Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 24 | No. 2 | Article ID B4223 | 2025
Original Research Paper
https://doi.org/10.46488/NEPT.2025.v24i02.B4223
Open Access Journal

Agrivoltaics: Dual Use of Land for Energy and Food Sustainability

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Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 07-06-2024
Revised: 09-07-2024
Accepted: 06-08-2024

Key Words:

Crop production
Agrivoltaics
Microclimate
Photovoltaic cells
Soil macronutrients

Citation for the Paper:

Islam, A., Satapathy, K.K., Kothari, S.K., Ghosh, B. and Koley, S., 2025. Agrivoltaics: Dual use of land for energy and food sustainability. *Nature Environment and Pollution Technology*, 24(2), B4223. https://doi.org/10.46488/NEPT.2025.v24i02.B4223

Note: From year 2025, the journal uses Article ID instead of page numbers in citation of the published articles.

ABSTRACT

Renewable energy has been of prime importance in the present era in meeting energy demand across all sectors. To meet this demand, solar energy has become a plausible option among scientists to reduce the fossil fuel effect and find an alternative solution. The main concern about large renewable energy installations on open land, mostly used for agricultural practices, is that they can displace different land uses and instigate the feed vs. fuel controversy in the long run. The current study reviewed the installation of solar panels on farmland's benefits and challenges. The present study also reviewed the effect of solar panels on agricultural crop microclimate, soil, water condition, and crop growth and yields. Crop production and solar PV electricity generation from the same land space have numerous benefits, such as improving land productivity, reducing irrigation, managing soil, protecting crops from adverse climatic conditions (heat, frost, rainfall, etc.), increasing PV panel efficiency, and meeting house and farm electricity needs. Fewer demerits of agrivoltaics are to be studied in the future, such as keeping a suitable crop cycle, limited crop suitability, high expenses, and a lack of technical expertise. A big change to meet future energy demand without much impact on the environment is the dual use of open land for crop production and solar energy generation. To maximize crop yield, the impact of solar panels on crop yields has not been studied for numerous crops. We found that the optimum arrangement of solar panels admits varying levels of solar radiation according to crop needs. Sustainable agriculture and efficient solar energy generation can be possible in the same field by perfecting shade design and selecting suitable crops.

INTRODUCTION

The world population is expected to reach around 9.7 billion by 2050 (Gorjian et al. 2022). Globally, it has been seen that in the last few decades, with increased industrialization, population growth, and intensifying human living standards, the world's energy demand has increased (Pandey et al. 2016). Undeniable benefits of using fossil fuels such as oil, gas, and coal as primary energy sources are that they are non-renewable and hurt the environment, such as the emission of hazardous gases (Gonocruz et al. 2021). The development of renewable energy sources is engrossed in meeting future energy demand and the simultaneous replacement of fossil fuels. In 1980, agrivoltaics (AGV) systems were first proposed to duel the use of lands for agriculture production and solar energy generation in between solar arrays (Goetzberger & Zastrow 1982, Wen et al. 2018). The concept of AGV systems advanced with elevated solar panels below land spaces used for agriculture crop production. The AGV system integrates solar electricity generation from cropland to upraise land-use efficiency and offers an unusual chance for proper interaction with greater crop production, more electricity generation, reduced water demand, decreased carbon emissions, and greater prosperity for human life (Proctor et al. 2021, Hernandez et al. 2019, Weselek et al. 2021). Proper installation of an AGV system can ease the trade-off between agricultural crop production, the safest energy production, and policymakers' scarce care of the open land area (Sekiyama & Nagashima 2019).

Understanding the possibility and efficiency of dual use of the same land for energy and crop production needs actual field experiments. The development and implementation of the AGV system will play a crucial role in the growing population's sustainable food and energy supply. Solar energy production from PV panels needs nearly flat and open lands, which are competitive with crop production lands. It has been reported that the traditional solar energy production project produces approximately 1 MW of energy per 2 hectares of open land (Santra et al. 2017). The land area competition between energy production and agricultural crop production will be a critical issue, especially in India, where many people depend on agriculture (Santra et al. 2018). Past research studies reported that solar light reaching more than the light saturation point for a crop does not improve the photosynthesis rate; it simply makes the plant thirsty and increases water demand (Marrou et al. 2013a).

PV modules can be installed and oriented in such a way that the required amount of sunlight reaches the crop, and from the excess sunlight, electricity can be harvested. In the AGV system, crops cultivated below solar PV panels will reduce the temperature of the panels, which improves the efficiency of electricity production. Additionally, AGV gives shade to crops and generates electricity simultaneously. Further studies are proposed to understand its practical applications, changes in microclimate impact on crop growth, and crop management as suitable crop rotation, selection of tolerable crops, orientation of solar PV panels, movement of farm machinery, etc. (Amaducci et al. 2018).

In particular, the possible performance of shade crops, which are expected to grow poorly in low-light environments, has not yet been fully explored for AGV systems (Hassanpour et al. 2018). It has been reported that even less than 1% of agricultural land has adopted AGV systems, which may offset the global energy demand (Adeh et al. 2019). An overview of the AGV technology is given in this review paper, along with examples of recent developments, possible application areas, and current applications. It also provides an overview of the corpus of current research on AGV systems. The goal of the analysis of early reports on crop production experiences in APV systems is to assess the current level of knowledge about AGV and how crop productivity is affected by shading. To determine whether AGV systems are suitable for use in agricultural food production, we also look at various technical and agronomic aspects of them, with a focus on how they affect crop yield and microclimate.

The present review also focused on the electrical energy production performance of the AGV systems, extending to maximize crop production objectives and understanding different challenges and possibilities for describing and classifying the AGV system. In addition to this, the review study provides wise recommendations for researchers, farmers, and policymakers on AGV for power production, energy, and food sustainability. The novelty of this study is to advance the field and present a few new concepts as follows:

i) a novel concept that combines agrivoltaics and concentrated solar power to generate a variety of beneficial outputs on agricultural fields to satisfy the demands of sustainable agriculture

ii) evaluation in comparison of various AGV orientations (fixed-vertical, tracking, and fixed-tilted) for various agricultural fields to find the best locations and operating parameters.

DEVELOPMENT OF AGRIVOLTAIC SYSTEMS

The development of AGV systems differs based on the optimization of solar energy generation and crop production using different land uses and climatic conditions (Fig. 2 (a-e)). Fig. 2 b shows lower elevated AGV systems (PV module stationary), which were more collective because of higher panel density and less installation cost (Santra et al. 2017). AGV systems have been classified into 2 different categories, namely open AGV systems and closed AGV systems (Fig. 1). Open AGV systems embrace interspaced solar PV, which are standard fixed or single-axis tracking ground-mounted systems, allowing for agricultural activity in-between or vertical with PV modules. Overhead PV systems are usually elevated (2-6 m) above ground level to ensure agricultural activity beneath the solar PV panels can continue unobstructed. Systems can either be fixed, single, or dual-axis tracking. The classification of AGV has been done based on system, application, farming type, PV structure, and flexibility (Fig. 1). AGV systems can be installed either near ground mounted or greater than 3m above soil mounted with space between rows of PV modules so that manual agricultural practices or farm machinery practices can have performed underneath the panel (Dinesh & Pearce 2016). Design and development of AGV system dimensions have been performed by understanding the height of the PV module, the orientation of PV panels, tilt angle, available solar radiation, types of crops, and local climatic conditions (Santra et al. 2018, Dinesh & Pearce 2016). The development of AGV systems and their adaption is highly dependent upon the morphological traits and physiological responses of selected crops under AGV shade (Marrou et al. 2013b). The best energy conversion is possible by south-directed by a flat-plate solar collector with a tilted angle equivalent to the latitude or slightly higher than that place's latitude (Goetzberger & Zastrow 1982). studied by using PV arrays (size 1.64 m × 0.992 m) of different rows and different interspaces between arrays with rainwater harvesting systems and resulted in 29 m^2 of land required to generate 1 kW power (Santra et al. 2020). Different densities of PV panels (4m elevated from the ground) were studied, and it predicted that 35 to 73 % of global land productivity for partially shaded crops increased (Dupraz et al. 2011). It has been reported that the spacing between PV panel rows of 1.6 m is recognized to get maximum solar energy production (Dupraz et al. 2011). In an AGV system, maximum solar radiation will be used by giving an optimum tilt angle, which highly depends on local geographic location (Santra et al. 2017). In the AGV system, the PV panel height influences solar light distribution. Fig. 2e shows increased height of PV panels increases light penetration underneath PV panels, so light distribution increases in comparison with the near-ground mounted system of PV panels (Dupraz et al. 2011). The regular solar-tracking system automatically adjusts PV panel orientation based on solar altitude, improves electricity generation, and increases solar radiation below the PV panel area (Valle et al. 2017). AGV systems were studied for broccoli crops by installing PV panels 4m high, and resulted that soil temperature, microclimate, and daily photosynthetic photon flux density (PPFD) have significantly changed below AGV system, resulting in a little decrease in agriculture production and transformed metabolites in broccoli crop due to the shading of PV panel that increases consumer fondness (Chae et al. 2022). PVSyst software version 7.2 model studied and showed that the adoption of AGV reduces carbon dioxide (CO_2) gas emissions and supply of uninterrupted power and offers employment opportunities (John & Mahto 2021). Shade-resilient crops in hot-arid climatic regions can increase their yield while alleviating the negative effects of excessive temperatures and solar radiation (Jain et al. 2021). The current enhancement of electric vehicles by utilizing AGV systems in wetlands, forested land, and protected lands can improve rural charging stations, which could support a decrease in carbon emissions due to electrical vehicle use (Steadman & Higgins 2022). Assessed the impacts of pasture-based AGV systems on the environment and showed that AGV system reduces the emission of greenhouse gases (Pascaris et al. 2021a, 2021b). Technical features of the AGV system vary for different regions to improve photovoltaic yields as well as improve crop growth under the AGV system. Crop biomass production improved for the controlled solar tracking system, but the photovoltaic yield was reduced in comparison with the dynamic solar tracking system (Valle et al. 2017). However, in AGV arrangement of solar panels over agricultural land has affected both electricity generation from solar PV panels and cultivated crop yields. Three different AGV system designs were observed, such as the cultivation of crops in between solar panel modules, cultivation of crops below solar panel where the panel is raised to a suitable height so that farm machinery can move, and cultivation of crops below less than 3m elevated PV modules (Pulipaka & Peparthy 2021). Fig. 2c shows the utilization of the AGV system over the greenhouse roof and the generated power utilized to run the greenhouse equipment (Marrou et al. 2013a).

EFFECTS OF AGRIVOLTAIC SYSTEM

The adoption of PV panels above the agricultural field removes solar light and land space, which will have a definite effect on crop growth and yield by reducing heat and water requirements (Ketzera et al. 2020). It has been reported

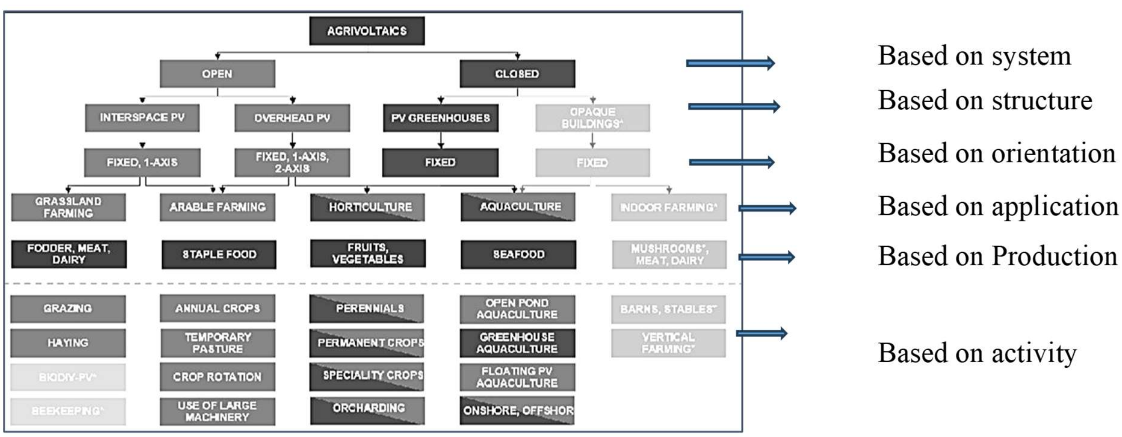
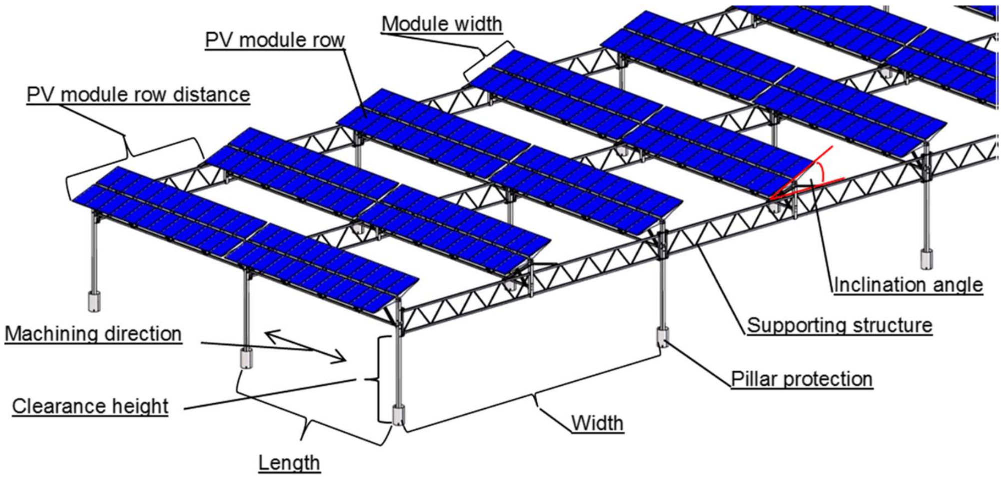


Fig. 1: Classification of AGV systems and examples of crop production (Varga et al. 2024).



a. Components of AGV system (Schindele et al. 2020).

b. AGV system with rainwater harvesting system (Santra et al. 2020).

c. AGV Greenhouse system (Marrou et al. 2013a).

d. AGV system with banana (Pulipaka & Peparthy 2021).

e. Elevated AGV system (Pulipaka & Peparthy 2021).

Fig. 2 (a-e): Utilised AGV system for different land-use conditions.

that AGV systems are expected to change the microclimate around the crop, which has both negative and positive effects on crops. Crops are categorized into 3 different categories, such as (i) Crops get benefits from shading, (ii) Crops do not have any shading effect, and (iii) Crops have highly utilized solar irradiation, which is not suitable for the AGV system (Beck et al. 2013).

AGRIVOLTAIC SYSTEM EFFECTS ON THE MICROENVIRONMENT

The optimum microclimate condition for a crop is one of the important concerns for crop growth and yield. AGV system affects microclimate conditions, resulting in an effect on crop growth, yields, and cropping duration. Solar PV panels above crop fields reduce solar radiation as well as some other factors also, such as its effects on air temperature, soil temperature, soil moisture condition, incident radiation, air humidity, wind speed, and evapotranspiration rate (Marrou et al. 2013b, Adeh et al. 2019, Amaducci et al. 2018). Reported that under the AGV system, the microclimatic conditions and crop production change by reducing 30 % photosynthetic active radiation and also reported that soil moisture and air temperatures reduced, and rain distribution changed (Weselek et al. 2021). AGV system lowered crop temperature by 2.83^{o}C and 0.71^{o}C, and PV energy generation efficiency improved by 1.13 to 1.42% and 0.28 to 0.35% on sunny days and cloudy days, respectively (Teng et al. 2022). An AGV study in the California desert estimated that 14-29 % of water evaporation was reduced by artificial irrigation water, and in the Arizona desert, 50% of water savings (Dinesh & Pearce 2016). A properly installed and oriented panel in an AGV system makes shadows that reduce water consumption by 20% and yield decrease by 10% or extension of the cropping cycle (et al. 2018). It has been reported that an AGV system decreases the potential evapotranspiration (PET) rate due to decreased solar radiation (Hassanpour et al. 2018). Studied net radiation and available photosynthetically active radiation (PAR) for open sun fields and under solar PV panel fields, resulted that on under solar panel fields lower PAR attains (Santra et al. 2017). Past studies on AGV systems on organic crop fields resulted in a significant impact on crop production fields (Weselek et al. 2021). Solar PV arrays caused seasonal and diurnal variation in air and soil microclimate during the summer (reduced temperature by up to 5.2°C) and during the winter (reduced temperature by up to 1.7°C) as compared with controlled area and under PV arrays (Armstrong et al. 2016). Under solar PV area reduces direct sunlight, which leads to reduced air temperature during daytime and warmer during nighttime and retains moisture (Gafford et al. 2019). Nearly uniform solar radiation was achieved from the AGV system by installing 2m elevated with a 6m row distance (Goetzberger & Zastrow 1982). Shading created by solar tracking AGV is indeed an interesting possibility with a high intrinsic economic value related to renewable energy production.

AGRIVILTAIC SYSTEMS EFFECTS ON CROP YIELD

AGV system has proposed to address the sustainable crop production and solar energy generation from the same land by using solar PV panels (Dinesh & Pearce 2016, Miskin et al. 2019). The demand for energy and food is increasing with an increasing population, so producing renewable energy (solar energy) from the cropland can be primed for next-generation living (Dinesh & Pearce 2016). It is not obvious that solar energy is year-round available in flat land, which is practiced for agriculture production (Adeh et al. 2019). In water-petrified areas, the implementation of solar PV panels can be productively utilized in semi-arid pastures with wet winters (Adeh et al. 2019). Solar PV panels shade the ground as per correlation with PV panels height, tilt angle, azimuth, and zenith positions of the sun, which affect crop growth by changing the amount of available PAR (Santra et al. 2020). Solar PV panels installed above 5m from the soil surface decrease sunlight by 20 to 25%, which reduces UV radiation that helps the plant grow well (Harinarayana & Vasavi 2014). AGV system impacts crop yields, but the loss can be reduced by generating additional earnings from energy utilized for selling electricity (Dinesh & Pearce 2016). The generated electrical energy can help sustainable agriculture by utilizing the produced energy in the farm itself for running irrigation pumps, operating post-harvest machinery, and controlling microclimate in greenhouse building. Under the AGV system, the land use efficiency and water productivity improved by reducing 20% irrigation water and a 10% decrease in yield and cropping cycle extension (Dupraz et al. 2011, Marrou et al. 2013c, Elamri et al. 2018). In rain-fed cultivation conditions, more grain yield and stable crop production can be possible by adopting an AGV system, reducing direct solar radiation, affecting soil temperature, evapotranspiration rate, and soil water balance, and providing favorable conditions than the open field condition (Schindele et al. 2020). Under PV, the photosynthesis rate and net ecosystem exchange are lower in the spring and winter duration (Armstrong et al. 2016). High solar radiation effect on crop and water use efficiency (Adeh et al. 2019). Arid climate cultivation of a crop and water productivity improves by reducing solar radiation using PV panels (Harinarayana & Vasavi 2014). Growing maize in rain-fed climatic conditions under solar PV panels improves crop resilience to climate change (Amaducci et al. 2018). Late session biomass increased by 90% for areas under PV panels

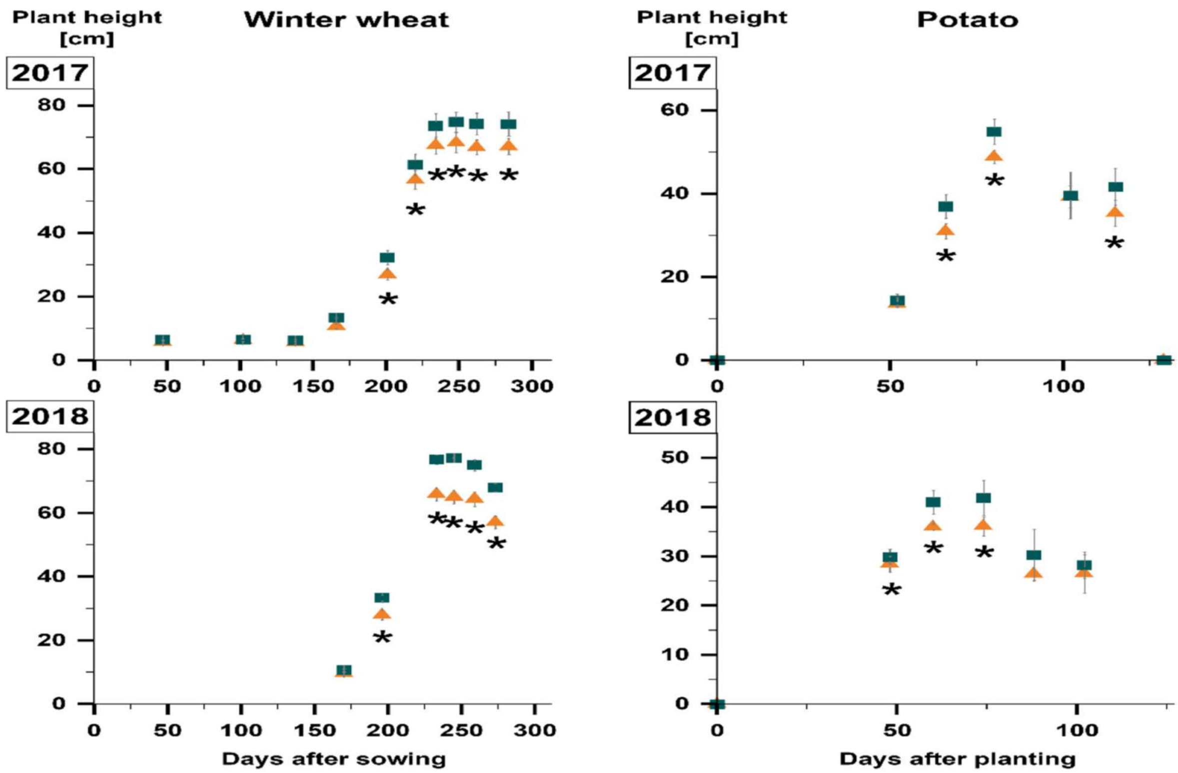


Fig. 3: PV underneath plant height of winter wheat (left) and potato (right) (Weselek et al. 2021).

(Adeh et al. 2019). Table 1 shows different past studies done for the development of AGV systems for triple-win abilities, such as improved food production, renewable energy generation, and water conservation from the same area of land. Weselek et al. (2021) studied different crop yields under AGV, and the control site was for hot-dry summer and found that crop yields of winter wheat and potato were increased for AGV by 2.7% and 11%, respectively (Fig. 3). A dynamic AGV system was investigated as a means of protecting trees from frost damage. The study revealed that less than 10% of flowers sustained injury during frost events, leading to the conclusion that autonomous vehicles (AVs) could effectively mitigate frost effects on flowers (Lopez et al. 2024). AGV system PV shade reduced 3.8°C in average air temperature and increased relative humidity by 14%, which has a positive effect on water relations, leaf morphophysiological characteristics, and yield determinants (Juillion et al. 2022). The weight and diameter reduction rates of fresh cabbage grown under APV conditions as compared to open-field conditions were 9.7% and 1.2%, respectively (Moon & Ku 2022). The AGV system did not negatively impact the yield of rye, corn, soybean, adzuki bean, or mixed plantings of corn and soybean (Jo et al. 2022).

AGRIVOLTAIC SYSTEM EFFECTS ON SOIL AND WATER

Solar photovoltaic (PV) installations over open land directly affect soil and water conditions compared to fields without PV installations due to the shadow cast by the panels. The reduction in radiation caused by solar PV panels lowers average soil temperature, soil water evaporation rate, and transpiration rate (Elamri et al. 2018, Amaducci et al. 2018). Higher soil moisture levels are achieved under the area covered by solar PV panels, resulting in a 328% improvement in water efficiency for maize crops (Adeh et al. 2019). AGV systems with solar PV panels reduce evapotranspiration by limiting light and heat under the panel area, leading to an overall water savings of 14 to 19%, depending on the percentage of shade (Marrou et al. 2013c). Barron et al. (2019) studied AGVs in dryland climates and found that water use efficiency for tomatoes and jalapenos was 157% and 65% greater than in control areas, respectively. Their research suggests that soil moisture is retained 15% more for every 2-day irrigation interval and 5% more for daily irrigation. Marrou et al. (2013c) conducted a study on the sensitivity of cucumbers to shade (solar PV panels installed above 4 meters), revealing a reduction in water use efficiency. Different shading con-

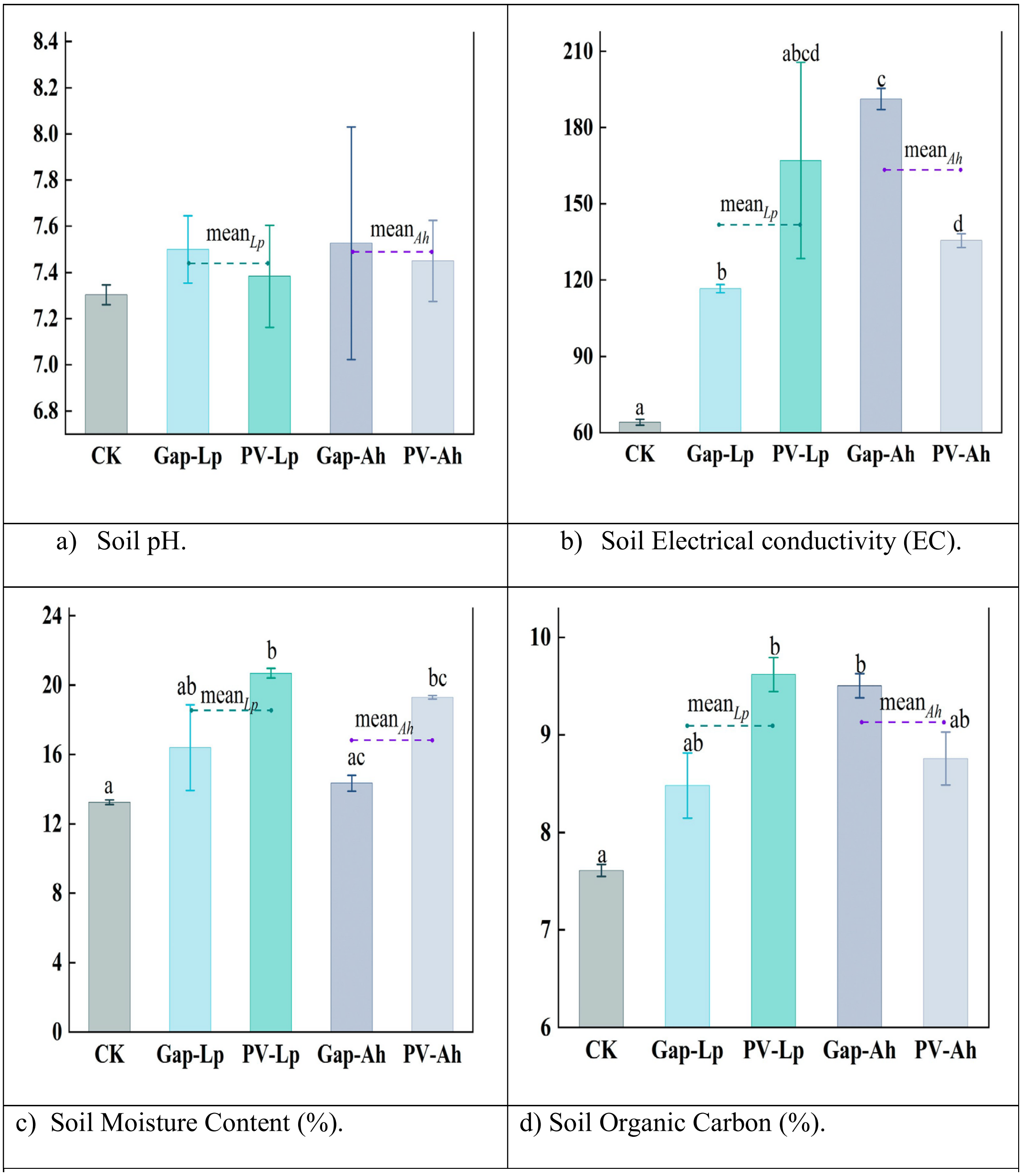
Table 1: Studies on the AGV System.

Sl. No.	Authors name	Study area	AGV system	Solar Tracking	Energy output	Crop cultivated	Outcome
1.	Goetzberger and Zastrow (1982)	Freiburg, Germany	Solar energy collectors were installed 2 m above the ground with rows distance of three times the height,	Stilt-mounted	-	-	Studied mathematical relations for different configurations of collar collectors with direct and diffuse light
2.	Nagashima (2014)	Japan	Structures created by pipes and rows of PV panels arranged in intervals	Stilt-mounted	-	-	Patented the pergola-like structure in a garden and recommended about 32% shading is adequate for the growth of crops.
3.	Czaloun (2017)	South Tyrol (Italy)	Pilot plant with rope and steel structure system elevated at 5-6 m height	double-axis module tracking	-	-	The system may be less expensive because less steel is required.
4.	Weselek et al. (2021)	Herdwangen-Schönach in south-west Germany	Steel columns mounted solar panels installed at 5 m height with a row distance and with as 6.3 m and 3.4 m respectively.	oriented in the south-west with a tilt angle of 20°	194 kW	celeriac, clover grass, wheat, and potato	Under the AGV system, yields were reduced, but favorable growing was possible during hot and dry weather.
5.	Adeh et al. (2019)	Oregon, USA	1.65 m wide solar panels were installed at 1.1 m above ground (Lower side) with a distance of 6 m.	East-west orientated and southward inclined with a tilt angle of 18^{o}	1435 kW	8 different types of grasses (Hordeum, Agrostis, Alopecurus, Schedonorus, Bromus, Calamagrostis, Cirsium, Dactylis)	Biomass production was increased for late-season grasses, and water efficiency increased to 328% under solar PV panels.
6.	Dupraz et al. (2011)	Montpellier, France	Solar panel installed above 4m from the ground and spaced 1.64 m between the lower sides of two consecutive panels with pillar distance 6.4 m apart.	South faced with the tilt angle in the range of 20^{o} to 35 ^{o}	1000Wm^{-2}	Durum wheat	Modelled Ex ante simulations and STICS (Simulateur multi-disciplinary pourles cultures standard) for light transmission under solar panels and predicted that around 35 to 73% of global land productivity could be increased.
7.	Santra et al. (2020)	Rajasthan, India	Different PV arrays row with 3 m, 6 m, 9 m interspaces between arrays installed by MS steel structure	South faced with tilt angle 26°	130kW	mung bean, moth bean, cluster bean, isabgol, cumin, taramira, cicer, chickpea, sonamukhi, sankpuspi, capsicum, cabbage, onion, garlic, cowpea, aloe vera.	Around 49% land area of an AGV system can be utilized for cultivating crops and around 1400 liter.KW^{-1} of rainwater can be harvested and utilized for PV panel cleaning purposes.
8.	Harinarayana and Vasavi (2014)	Ahmedabad, India	Solar panel installed at 5m above the ground with 3.8/7.6/11.4 m pitch distance.	South faced with tilt angle 25°	-	-	Studied using PV-Syst software for various places and resulted that the pitch distance of 7.6, 11.4 with chess board pattern installation was suitable for agriculture.
9.	Marrou et al. (2013a)	Montpellier, France	0.8m wide solar panel strip installed in East-West at 4 m above with a square grid of 6.4 m by 6.4 m	Southward with a tilt angle of 25°C.	-	Lettuce, Cucumbers, wheat	This resulted in water use efficiency increasing by reducing soil water evaporation loss and more water for plants.

Table Cont....

Sl. No.	Authors name	Study area	AGV system	Solar Tracking	Energy output	Crop cultivated	Outcome
10.	Elamri et al. (2018)	Montpellier, France	4 different shading are arranged with 2×1 m size solar panels installed at 5 m above ground surface with 6.4 m pole spacing.	Southward with a tilt angle of 25°C.	-	Lettuce	Shade reduces 20%, water demands and 5–7 days delay in maturity with -15% to -25% decrease of crop yield.
11.	Gonocruz et al. (2021)	Tokyo, Japan	3 m above the ground systems.	Fixed horizontal angle	-	Rice	Reported that at least 80% of rice yield was possible for the allowable shading ranges from 27 to 39%.
12.	Schindele et al. (2018)	Castelvetro, Piacenza, Italy	On suspended structures at 4.83 m above ground	Southward 30^o tilt angle	-	Maize	Studied by reducing solar radiation by 28.7% and 56.5% for two configuration systems and reported that more grain yield and stable crop production can be possible.
13.	Movellan (2013)	Chiba Prefecture, Japan	Installed plastic pipes at 3m high from the ground with row spacing of 5 m.	-	35,000 kWh	Cabbage, cucumber, eggplant, peanut, tomato, taro, yam	This resulted that the rate of photosynthesis did not increase even if the light reached beyond the light saturation point.
14.	Armstrong et al. (2016)	Westmill Solar Park, UK	PV rows installed at 4 m Wide and 11.2 m row spaced	South faced with an angle of 30°.	5 MW	Forbs, Legumes, Grasses	Reported that seasonal and diurnal microclimates changed under the PV module.
15.	Valle et al. (2017)	Montpellier, France	1.6 m and 3.2 m PV panel row spacing for full density and Half density and 4 m elevated above ground.	Faced 11° south-west with the tilt of 25° and with trackers	-	Lettuce	Solar tracking systems achieved high productivity per land area as compared with stationary AGV systems.
16.	Sanchez et al. (2012)	Almeria, Spain	PV Greenhouse- 9.8 % roof area Covering	-	2766 kW h (crop/cycle)	Tomato	PV Greenhouse's 9.8 % roof area covering has not altered tomato yield, but fruit size and color were affected.
17.	Alonso et al. (2012)	South Eastern Spain	PV greenhouse- 9.79% area covering (roof)	-	8.25 kW h/m2	Tomato	Reported that PAR was not significant for plants growing due to sunlight blocking effect.
18.	Cossu et al. (2014)	Decimomannu, Italy	PV greenhouse-south-roofs were completely covered with PV module (1/2 of the roof covered)	Southward side tilt 30°	107,885 kWh	Tomato	Reported that tomato yield decreased under AGV system in comparison with traditional greenhouse.
19.	Bulgari et al. (2015)	Lombardy, Italy	PV greenhouse 50 % roof area covering	-	-	Tomato	Reduces solar radiation and that effect on tomato production (Reduction)
20.	Barron et al. (2019)	USA	3.3 m PV array	Tilt of 32°	-	Chiltepin pepper, jalapeño, and cherry tomato	AGV system reduced plant Drought stress, PV panel temperature, and improved food production.

ditions resulted in a 20% reduction in water requirements for lettuce cultivation and a 5 to 7-day delay in maturity, leading to a 15 to 25% decrease in yield compared to areas without solar panels (Elamri et al. 2018). Soil physicochemical and biochemical parameters were studied for different conditions and resulted in the AGV significantly enhancing soil moisture (Fig. 4a), organic carbon (Fig. 4d), soil EC (Fig. 4b), soil pH (Fig. 4a) nitrogen-phosphorus-potassium nutrients, microbial biomass, and urease activity (Luo et al. 2024). Additionally, it was reported that gap cultivation



a) Soil pH.

b) Soil Electrical conductivity (EC).

c) Soil Moisture Content (%).

d) Soil Organic Carbon (%).

Fig. 4 (a-d): Agrivoltaics responses to soil physicochemical properties for control area outside the PV array (CK), gap ryegrass (Gap-Lp), under-panel ryegrass (PV-Lp), gap peanuts (Gap-Ah), under-panel peanuts (PV-Ah).

resulted in a noticeable definite influence on soil quality than under-panel cultivation, and the cultivation of peanuts had a greater effect on soil quality and multifunctionality improvement than ryegrass (Luo et al. 2024).

SOLAR FARMING POTENTIAL IN INDIA

India has witnessed considerable progress in its electrical infrastructure, improving its ranking from 137 to 115 in electrical reliability between 2014 and 2019 (World Bank 2019). As a prominent player in renewable energy, India has expanded its solar power generation capacity to 57.705 GW by June 30, 2022. With a substantial portion of its landmass suitable for solar (84.40%) and wind energy production (81.33%), India possesses immense potential for renewable energy. Past studies have highlighted limitations associated with wind energy generation plants, including the need for open spaces, topographic considerations, wind intensity, and wake effects (Saraswat et al. 2021). India experiences a consistent solar irradiance of 5.6 kWh m-2 day-1 across its

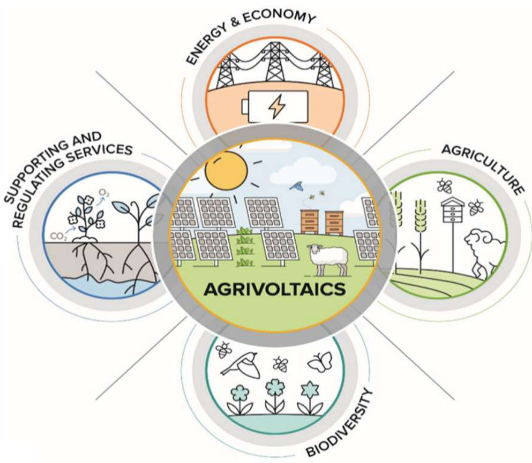


Fig 5: AGVs systems on different ecosystem services (Walston et al. 2022).

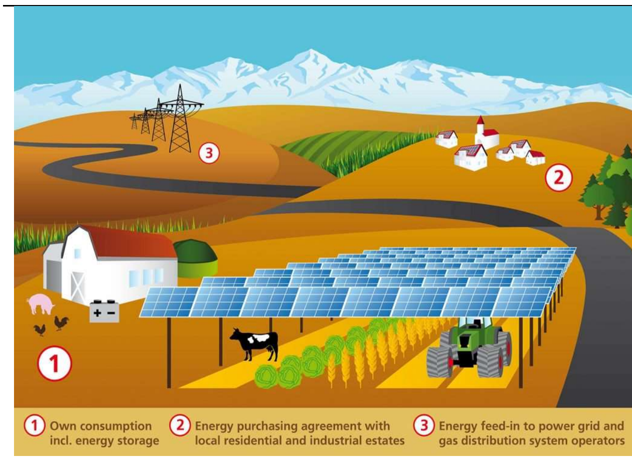


Fig 6: AGV energy utilization (Source: https://metsolar.eu/blog/what-is-agrivoltaics-how-can-solar-energy-and-agriculture-work-together/#!).

horizontal surface (NAAS 2018). Notably, the western region of India receives higher solar irradiation levels (6000–7000 kWh) compared to other areas, as depicted in Fig. 5 (NAAS 2018). The cold, arid zone encompassing Leh and Ladakh receives a solar irradiation of 7 to 7.5 kWh m-2 day-1 (NAAS, 2018). To effectively harness this abundant solar irradiation, the adoption and development of Agri-voltaic (AGV) systems are crucial throughout India. In India, three types of pilot AGV plants have been implemented based on cultivation space: (i) interspace cultivation (utilizing the space between ground-level elevated PV panels); (ii) cultivation beneath solar PV panels and between rows of ground-mounted PV panels (fixed tilt angle only; manual cultivation); and (iii) cultivation under solar PV panels mounted on an elevated structure (< 3 m) (maintaining sufficient row spacing; employing farm machinery) (Pulipaka & Peparthy 2021). The potential impact of AGV on various ecosystem services varies depending on implementation goals and priorities (Fig 5). AGV systems directly contribute to energy production and economic growth by generating electricity (Fig. 5). Furthermore, AGV can promote plant and animal biodiversity, facilitating conservation efforts through crop production, carbon sequestration, and water and soil conservation (Fig. 5). Fig. 6 illustrates various applications of solar electricity generated from farmland. Table 2 displays different AGV projects developed across diverse crop climate conditions. The AGV system in Junagadh, India, produced solar energy equivalent to that generated by installed solar PV systems and resulted in an impressive performance during the experiment, achieving an efficiency of 80.83%, a capacity factor of 16.03%, and an overall performance ratio of 12.07% (Patel et al. 2024).

CHALLENGES AND ADVANTAGES OF AGRIVOLTAIC SYSTEMS

Table 2: Different operational AGV Project plants in India.

Sl. No.	Project developer name and location	Type of AGV plant	Power production and year of establishment	Crop producing	Remarks
1..	Gujarat State Electricity Company Limited, Harsha Abakus plant near Sikka, Gujarat (Lat: 22.37903, Long: 73.05033	Interspace/Overhead stilted hybrid	1MW -2016	pearl millet, fodder, black gram, pigeon pea, cotton, green gram, cluster bean chickpea, wheat, Groundnut, soybean, mustard, Lucerne, sesame, maize,	Solar panel installed at 3 m height with manual adjustable tilt angle. They focused on the impact on crop growth due to inter-module and array gaps shading patterns.
2.	Gujarat State Electricity Company Limited, Vastan, Gujarat (Lat: 21.41111, Long: 73.12264)	Interspace / Overhead Hybrid	1MW -2016	Tomato, Ladyfingers, chili, bottle gourd, coriander, cluster beans, mug, cucumber, zucchini,	Solar PV panel (manually tilted) installed 3 m above ground with 25, 150, and 250 mm spacing between panels.
3.	Gujarat State Electricity Company Limited, Gujarat, District Kutch, Panandhro (Lat. 23.66482, Long: 68.77906)	Interspace/Overhead Hybrid Manual Seasonal tilt: 0, 10- and 25-degree	1MW -2016	Brinjal, Green gram, cluster beans, peas, coriander, ladyfinger, sesame, bottle gourd, zucchini, black gram	Different crops were grown during summer and winter seasons with a 3- 6 ft average crop height.
4.	CAZRI: Central Arid Zone Research Institute plants- Jodhpur, Rajasthan)	Single axis fixed tracking 26°, With arrays: (i) one-row PV module 3 m interspace), (ii) two-row PV modules (6 m interspace), and (iii) three-row PV modules (9 m interspaces)	100 kW	Aloe vera, isabgol, cluster bean, sonamukhi, cumin, chickpea, sankhpuspi, chili, cabbage, onion, mung bean, moth bean, garlic,	Growth and yield of isabgol, medicinal crops, and *Solanum melongena* except mungbean, were significantly affected due to panel shade. This resulted in around 49% of land area being utilized for crops growing and a 1.41 Land equivalent ratio.
5.	Amity University plant in Noida, Uttar Pradesh (Lat.: 28.54162, Long.: 77.33241)	Single column, optimum tilt angle with a height of 4.6 m from the ground.	10 kW-2017	Mustard, maize, brinjal, potato,	Under the AGV system around 90% of land can be used for crop growing, and crop yields are not significantly changed.
6.	DAU: Dayalbagh Agriculture University, plant in Agra, Uttar Pradesh (Lat: 27.22671, Long: 78.01072)	18 feet mounted structure with the single tracking system	200 kW- 2020	Grams, brinjal, tomato, wheat, spinach, cauliflower, carrot	Sufficient space and height of structure help to use of farm machinery.
7.	JAU: Junagadh Agriculture University plant in Junagadh, Gujarat. (Lat.: 21.50109, Long.: 70.44758)	3 m height overhead tilted with solar PV panels arrangement of Chequered module	7 kW-2017	Tomato, capsicum	Greenhouse gutter harvested water was used for manual cleaning of the PV panel and studied tomato and capsicum yields in the open field and AGV field.
8.	Abellon Energy plant in Aravalli, Gujarat. (Lat.: 23.55983, Long.: 73.28684)	Interspace ground mounted, manual cleaning	1 MW-2012	Ginger, chili bottle gourd, ladyfinger watermelon, turmeric	Water used to cleanse the panel is reused for crop Irrigation.
9.	Mahindra Susten plant at Tandur, Telangana. (Lat.: 17.36825, Long.: 77.54105)	Interspace ground mounted, manual cleaning	400 kW-2016	Chilies, onions, lemon grass, ladyfinger annatto dye, brinjals.	For manual cleaning, 2.50 liters per Panel of water is required every fortnightly.

Table Cont....

Sl. No.	Project developer name and location	Type of AGV plant	Power production and year of establishment	Crop producing	Remarks
9.	Jain Irrigation plants at Jalgaon, Maharashtra. (Lat.: 20.99144, Long.: 75.5073)	Overhead stilted with single axis mounted for banana, fixed for rice, dual axis for cotton	74.4 kW	Banana, rice, cotton	Banana yields improved from 14 to 34.5 tons/acre and Rice from 3.1 to 3.8 tons/acre.
10.	NISE plant near Gurgaon, Haryana. (Lat.: 28.42754, Long.: 77.16071)	Interspace	100 kW-2020	Tomato, chili, flowers, Kufri Lima potato	-
11.	Cochin Airport plant in Kerala (Lat.: 10.15667, Long.: 76.38253)	Interspace	12 MW-2015	Tomato, green chili, Ginger, turmeric, bitter gourd, Pumpkin, Snake gourd, bottle gourd, ash gourd, Ladies finger, cucumber	Completely organic way cultivation.
12.	KVK: Krishi Vigyan Kendra, under National Horticultural Research and Development Foundation, New Delhi. (Lat.: 28.57134, Long.: 76.89579)	3.5 m elevated structure with a 15-degree tilt	110 kW-2021	leafy vegetables, root vegetables, brinjal, Okra, tomato, capsicum, and cole crops	Established as a pilot project
13.	APVRT: Hinren Agri-PV Rooftop System, Bangalore, (Lat.: 12.90890, Long.: 77.59428)	2.3 m elevated structure with fixed tilt	3 kW-2019	Papaya, cauliflower, lettuce coriander, pomegranate, tomato, lemon, ladies' finger, spinach, rosemary, bitter gourd, brinjal, beans, basil, and chili	Resulting from carbon emission-free electricity and pesticide-free different vegetables.

The main challenge for producing electricity by using solar is that they need large open land space, which is suitable for agriculture. One of the main challenges for large-scale adoption of AGV is that all types of crops are not suitable to cultivate under PV panel shade and the cost of materials and installation (Pascaris et al. 2020, 2021a). The trade-off between the extra costs required for the installation of solar PV panels in agricultural crop fields has limited reports. From the stakeholder's point of view, it is truly required to improve the efficiency of the AGV system. To succeed, AGV farmers' perceptions of the application, difficulties, and opportunities of this dual land-use system are crucial (Winkler et al. 2018). For adopting AGV, the farmers are concerned about sustained land productivity because of the size of the plot and the permanence of the AGV system, the lifespan of solar panel systems, and the restriction of agricultural maintenance (Irie et al. 2019, Yeongseo & Yekang 2020). From the farmer's side, the main challenge to the adoption of AGV is the use of land for dual purposes, and a few other challenges are: 1) There are several unknown processes, and farmers are worried about demand instability (Babatunde et al. 2019, Ibrahim & Kumari 2020); 2) For the installation of the AGV system, farmers are asking for compensation for their adopted land (Santos 2020, Yano et al. 2014, Kadowaki et al. 2012); 3) AGV adaptability to accommodate varying activity sizes and types as well as changing farming practices (Cossu et al. 2018, Pascaris et al. 2021a) 4) Farmers lack knowledge about the adoption of AGV systems with positive economic and no non-negative environmental effects (Irie et al. 2019, Agostini et al. 2021); 5) Certain PV infrastructure designs should give priority to potential reversibility (Valle et al. 2017); 6) proactive awareness-raising activities to promote AGV (Kostik et al. 2020, Winklers et al. 2018). AGV faced another most important challenge: ensuring maximum crop yield under PV panels because the area underneath the PV panels receives 20% of solar energy on a clear day, which is usually not sufficient for many crops (Liu et al. 2023). Limited studies are being done on the potential of different field layout designs (Height, tilt angle, spacing between panels), PV panel types, and PV module row spacing for different crop production under the AGV system. From the operation side, the other main challenges are land utilization, technical standards, and financial intervention for AGV. Land utilization basis, it is necessary to have such guidelines of policies so that the farmers can get subsidies. As such no technical standards or norms are established to avoid improper installation of AGV systems in crop land by giving fewer priorities to crop yields. From the technical point of view, there is one more major barrier to utilizing the AGV system: the cleaning challenges for highly elevated structures, including the cleaned waterfall, may affect crops. As of now, no such study is being done about the shade of AGV system's effects on important soil macronutrient (N, P, K) levels due to the shade created underneath solar PV. So, there is indeed a way to understand the soil's important micronutrient behavior under the AGV system.

Studies on AGV systems are in the developing stage, so there is wide scope for technical and field scale improvement. The past study showed that PV modules installed with a solar tracking (Optimum) system allow solar radiation on the crop canopy, so efficient crop production and both biomass production and electricity production improved (Valle et al. 2017). The AGV system has widespread opportunities based on local climate and soil water resources for utilizing the power produced for irrigation pumping purposes and post-harvest operations (Mekhilef et al. 2013, Hyvärinen 2019). However, the AGV system can be utilized for future agricultural practices with current challenges, such as climate change, global energy demand, food security, and land use (Weselek et al. 2021). The AGV technology exploits the advantage of the connections between crop cultivation and energy production to generate an array of social, economic, and ecological benefits. AGV supports sustainable development goals by enhancing soil health by lowering soil erosion and water evaporation, raising soil temperature, which is good for soil organisms and plant growth, and addressing land shortage issues (Roxani et al. 2023). AGVs can sustain natural habitats, including those used by bees, birds, and other creatures, potentially increasing biodiversity (Walston et al. 2022). AGV increases farmers' additional revenue by selling solar electrical energy, making farmers more economically stable (Lee et al. 2023). Installation of solar PV over agricultural fields works as a shield for the crop from harsh weather conditions like hailstorms, intense heat waves, or torrential rain (Wydra et al. 2023). In the fields of agriculture and solar energy, AGV projects can lead to new employment opportunities in installation, maintenance, crop management, and system monitoring (Gorjian et al. 2020). Using solar tracking in AGV can instance, optimize the sunlight for crops, and it can increase solar PV module efficiency through improved convective cooling from below microclimatic conditions. Using bifacial PV modules can use light from both sides to generate electricity due to the distances between the ground and the PV module. Despite a few key barriers to the adoption of AV technology, experts in the agriculture sector think that the installation of AGV appears to be able to benefit them personally (Abidin et al. 2021). By demonstrating the optimal synergy achieved through the application of AGV fields, we can ensure food security, mitigate the effects of climate change, and simultaneously create a more sustainable, efficient, and aesthetically pleasing landscape. AGV demonstrated a payback period of five years or less, generating greater value compared to photovoltaic (PV) systems alone or traditional agricultural production (Geyer 2024).

CONCLUSIONS

Our review delved into the current understanding of agricultural electricity and its potential for future expansion. Through a thorough examination of existing literature, we identified 77 relevant studies, primarily focusing on food production. A significant portion of this research explored the integration of electricity generation with farming practices. Vegetables, particularly lettuce and tomatoes, were frequently highlighted in these studies. In agro-galvanic systems, factors such as geographical location and seasonal variations play a pivotal role in determining crop success. The escalating global population and burgeoning industries are driving an ever-increasing demand for food, energy, and water. These growing demands present significant challenges, leading to the development of solutions that utilize carbon-free renewable energy and food production techniques relying on fresh soil and water resources. The AGV (Agro-galvanic) approach addresses these challenges by merging food production with the generation of carbon-free renewable energy. In AGV systems, crops such as cumin, mungbean, cluster bean, sankhpuspi, isabgol, aloe vera, sonamukhi, moth bean, and chickpea can thrive beneath solar panels and in the spaces between rows, effectively utilizing approximately 49% of the land area. Our review concluded that installing solar panels over agricultural land provides shade, which can influence crop growth parameters by mitigating excessive solar radiation and temperature, leading to alterations in the crop's microclimate. While this shade can reduce crop production (except for biomass), the resulting loss can be offset by using the generated electricity. Ultimately, optimizing the design of AGV systems, with a primary focus on agricultural objectives, can significantly enhance land use efficiency while simultaneously producing electricity.

ACKNOWLEDGEMENTS

We acknowledge The Neotia University, Sarisha, for providing us with all the support to carry out this research.

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