomplish both jobs. This strategy increases field efficiency, decreases operational costs, and lessens reliance on manpower [5].

The equipment's primary power source is solar energy. It reduces operating expenses and runs without fuel. The system is sustainable and ecologically friendly thanks to this design. The device is still small and simple to use. It works well in remote areas with little or no access to grid electricity. The system increases field productivity and decreases manual labor. By using green energy it also promotes sustainable farming. The created equipment's design, operating principles, materials, testing results, and overall performance are all presented in this study [6]. In order to increase agricultural output, crop protection is essential. Numerous crops are at risk from pests and diseases, which also result in large output losses [7]. Reducing these losses and increasing the effectiveness of other agricultural inputs are two benefits of effective plant protection [8]. Applying chemicals correctly is essential to effective pest control. Effective spraying methods, regulated dosage, and proper management are crucial. In agriculture, chemical application is still the only completely automated process that calls for specific equipment. For the application of fertilizers, insecticides, and herbicides, sprayers are essential equipment. In farming techniques, they provide consistent coverage, minimize worker effort, and increase application efficiency [9–12].

We set out to develop an agricultural device powered by solar energy that performs spraying of pesticides or water as well as taking care of mechanical weeding, in a single operation. Solar energy operates the whole process, so farmers are not dependent on fossil fuels. The idea is easy to understand: a solitary machine which removes weeds and applies spray, cutting down on time and cutting down on manual labor. We additionally concentrated on creating a lightweight version, affordable, and accessible for small and marginal farmers to handle without complications.

2 Materials and Methods

2.1. Materials used

The choice of materials and components was based on factors like cost, availability, mechanical strength, energy efficiency, and ease of assembly. The main materials used in this project include mild steel (MS) and aluminium sheets. These materials were chosen for the main chassis and frame because of their strong strength-to-weight ratio and resistance to corrosion. The wheels and axles were designed for heavy-duty performance. They include rubber wheels with a suitable grip for rough terrain, mounted on metal axles for better mobility. The rotary blades were made from stainless steel cutters or tins, serving as the weeding mechanism. The sprayer tank is a chemical-resistant plastic or fibre-based tank that holds water or pesticide, typically with a capacity of 10 to 15 liters. The solar panels are either monocrystalline or polycrystalline photovoltaic (PV) panels, usually rated between 50 and 100 watts for collecting solar energy.

The rechargeable battery either a 12-volt lead-acid or lithium-ion type with at least 12 amphoursstores energy and powers the motor along with other systems. For the drive and rotary parts, high-torque DC motors run on 12 or 24 volts, giving the machine the push it needs. The pump motor, which can be a diaphragm or a submersible DC pump, handles pressurized spraying. Control switches and relays keep everything on track, running the sprayer, weeder, and drive as needed. A solar charge controller keeps an eye on the battery, making sure it charges safely and doesn't overcharge or run down too far. You can see all the main mechanical and electrical components in Figure 1. The mechanical parts include the frame, wheels, shafts, and spraying nozzles; these provide support, mobility, and allow for effective spraying and weeding. The electrical parts consist of a solar-powered battery system, an electric motor, switches, and control circuits. They supply clean energy, cut down on fossil fuel use, and ensure smooth operation of the spraying and weeding mechanisms. Together, these parts work well to improve the design, durability, and ease of use; this makes the equipment ideal for small and medium-sized farmers in different field conditions.

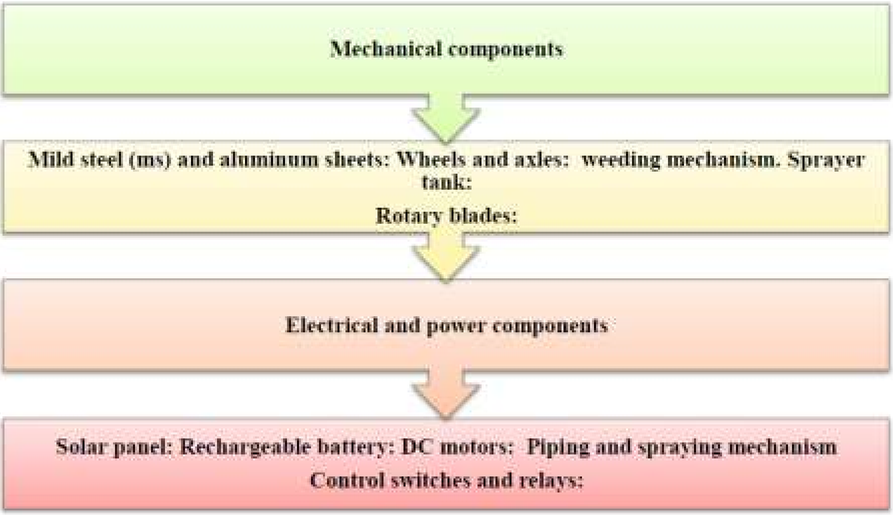

Fig.1 Used mechanical and Electrical Components

2.2. Design Methodology

The method used for designing and building the agricultural equipment was divided into clear phases to ensure it is technically feasible, suitable for users, and performs well in the field. Each phase focused on specific design goals while considering the practical needs of small and medium-scale farmers. The flow chart in Figure 2 shows the method used for designing and building the agricultural equipment, which is divided into six sequential phases. It starts with Research and Requirement Analysis, where existing machinery is examined, limitations are identified, farmer needs are evaluated, and system requirements are defined. Next is Conceptual Design, which includes generating, evaluating, and selecting the best design idea. The detailed design and CAD modelling phase involves creating detailed drawings, running simulations, and making improvements to ensure performance, comfort, and cost-effectiveness. Prototype fabrication includes getting materials, putting components together, and integrating systems into a working model. The testing and evaluation phase involves field trials to check performance, toughness, and usability, with improvements noted for further refinement. In the last phase of development and execution, Final requirements have been established, and adaptations identified during testing have been incorporated. To establish a strong basis for the design process, the initial phase focused on extensive investigations and requirements analysis.

A detailed study examined existing agricultural machinery for spraying and weeding. This included manual, engine-powered, and solar-assisted systems currently on the market. The analysis revealed several key issues, such as high operational costs, reliance on fossil fuels, excessive weight, complicated operation, and a lack of suitability for small landholdings. To ensure a user-centered design, we carefully considered the needs of small and medium-scale farmers. Factors like affordability, ease of operation, reduced physical effort, low maintenance, and adaptability to different field conditions were taken into account. Special attention focused on challenges in rural areas, like limited fuel access, unreliable power supply, and the need for eco-friendly solutions. Based on this analysis, we defined system requirements. These included power requirements appropriate for solar operation, functional needs for effective spraying and weeding, adaptability to various crop patterns and soil types, and ergonomic features for ease of handling. We emphasized making the equipment efficient with minimal technical knowledge, which would help farmers with little mechanization experience. The second phase involved developing the conceptual design and layout of the system. We created initial sketches to visualize the overall configuration of the equipment. These sketches helped us determine the placement of major components, including the solar panel, electric motor drive system, spraying unit, weeding mechanism, and chassis. After the initial sketches, we developed computer-aided design (CAD) models to refine the design and assess spatial arrangements. CAD modeling allowed for accurate visualization of how components fit together, weight distribution, and structural stability. We optimized the solar panel placement to maximize sunlight exposure while ensuring balance and manoeuvrability.

Appropriate drive mechanisms, like chain-sprocket or belt drives, were assessed and chosen based on the terrain, load needs, and efficiency. This selection ensured reliable power transmission with minimal losses in the field. Additionally, we finalized the equipment's overall dimensions by considering crop row spacing, turning radius, and field manoeuvrability. This made sure it worked well with common agricultural practices. This phase ended with a clear conceptual design that balanced functionality, efficiency, and ease of use, establishing a strong foundation for detailed design and later manufacturing.

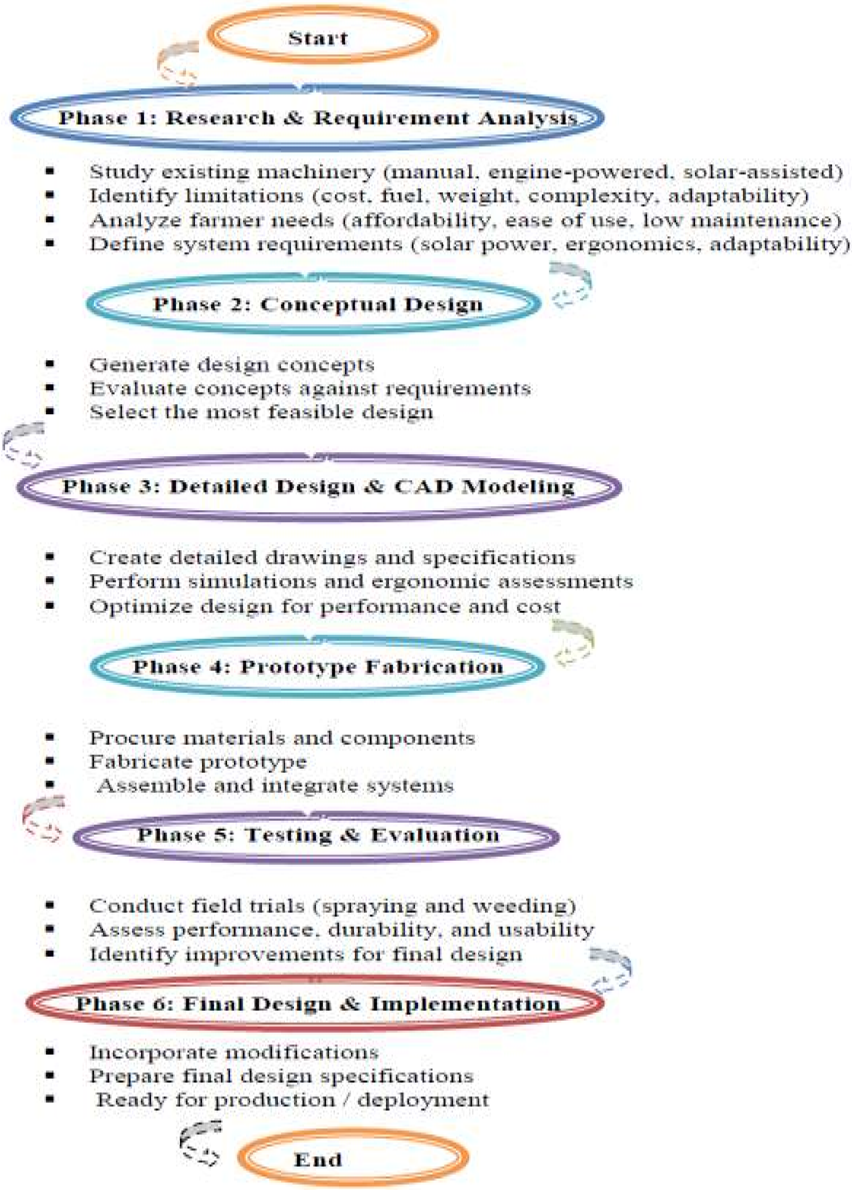

Fig.2 Flow Chart: Design and Fabrication of Agricultural Equipment

3 Results and Discussion

A performance evaluation compared how well manually operated multi-nozzle sprayers work against solar-powered sprayers. The experiment sprayed an area of 2m x 30m, as shown in Figure 3, for a total of five repetitions using both sprayer types. We used a stopwatch to measure the spraying time for the manual sprayer, the solar-powered sprayer, and a knapsack hand sprayer for comparison. Afterwards, we analyzed and compared the results. To assess the solar-powered sprayer's performance, we tested it in the field, measuring the amount of sprayed solution to check its practical effectiveness. We calculated both theoretical and actual field capacities based on our observations. We also determined field efficiency to evaluate the performance of the solar-powered sprayer, which had a chain and sprocket mechanism.

Fig.3 Final design of multipurpose solar-powered agriculture machine

The team made a number of important notes while designing, building, and testing the solar-powered heavy-duty multipurpose farming equipment in the field. Performance, energy efficiency, handling, and practical use were the main topics of these observations. The outcomes demonstrate the system's performance under actual field conditions. Additionally, they draw attention to functional strengths and areas that require additional development for increased dependability and usability.

3.1 Observations of Results

A. Functional Performance

The equipment successfully carried out both spraying and weeding tasks, either on their own or together, without any major decline in performance. The spraying system delivered an even spray distribution, covering an area of about 1.5 to 2 meters, depending on the nozzle setup and pump pressure. The mechanical weeder efficiently took out surface-level weeds, particularly in loose or moderately compacted soil. The rotary blades loosened the soil and improved soil aeration without disturbing crop roots when properly aligned.

B.Power and Energy Management

The solar panel (50–100W) produced enough power to run the system in direct sunlight. The 12V battery provided reliable operation, even during brief cloud cover. On average, a fully charged battery allowed continuous use for 2.5 to 3 hours, covering about 2500–3000 square meters. The solar charge controller managed the charging well, and we did not face any overcharging or battery drainage problems during tests.

C. Mobility and Handling

The equipment was easy to move over flat and slightly uneven farmland. The wheel and axle system offered enough ground clearance and stability. Some challenges arose on very uneven terrain or in soil with large stones, which sometimes interfered with the rotation of the weeding blades. The control switches were placed conveniently, allowing operators to switch between spraying and weeding functions without any issues.

D. Structural Integrity

The chassis structure, made of mild steel, stayed stable under operational loads. This included the filled spray tank and the vibrations from the rotary motion. The weight distribution was well-balanced, which reduced the risk of tipping or skidding during operation.

E. Efficiency and Time Savings

The combined use of spraying and weeding in one pass cut operation time by about 30 to 40% compared to doing these tasks separately with manual tools. Labor needs were reduced, and only one operator was necessary to handle the equipment during field operations.

F. Environmental and Economic Impact

The use of solar energy removed fuel costs and cut greenhouse gas emissions. This made the equipment both eco-friendly and financially sustainable. Maintenance needs were minimal. They included regular cleaning of nozzles, lubrication of moving parts, and occasional battery checks. Table 1 shows the main design parameters and the results from testing the agricultural equipment. The table covers important factors like spraying capacity, weeding efficiency, power use, operational speed, and ergonomic performance. These parameters were measured to assess how well the equipment works and how suitable it is for small and medium-sized farms. The results demonstrate the equipment's ability to operate effectively in different field conditions while keeping energy use low, being easy to operate, and offering reliability. This provides a clear picture of its technical performance and practical use.

Table.1 Summary table of parameters and results

Parameter	Observation Result
Spraying Efficiency	Uniform, adjustable flow; 1.5–2 m coverage
Weeding Performance	Effective on soft to moderate soil
Battery Backup	2.5–3 hours per full charge
Area Covered per Charge	2500–3000 m² approx.
Power Source	Stable solar power input via 50–100W panel
Labor Requirement	Single operator sufficient
Time Efficiency	Reduced operation time by 30–40%
Environmental Benefit	Zero emissions; fuel-free operation

3.2 Discussion

The results that were observed for the Solar-Powered Medium-Duty Multipurpose Farming Machinery Design are discussed here, along with what each parameter means in terms of sustainability, practicality, and system performance. With an effective distribution range of 1.5-2 meters, the apparatus showed consistent and controllable spray flow. This shows that the spraying mechanism has become well-designed to distribute chemicals or nutrients consistently, reduce waste, and improve crop protection. The flexibility increases versatility across various farming applications by enabling the operator to modify spraying intensity dependent upon crop type along with field conditions.

The results show that the solar-powered multipurpose equipment meets its intended purpose and offers several benefits. Combining the spraying and weeding functions into one unit not only boosts productivity but also makes farm management easier for small to medium-sized farmers. In terms of power management, the solar system supplied reliable energy for daily activities, and the battery provided enough backup. However, extended periods of cloudy weather might require more battery capacity or a hybrid charging system.

Reliable energy storage and effective power use are demonstrated by a battery backup life of 2.5–3 hours per full charge. This makes it possible to continue operating even when there are brief drops in solar strength, such when it's cloudy. For ordinary farming chores, the backup time is adequate, guaranteeing operational flexibility and dependability in real-world settings.

The ergonomic and structural design provided good maneuverability and balance. However, the system would improve with suspension or shock absorption features in uneven field conditions. Overall, the design shows that solar-powered multipurpose agricultural equipment can be a sustainable, low-cost, and effective tool for boosting rural farming productivity. With minor adjustments and scaling, the system has potential for commercialization and wider use. The device has a good equilibrium between energy consumption along with operational output, covering about 2500–3000 m^2 every charge. For smallholder and partially commercial farmers in particular, this coverage increases production and decreases downtime by making the system useful for everyday cultivation activities without frequent recharging.

3.3 Benefits of Present Design

The shift to solar-powered heavy work machinery offers various environmental, economic, and social benefits, as shown in Figure 4. Solar-powered equipment removes tailpipe emissions, which greatly cut down on carbon dioxide and particulate pollution linked to diesel engines. This helps address climate change and improves air quality in rural areas. Although the initial costs for PV panels and battery systems can be higher, operational costs decrease significantly since sunlight is free. Over time, savings on fuel and lower maintenance needs often balance out the initial investment. By taking advantage of abundant solar resources, especially in regions with strong sunlight like many parts of India, farmers can rely less on unstable fuel markets and inconsistent grid access. Smaller solar-powered tractors and multipurpose machines are especially beneficial for smallholders who cannot afford traditional heavy machinery. This expands access to mechanization and boosts farm productivity.

Using a 50–100 W solar panel offers a reliable and sustainable power source. This demonstrates that the system can function without the use of fossil fuels or grid electricity. The equipment is especially appropriate for rural and off-grid agricultural areas due to the solar power integration, which also improves sustainability. Because the system only needs one operator, labor dependency is greatly reduced. This is particularly helpful in places where labor costs are rising or there is a labor shortage. Even less physically demanding users can utilise the equipment thanks to its automated and ergonomic features. When compared to traditional manual or fuel-powered systems, operational time was cut by 30–40%. This enhancement demonstrates the efficiency of integrating several farming processes into a single system, enabling farmers to finish jobs more quickly and devote time to other agricultural pursuits.

The machinery is environmentally benign because it runs completely without fuel and emits no pollution. By lowering carbon emissions, air pollution, and noise levels, this promotes sustainable farming methods and supports international objectives for the use of clean energy in agriculture. The battery-powered heavy-duty multifunctional farming equipment provides effective, environmentally friendly, and useful for contemporary agriculture, according to the observed results. Its performance shows a great potential to boost sustainable farming, lower operating costs, and increase productivity especially in rural and energy-constrained places.

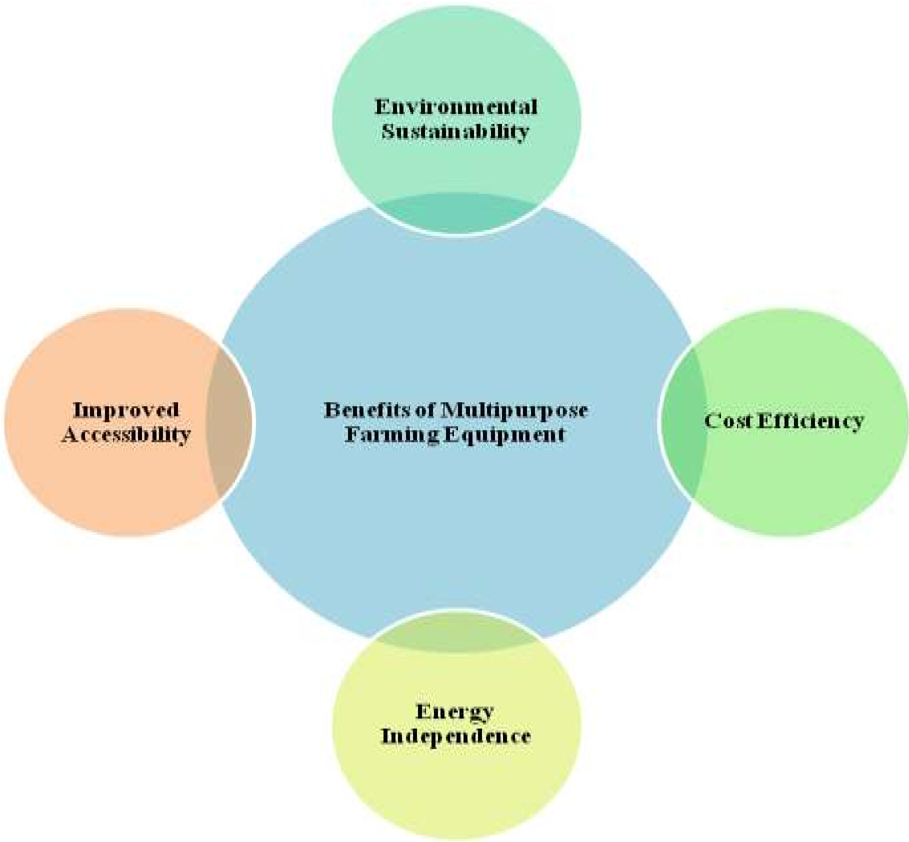

Fig.4 Benefits of multipurpose solar-powered seed beeder

3.4 Challenges and Limitations

Despite clear advantages, solar-powered agricultural machinery also faces significant challenges. The initial investment for solar PV modules, batteries, and power electronics is still high for many farmers, particularly small and marginal ones. The power density and range of solar energy vary with weather conditions, and the limited panel surface area on mobile equipment restricts the maximum power output. Consequently, equipment may need to be combined with batteries or additional power sources for heavy or extended tasks. The technical complexity lies in designing, installing, and maintaining solar systems, which requires specialized knowledge that may not be available in rural areas.

3.5 Applications and Future Outlook

Solar-powered heavy work equipment is already being tested and used in different settings. For example, solar-powered mini tractors in India have allowed farmers to carry out tilling and cultivation tasks without relying on traditional fuel. These tractors can run efficiently for several hours on a full solar charge. Research in academics and engineering is focused on creating more capable and versatile designs that combine solar power with electric drives and smart controls. As photovoltaic technology becomes cheaper and energy storage systems get better, solar-powered multipurpose agricultural machines are expected to play a larger role in sustainable farming. In addition, supportive policies and financing options will be key to increasing adoption among smallholder farmers [17].

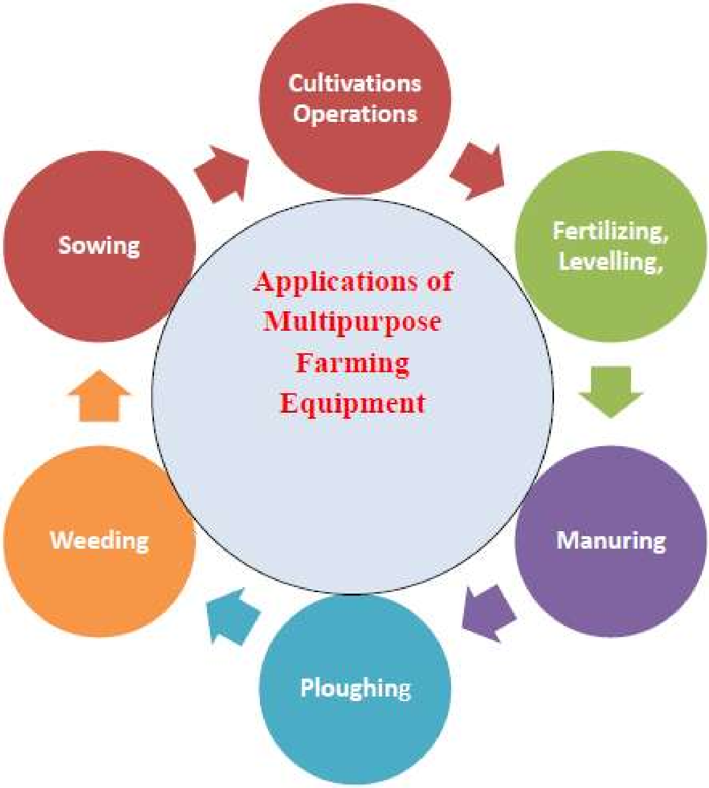

Fig.5 Various Applications of multipurpose Solar-powered heavy work equipment

4 Conclusion

Solar-powered heavy-duty multipurpose farming The rechargeable battery—either a 12-volt lead-acid or lithium-ion type with at least 12 amp-hoursstores energy and powers the motor along with other systems. For the drive and rotary parts, high-torque DC motors run on 12 or 24 volts, giving the machine the push it needs. The pump motor, which can be a diaphragm or a submersible DC pump, handles pressurized spraying. Control switches and relays keep everything on track, running the sprayer, weeder, and drive as needed. A solar charge controller keeps an eye on the battery, making sure it charges safely and doesn't overcharge or run down too far. You can see all the main mechanical and electrical components in Figure 1.

Overall, the proposed approach demonstrates a practical, economically viable, and environmentally responsible pathway toward sustainable and climate-resilient agriculture, supporting both large-scale and smallholder farming systems. The proposed solar-powered heavy work multipurpose farming equipment represents a significant step forward in sustainable agriculture. By using renewable energy, these machines cut down on fossil fuel use, lower operating costs, and reduce their environmental impact. Their ability to perform various tasks such as ploughing, sowing, spraying, and transporting makes them efficient and practical for farmers. Improvements like automation, sensor integration, and modular design boost productivity and accuracy. This innovation not only supports eco-friendly farming but also aids small and marginal farmers by cutting labor costs and improving crop yields. With ongoing development, this equipment will play an important role in the future of agriculture.

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