



Solar-powered agricultural vehicles: Advancing sustainable farming in India

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Agriculture, foundational to human civilization for millennia, remains critical for sustenance (Bachche 2015). However, modern agricultural practices heavily rely on non-renewable energy sources, contributing to greenhouse gas emissions and environmental degradation (Becerril and Rios 2016, Holmberg and Erdemir 2017). The increasing demand for food production has driven significant changes in agriculture, including farm consolidation, greater mechanization and crop advancements through breeding and genetic modification. While these developments have boosted productivity, they also present challenges in meeting future food demands sustainably (Mileusnic *et al.* 2022). The use of diverse vehicles and machinery for various operations can cause soil compaction and extensive damage, exacerbating environmental concerns. As a solution, there is a growing focus on alternative and renewable energy sources in agriculture.

Solar energy-operated farm vehicles and machines offer advantages such as higher energy efficiency and remote use capabilities. Implementing on-site energy production for agricultural operations could lead to cleaner and more sustainable practices, potentially mitigating the environmental impact of increased mechanization. A versatile vehicle capable of performing multiple operations efficiently could help conserve soil and reduce environmental impact. When designing such machines, it's crucial to consider both the precision requirements of the task and the energy needed for operation (Rai *et al.* 2022). This approach aligns with the goal of achieving sustainable agriculture without compromising productivity (Bawden *et al.* 2014).

However, the implementation of solar-powered agricultural vehicles faces several challenges. These include limited energy storage capacity affecting performance during low sunlight periods (Xue 2017), high initial costs potentially deterring small-scale farmers (Bontinck *et al.*

2021), the need for more robust and efficient solar panels suitable for harsh agricultural environments (Notton *et al.* 2010) and a lack of standardization in solar vehicle design and components, which hinders widespread adoption and maintenance (Reinders *et al.* 2017).

To tackle these challenges, we have developed a solar-powered vehicle capable of performing seven essential agricultural field tasks, i.e. irrigation, ploughing, leveling the soil, harvesting, weeding, seed distribution and fertilizer or pesticide spraying. By incorporating these functionalities into a single machine, this vehicle significantly enhances the efficiency and sustainability of agricultural operations, offering a practical solution to modern farming challenges.

The solar-powered agricultural vehicle (420 cm × 188 cm) was designed and constructed with a focus on efficiency and versatility in farming operations during the years 2021–24 at Amity International School, Pushp Vihar, New Delhi, India. The power system consists of six 12 V solar panels connected in series, producing a total of 72 V, with 60 V used for main power generation and 12 V for spray and irrigation systems. Energy is stored in a 60 V, 72 Ah lithium iron phosphate battery. The vehicle has a maximum speed of 25 km/h and is equipped with wide, field-suitable wheels. It can cover a maximum distance of 60 km with solar power (25 km without) and has a backup time of 120 min with solar power (60 min without). The vehicle integrates multiple tools including a cultivator tilling machine and weeding machine at the back, a GPS system in front of the driver's seat, a rear-mounted sprinkler for irrigation and folded tubes with circular sprays on both sides for fertilizer application. Solar panels are mounted on the roof and a storage unit at the back accommodates grains and tools. This integrated design aims to enhance farming efficiency while reducing environmental impact.

Operational mechanism of solar-powered agricultural vehicle: The solar-operated agricultural vehicle was made of a combination of metals, which are lightweight and weatherproof paint to make it robust to work in the agricultural fields. The broad wheels are used to work on

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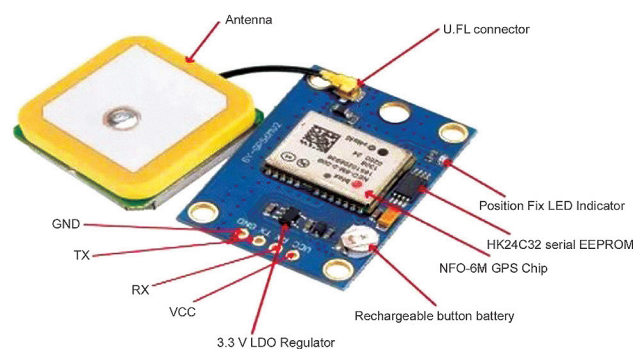


Fig. 1 GPS enabled system.



Fig. 2 Solar-operated agricultural vehicle.

the field. The driver's seat is at the front. The vehicle has a GPS-enabled system (Fig. 1) in front of the driver seat (Fig. 2), which guides the farmers as to which part of the field has been worked upon by showing a map. We have used the New NEO 7 series, which includes the Ublox Neo-6M GPS module with EEPROM.

The vehicle is a multi-utility vehicle comprising various accessories such as tilling machine, weeding machine, irrigation pipes, fertiliser applicator, leveller etc. Each tool is connected to one of the solar panels of 12 V, which is operated on solar energy. The vehicle also contains solar panels, battery and battery charger. Other accessories include GPS module, memory, screen, communication interface, motors, water pump, solenoid valves, pipes and storage containers (Table 1).

The tilling machine prepares the soil to sow the seeds. The vehicle is installed with the weeding tool to remove the

excess useless plants. The irrigation pipes are used to water the plants. The fertiliser tool uses solid and liquid fertiliser to make the soil better for the crops. The leveller levels the soil to plant the crops. The solar panels generate the energy to drive the vehicle (Fig. 3A). They are installed on the roof. There is a special storage compartment for the various tools, which can be retracted inside this. The irrigation pipes are on the sides and the leveller and the fertiliser unit are at the back. The seeds can also be sown through the fertiliser unit. The storage unit is at the back of the vehicle, which can store the seed/inputs/grains (Fig. 3B). Therefore, the same vehicle can be used for multiple operations.

The control centre is ahead of the driver's seat, comprising the steering wheel, buttons, and levers to control the functions. The compartment below it has an extendable tube for sowing seeds. The sowing can be done with the help of a device attached to the control centre. It is standing upright and can be taken out when sowing seeds. The long tube can have big syringe-like structures at frequent intervals that can sow the seeds at the required depth.

The main body has a folded tube attached to it on both sides. The tube has small circular sprays which release the fertilisers. The tube can release fertilisers as the body moves. The tube is made of copper, with a special coating to prevent reactions when metal encounters fertilisers (Fig. 3C).

Again, the main body has a tube to release water. The height can be adjusted as the water must be given at the tip or above. The tube is capable of irrigating the field as the body moves. A sprinkler is also on the back of the body, which helps with irrigation (Fig. 3D). All the water comes from the water tanker inside the body. The main body has a folded tube attached to it on both sides.

The vehicle has an extendable arm in the back to change the tools for tilling, a leveller and weeding equipment. The storage tanks are provided to store fertiliser and water. The pipes for fertiliser and water are the same, as irrigation needs to be directed and accurate. To evaluate the efficiency and effectiveness of the integrated agricultural tools, we have conducted performance tests for each component. Table 2 summarizes the results of these tests, providing insights into the vehicle's capabilities across various agricultural tasks.

This solar powered vehicle requires the same time to till 1-acre land as taken by a tractor with around 40–50 horsepower (HP) and a 2-bottom plough or disc harrow, however, saves 3–5 L of diesel (Kamboj and Singh 2017). The irrigation and fertigation efficiency of the vehicle can be improved by attaching the sprinkler system (Singh and Singh 2015).

Thus, the present vehicle is affordable, does not require much maintenance and helps farmers cope with the money spent on labour. Farmers don't need any special skills to use this device. However, crop production is also highly dependent on the resources, such as seed and fertiliser quality.

Comparative analysis of with and without solar power: A solar power connection of 6 solar cells of size 83 cm × 71 cm each of them with 12 V, facilitated increased distance

Table 1 Specifications of tools used

Tools	Size
Solar panel	83 cm (L) × 71 cm (W)
Irrigation system	125 cm (L) with a diameter of 5 cm
Leveller	190 cm (L)
Tilling machine	180 cm (L) × 20 cm (H)
Drilling	91 cm (H)
Fertilizer unit	152 cm (L)
Spraying system	160 cm with a 5 cm diameter
Water or fertilizer storage	60 L



Fig. 3 Different components of solar-operated agricultural vehicle. (A) Solar panel on the roof, (B) Storage compartment for the various tools, (C) Circular sprayers for fertilisers and (D) Sprinklers for irrigation.

coverage and extended backup time during transportation. In the solar-connected mode, where power was added or generated, the maximum distance covered reached 60 km with a backup time of 120 min. Conversely, in disconnected mode, relying solely on stored battery power, the total distance covered was 25 km with a backup time of 60 min. This disparity underscores the efficacy of solar power in augmenting transportation capabilities. Notably, solar-connected farm rickshaws exhibited a 42% increase in distance covered compared to their non-solar-connected counterparts.

The development and implementation of the solar-powered agricultural vehicle represents a significant advancement in sustainable farming practices. The vehicle's performance metrics, as shown in Table 2 and 3, demonstrate its potential to revolutionize agricultural operations while promoting environmental sustainability. The integrated agricultural tools showcase the vehicle's versatility and efficiency (Table 1 and 2). For instance, tilling machine has the ability to cover 1.20 acres/h and the fertilizer unit's application rate of 0.70/h indicates substantial improvements in operational efficiency compared to traditional methods. This multifunctionality aligns with the findings of Rai *et al.* (2022), who emphasized the importance of multipurpose farming applications in smart autonomous agricultural robots. The comparative analysis

of the vehicle's performance with and without solar power highlights the significant advantages of solar integration (Table 3). The 42% increase in distance covered and the doubling of backup time demonstrate the potential of solar power in enhancing the vehicle's operational capabilities. This improvement in range and endurance addresses one of the key challenges in electric agricultural vehicles, as identified by Gorjian *et al.* (2021).

Techno-economics of the developed agriculture vehicle: The concept is distinct to fulfil the requirements of farmers with four portable tools powered by solar energy. Additionally, the vehicle is precisely engineered to minimise its carbon emissions to support achieving sustainable development goals (SDGs). In addition to its agricultural applications, the vehicle can be used as a personal car. The vehicle is designed according to the circular economy principles and constructed using recycled materials. The "solar operated agriculture vehicle with portable tools" is a versatile and economical solution designed specifically for farmers (Gorjian *et al.* 2021). To provide a comprehensive overview of the solar-powered agricultural vehicle developed in this study, Supplementary Table 1 presents the key specifications of the vehicle, including its energy system, capacity, and features.

The vehicle's specifications (Supplementary Table 1) further underscore its advanced design and capabilities. The 4.5 kWh solar panel capacity coupled with a 72 Ah lithium iron phosphate battery provides a robust power system. This configuration not only ensures extended operational hours but also contributes to reduced operational costs, as evidenced by the decrease from 4 ₹/km–2 ₹/km when using solar power. The integration of a GPS system and multiple tools into a single vehicle addresses the need for precision agriculture, a trend highlighted by Shamshiri *et al.* (2018) in their review of advanced technologies for smart greenhouse systems. This integration not only enhances efficiency but also potentially reduces soil compaction by minimizing the number of separate machines needed for different operations. Moreover, the vehicle's design, which incorporates recycled materials and adheres to circular economy principles, aligns with the growing emphasis on sustainability in agricultural technology. This approach resonates with the findings of Klerkx and Rose (2020), who stressed the importance of considering broader sustainability impacts in agri-food tech innovations.

Table 2 Performance of integrated agricultural tools in solar powered vehicle

Tool	Function	Performance metric	Value (acre)
Tilling machine (Cultivator)	Soil preparation	Area tilled/h	1.20
Weeding machine (Hoes)	Weed removal	Area weeded/h	0.50
Irrigation system	Plant watering	Water coverage area/h	0.60
Fertilizer unit (Liquid)	Soil enrichment	Fertilizer application rate	0.70
Leveller	Soil levelling	Area levelled/h	0.50
Seed sowing unit	Planting	Seeds sown/h	0.70
Spraying system	Pesticide/herbicide application	Spray coverage area/h	0.60

Table 3 Comparison of vehicle performance with and without solar power

Parameter	With solar power	Without solar power
Maximum distance covered (km)	60	25
Backup time (min)	120	60
Percentage increase in distance covered (%)	42	-
Daily operational hours (h)	8	4
Operational cost per km (₹)	2	4
Average speed (km/h)	10	10

In conclusion, our solar-powered agricultural vehicle is one of the steps needed to ensure a greener and more efficient Indian farming future. We all believe that this vehicle not only solves environmental concerns but also the practical demands of farmers, which it fulfills by using solar energy and integrating multiple farming functions. Not only does this breakthrough in agricultural technology have the potential to transform farming operations, but also become commercially and economically sustainable for farmers across India (and potentially elsewhere) going forward. As this technology develops and scales, it has the potential to revolutionize agriculture in India while also contributing to broader sustainability goals around the globe. In the future, we must develop efficient energy storage vehicles while reducing costs to make this technology accessible to small farmers.

SUMMARY

The solar-powered agricultural vehicle (420 cm × 188 cm) was designed and constructed during the years 2021–24 at Amity International School, Pushp Vihar, New Delhi, India to explore its development and potential impact in promoting sustainable agricultural practices in India. The vehicle, equipped with a 4.5 kWh solar panel system and a lithium iron phosphate (LiFePO₄) battery (60 V, 72 Ah), generates and stores renewable energy for operation, reducing reliance on fossil fuels. Constructed from lightweight metals and featuring wide wheels for enhanced traction on uneven terrain, the vehicle is optimized for use in agricultural environments, with a cargo capacity of 400 kg. This study assesses the vehicle's cost-effectiveness, low maintenance requirements, and environmental benefits, particularly its role in reducing carbon emissions and minimizing labour costs for farmers. By offering an alternative to traditional, fuel-powered machinery, the solar-powered farm vehicle helps lower greenhouse gas emissions and supports the transition toward more sustainable farming practices. The paper also discusses the broader implications for scaling solar-powered transportation in rural regions, energy independence for farmers and the role of renewable energy in addressing climate change. The findings suggest that solar-powered vehicles can play a key role in transforming

agricultural practices, contributing to both economic and environmental sustainability in developing regions.

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