

Agrivoltaics Systems in Egypt: Opportunities, Challenges, and Future Prospects

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ABSTRACT

Agrivoltaic systems are defined as the integration of renewable energy generation and agricultural activities within the same landscape. This innovative approach could address some of the most pressing challenges facing both sectors in Egypt and provide a sustainable and reliable long-term solution. The agricultural sector currently faces serious issues, including water scarcity, land degradation, and the fact that nearly 95% of the country's land is arid. In response, the Egyptian government's Vision 2030 highlights the importance of expanding renewable energy, particularly solar energy, due to Egypt's abundant sunlight. Because of the country's dry conditions, agrivoltaic systems would allow land to be used for both farming and electricity generation. The installed solar panels could provide necessary shade for crops, reduce water evaporation, improve the surrounding microclimate, and make crops more resilient to harsh environmental conditions. Successful studies and applications in countries such as India, France, and Spain have shown that agrivoltaics can increase land productivity, generate clean energy, and improve water-use efficiency. These results suggest that Egypt has strong potential to make agrivoltaics a leading initiative in both the agricultural and energy sectors. However, implementation in Egypt may face several challenges, including high initial costs, technical complexity, and the need for supportive policies. This paper examines the potential of agrivoltaic systems in Egypt, focusing on sustainable agriculture, renewable energy generation, and rural development. By addressing financial, technical, and policy barriers, Egypt could use agrivoltaics to support its Vision 2030 goals and provide an example for countries facing similar challenges.

1. Introduction

As the demand for renewable energy grows worldwide, using photovoltaic systems in agriculture seems like a great way to make the most of land by growing crops and generating solar power at the same time [1, 2]. Agrivoltaics "co-located dual use of the same area of land for both solar power and agriculture" systems are emerging as a crucial near-term means to address food security and renewable energy generation in the world today [3]. This concept is very appealing in countries such as Egypt, where both solar energy source and agricultural demand are massive [4]. Being part of the Sun Egypt is among the highest solar intensities in the world also it is one of the most populated countries. Egypt is expected to also expand its renewable energy presence in a domestic context for its Vision 2030 road map. Solar power is a perfect means of diversifying energy, according to the government in the country [5]. Despite the benefits Egypt possess, still it is plagued by a plethora of agricultural issues that have a direct bearing on such development and one or more have been outlined in this study from water shortages to soil erosion and land competition [6]. Agrivoltaics system can be a solution to such issue by maximizing the land usage and improving water management and reducing soil evaporation in the shadow of the solar panel [7]. Numerous research has proved that Agrivoltaics systems enable not only to maximize crop yields, but also to produce renewable power especially in dryland and semi-arid climate [8]. Studies conducted in

India and Spain showed that certain crops and sensitive species (like tomato and lettuce) can do better when grown under partially shaded conditions of solar panels [9, 10]. This microclimate conditioning mitigates heat stress, enhances water holding capacity and encourages sustainable agriculture [11]. The implementation of Agrivoltaics systems can mitigate some of the detrimental consequences of the arid lands (over 95% of Egypt's lands are arid) that plague Egypt and promote the country's renewable energy goals [12] However, despite these appealing prospects, the execution of Agrivoltaics systems in Egypt faces several challenges. The major limiting factors are high upfront investment, low technical expertise and government regulations [13]. Furthermore, the method was rarely adjusted for the local Egyptian climate and agricultural scenario. Mitigating these challenges would essentially require a collaborative action between policy makers, scientists and potential private investors for the successful introduction of Agrivoltaics system in Egypt energy and agriculture sectors.

The study collected and analyzed recent research on Agrivoltaics systems globally, with a focus on relevance to Egypt's energy and agricultural challenges. A systematic search of key academic databases, including Scopus, Web of Science, Google Scholar, and ScienceDirect, was conducted, prioritizing papers published from 2020 onward to capture recent developments. Search terms such as "Agrivoltaics," "solar energy," "solar radiation," "crop yield," and "water-use efficiency," combined with terms related to Egypt, the MENA region, and global

Agrivoltaics, were applied. Boolean operators, including (“Agrivoltaics” AND “solar energy” AND “global case studies”) OR (“photovoltaic systems” AND “crop yield” AND “Egypt”), were used to refine results. Studies were selected based on experimental data, simulation models, or field-based case studies from agro-climatic regions relevant to Egypt, including India, France, Spain, and the USA, while theoretical studies lacking empirical evidence or unrelated to arid or semi-arid environments were excluded. From each study, information was extracted regarding location, system configuration, crop type, key findings, and identified technical, financial, or policy-related limitations. Additionally, a scenario-based Land Equivalent Ratio (LER) assessment was performed to quantify the potential dual land-use efficiency of Agrivoltaics systems under Egyptian conditions, using simulated potato, tomato, and eggplant production data and Agrivoltaics technology overview and configuration

Agrivoltaics integrate photovoltaic (PV) technology with agriculture, enabling simultaneous generation of clean energy and crops while efficiently utilizing land, which is especially valuable in regions with high energy and food demand [14]. These systems allow agricultural lands to coexist with solar fields, providing electricity without sacrificing crop yields, unlike conventional solar farms [1]. By co-locating solar panels with crops, Agrivoltaics produces energy and food on the same land, supporting both industries [3, 15]. A key advantage is their modular design, which can be adapted to regional agricultural and environmental requirements [16]. In areas such as West Africa, Agrivoltaics improves water retention, crop yield, and energy production simultaneously [17]. Additionally, these systems help mitigate environmental hazards like heatwaves and droughts by regulating local microclimates and reducing the need for additional farmland [18]. System performance depends on PV layout, crop type, panel height, tilt, orientation, spacing, and whether dynamic systems are used, all of which influence both energy output and agricultural productivity [19].

Agrivoltaics can be implemented in several configurations depending on crop type, climate, and energy goals. The main configurations include fixed-tilt panels, tracking or dynamic panels, and vertical bifacial panels. Each setup offers distinct advantages in terms of energy capture, shading patterns, and microclimate effects on crops, which can be tailored to optimize both agricultural and solar energy outputs.

2.1 Fixed-Tilt Solar Panels

Fixed-tilt systems are among the simplest and most widely used Agrivoltaics designs. Panels are mounted at a set angle to maximize sunlight capture during peak hours, providing regular shading to crops—a benefit in regions with high solar intensity, such as deserts or semi-arid areas. Fig. 1 illustrates an Agrivoltaics installation where solar panels are elevated above an active field area. This configuration mitigates risks of sun-induced crop stress and allows for effective dual-use of land, balancing agricultural production with renewable energy generation [20]. These systems are relatively simple and cost-effective, making them suitable for small-scale Agrivoltaics projects. However, their fixed orientation limits adaptation to changing sunlight conditions, resulting in lower overall energy output compared to dynamic or tracking systems [21].

2.2 Dynamic/Tracking solar panels

Dynamic or tracking solar panels are equipped with mechanisms that allow them to follow the sun’s trajectory throughout the day, optimizing energy capture by adjusting their angle automatically as the ones shown in Fig. 2.



Fig. 1 Example of a fixed-tilt solar panel [22].



Fig. 2 Solar panel with a tracking system installed [23].



Fig. 3 Example of Vertical Bifacial Solar Panels [24].

This configuration can increase energy production by approximately 25–30% compared to fixed-tilt systems [25]. The ability to adjust throughout the day also creates variable shading patterns, which can benefit crops that tolerate partial shade. By controlling light exposure and reducing soil water evaporation, dynamic panels support co-benefits for both energy production and agricultural growth, particularly in dryland regions [26].

2.3 Vertical bifacial solar panels

Vertical bifacial panels are mounted upright, capturing sunlight on both their front and rear surfaces as shown in Figure 3, which allows them to utilize direct, reflected, and diffuse light [27]. This configuration creates alternating light and shade zones that moderate leaf and soil temperatures, reduce evapotranspiration, and improve water-use efficiency. Row spacing, panel height, and orientation can be optimized to balance energy capture and crop light requirements, making this setup suitable for shade-tolerant or partial-shade-adapted crops such as leafy greens, tomatoes, and medicinal plants. By integrating energy production with crop cultivation, vertical bifacial panels enhance land-use efficiency and allow both agricultural and solar outputs to be maximized simultaneously [28, 29].

2.4 Semi-Transparent Solar Panels

Semi-transparent solar panels enhance Agrivoltaics flexibility by allowing sunlight to reach crops while generating electricity. The degree of transparency can be adjusted to meet crop-specific light requirements [30]. These panels as demonstrated in Figure 4 are particularly suitable for leafy greens, herbs, and partial-shade vegetables, providing enough light for photosynthesis while protecting crops from excess heat. Semi-transparent panels also reduce soil water evaporation by lowering surface temperatures [31]. Semi-transparent solar panels have been successfully tested in greenhouses, where they supply power to climate control systems without compromising crop growth [32]. These systems are well-suited for urban agriculture and areas with limited space, enabling dual-use of rooftops or constrained land for both energy and food production.

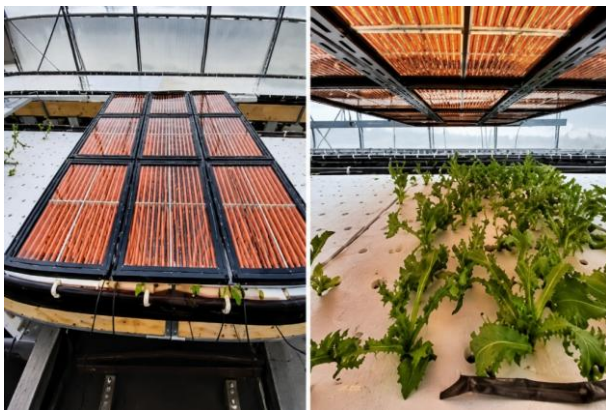


Fig. 4 Display plants growing under semi-transparent panels [33].

2.4 Panel height and interspace

Yet another consideration in designing Agrivoltaics systems is the height of solar panels and distance between rows. Taller panels allow the growing of taller crops or machines for agricultural processing under solar panels, whereas row spacing ensures that they can benefit from the sunlight for photosynthesis [34]. In environments characterized by reduced panel heights, crops including leafy greens and shade-tolerant vegetables generally exhibit favorable growth outcomes. Taller panel systems, conversely, are more advantageous for crops that necessitate increased sunlight exposure, as they facilitate improved light penetration to the plants situated beneath them.

2.5 Robotics and Automation

Operation and maintenance of Agrivoltaics systems are increasingly depending on robotics and automation. Example of that is the PV cleaning robotics in Figure 5. Designed to reduce dust collection and preserve constant energy production, automated solutions are in developed for solar panel cleaning. Robotic cleaners driven by artificial intelligence independently maintain panels in dry areas, therefore eliminating the hindrance of energy generation by dust and waste [35].

2.6 Shading, PAR and crop selection

Shading level is a key factor in Agrivoltaics systems because PV panels reduce photosynthetically active radiation (PAR) available for crops [36,37]. Panel spacing, height, orientation, and transparency determine the transmitted PAR; for example, maintaining ~80% of open-sky PAR may require only ~50% panel coverage [38]. Experimental evidence shows PAR reduction can range from 4% to 95%, with moderate shading around 48% and substantial reductions (60–70%) often causing yield decline [28].

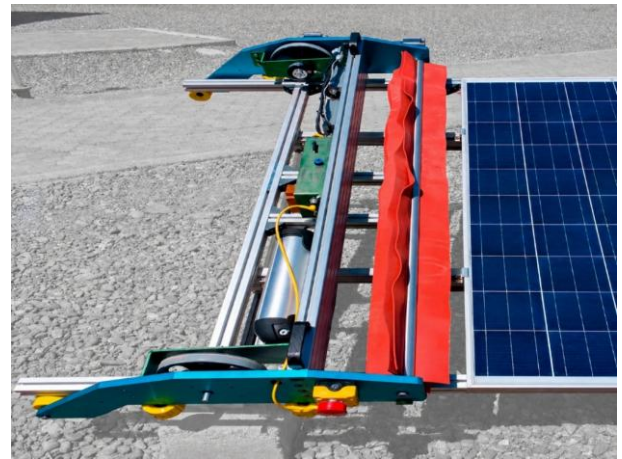


Fig. 5 Displays robotic systems deployed for cleaning PV panels [39].

Crop responses are species-specific: most tolerate up to 15% radiation loss with minimal yield impact, berries and fruity vegetables may benefit from 20–30% shading, leafy vegetables and tubers tolerate low-to-moderate shade, while maize and legumes are sensitive even at low reductions [40]. In hot, arid conditions, moderate shading can improve performance by lowering canopy temperature, reducing evapotranspiration, and alleviating drought stress, partially compensating for reduced light [31, 36]. Thus, crop selection should consider economic value, shade tolerance, PAR requirements, and local climate [28, 40].

3. Benefits and Limitations of Agrivoltaics Technology

Agrivoltaics systems provide a novel method of aggregating solar energy generation with agricultural output on the same site. Although this technology offers many advantages, one should also take significant consideration of some limits. This part looks at the benefits and drawbacks of Agrivoltaics systems, therefore giving a whole picture of their possibilities as well as the difficulties that need to be solved for further acceptance.

3.1 Benefits of Agrivoltaics Technologies

Agrivoltaics offer multiple benefits by enabling dual land use, allowing land to produce both electricity and crops, which is particularly valuable in urban or densely populated areas with limited farmland. Falling solar costs may further encourage installations without subsidies, potentially doubling land-use efficiency to 60–70% compared with conventional cropping when optimized for combined food and energy production [41]. The partial shading provided by PV panels enhances crop resilience by reducing heat stress, lowering soil moisture evaporation, and protecting plants from harsh conditions such as drought or extreme sun exposure, thereby maintaining yields in challenging climates [42, 43]. Controlled shading also helps create a favorable microclimate, warming soil in cooler regions or preventing sunburn in hot climates for delicate crops like tomatoes and grapes [37, 44]. Furthermore, Agrivoltaics improves water-use efficiency, reducing irrigation needs by up to 30% and supporting sustainable farming in water-scarce areas [45]. Finally, the dual-income potential from electricity sales provides financial stability to farmers, especially in regions with unpredictable weather, supplementing agricultural profits [46, 47].

3.2 Limitations of Agrivoltaics Technologies

Despite their advantages, Agrivoltaics have several limitations. High initial investment for panels, mounting structures, and automation equipment can be prohibitive for smaller farms, limiting widespread adoption despite potential long-term savings [48, 49].

Shading and crop selection challenges arise because some crops, such as wheat and maize, require full sun and may not thrive under partial shading, while leafy greens and herbs benefit from it; careful crop selection is therefore essential [40, 50]. Maintenance and operational complexity include regular cleaning of panels—particularly in dusty environments—and upkeep of automated systems, which can add to running costs [35, 51]. Land-use trade-offs can restrict crop choice and the use of agricultural machinery, especially on large-scale farms, complicating the balance between energy and food production [34, 52]. Finally, geographical and weather conditions influence system efficiency, as low solar irradiation, frequent cloud cover, strong winds, or heavy snowfall may require additional support or reduce energy generation, affecting overall cost-effectiveness [53, 54].

4. Global Examples of Agrivoltaics Systems and Their Implications for Egypt

Agrivoltaics systems have been implemented worldwide to simultaneously enhance energy production and crop yields. The following examples highlight successful experiments and discuss their relevance to Egyptian agricultural and climatic conditions.

4.1 France's Agrivoltaics Systems

A systematic review by Sarr et al [34] compiled results from multiple Agrivoltaics installations, highlighting the effects of panel height, spacing, and shading across different crops and locations in Table 1. In Montpellier, France, elevated panels at 4 m with a 25° tilt reduced evapotranspiration for lettuce and cucumber by 62–70% and 73–81%, respectively, while shaded lettuce treatments achieved up to 150% higher canopy cover during critical growth periods.

Durum wheat grown under the same conditions showed 11–29% reductions in dry matter and 8–11% lower yields. Similar studies in the USA (Kansas) indicated that lettuce yields decreased by 42% at a 3.2 m row spacing during summer, while larger 6.4 m spacings mitigated losses, illustrating the critical role of panel spacing and seasonal light intensity. In South Korea, maize yields under 21.3% shading increased by 6%, whereas sesame, soybean, mung bean, and kidney bean suffered decreases up to 53% under higher shading levels (32%), demonstrating species-specific responses to shade. Italian trials (Monticelli d'Ongina) showed that moderate shading (16%) could slightly improve soybean yield, whereas higher shading (18–27%) reduced both plant height and grain yield. These findings offer direct lessons for Egypt. Upper Egypt, characterized by intense solar irradiance and arid conditions, could benefit from elevated panels to reduce evapotranspiration and improve water-use efficiency, essential in water-limited environments. Leafy crops like lettuce and cucurbits, already shown to tolerate partial shading in Montpellier, are suitable candidates for the Nile Delta, where climate is warmer and more humid. Adjusting panel heights (≥ 4 m) and optimizing row spacing could prevent excessive shading and maintain yields, as observed in Kansas and Italian trials. Furthermore, the variability in species response across shading levels underscores the importance of crop selection in Egypt: shade-tolerant or partial-shade-adapted crops are likely to perform better, while sensitive crops may require wider panel spacing or dynamic configurations. Overall, the French studies indicate that careful system design can simultaneously conserve water, sustain crop productivity, and maximize PV energy output, offering a promising model for Egypt's dual-use land strategy.

Table 1 Data concluded by Sarr on the impact of PV cells on crops in different locations [34].

Study area	Crop	Spacing/height/rate of shading	Impact
Montpellier, France [55]	Lettuce and Cucumber	Height of 4 m, tilt of 25°	Evapotranspiration reduction: Lettuce: 62–70% Cucumber: 73–81% Crop cover increase: Shaded treatments had 150% higher crop cover between days 124 and 144.
Montpellier, France [56]	Durum wheat	Height of 4 m, spacing 1.64 m (distance between the lower side of two consecutive panels), tilt of 25°	The study observed reductions ranging from 11% to 29% in dry matter production, accompanied by yield decreases between 8% and 11%.
Kansas, USA state [57]	Lettuce	Height of 4 m, two spacings: 6.4 m in half density and 3.2 m between rows in full density	In summer, yields decreased by 42% at 3.2 m spacing and by 19% at 6.4 m spacing. During spring, the 6.4 m spacing showed no yield impact, while the 3.2 m spacing resulted in a 21% reduction.
Jeollanam-do, South Korea [58]	Sesame, mung bean, kidney bean, corn and soybean	Height of 5.42 m, shading rates of 32%, 25.6% and 21.3%	Maize yields increased (+6%) at 21.3% shade, while other crop yields decreased for sesame (−7%), soybean (−13%), mung bean (−21%) and kidney bean (−26%). Under a higher shade index 25.6% sesame suffered a 14% drop while beans decreased by 35–44%. In 32% shade, sesame production decreased by 53% and other crops showed reductions of 30–44%.
Monticelli d'Ongina, Italy [59]	Soybean	The experimental setup featured panel heights of 4–4.5 m with 12 m spacing between tracker rows. Four shading treatments were implemented: 27%, 18%, 16%, and 9% shade levels.	Crop Height: Highest at 27% shade (98.25 cm), lowest at 9% shade (85.04 cm), with full sun at 87.8 cm. Pods: Fewer pods under 27% (19.4% decrease) and 18% (18.2% decrease) shade, compared to lower shades. Grain Yield: Declined at higher shades (8% at 27%, 11.8% at 18%) but slightly increased at 16% shade (4.4%). Moderate shading (16%) slightly improved yield higher shades reduced crop height and yield

Table 2 Data provided by Panda on the study [60].

Parameter	Findings	Implications
Land Use Efficiency	Combined "crop + PV" systems increase land productivity by 60–160% (vs. separate uses).	Dual-use systems optimize spatial efficiency, especially in land-scarce regions.
Crop Yields	- Horticulture: Yield changes range from -30% to +60% depending on crop shade tolerance. - Leafy greens/berries perform better than grain crops (e.g., corn, wheat).	Shade-tolerant crops thrive; grain crops may face yield reductions.
Microclimate Benefits	- Soil moisture: Up to 9.4% higher under PV panels. - Evapotranspiration: Reduced by shading, conserving water.	Improved water retention benefits arid regions and reduces irrigation needs.
Energy Yield	PV panels in Agrivoltaics systems produce 50–90% of ground-mounted PV output.	Slight energy trade-off for dual-use land, offset by agricultural gains.
Economic Viability	- Income increase: Up to 75% for horticulture, 50% for livestock. Levelized Cost of Energy (LCOE): Comparable to conventional PV.	Farmers gain additional revenue from energy sales.
Environmental Impact	- GHG emissions: Reduced by 10–50%. - Resource use: Lower than ground-mounted PV (except for mineral/metal use).	Sustainable alternative to fossil fuels and traditional solar farms.
Human Comfort	Shade from PV panels reduces heat stress for workers (lower Wet Bulb Globe Temperature).	Enhances labor conditions in hot climates.

Table 3 Data collected by Disciglio group on the conducted study on medical plants [61].

Parameter	T (Full Sun)	BP (Between Panels)	UP (Under Panels)	Key Insights
Total Yield (kg/row)	Full Sun: 88.42 (a), 68.13 (b) Deficit: 72.54 (a), 68.30 (b)	Full Sun: 53.59 (a), 32.76 (b) Deficit: [Data not specified]	Full Sun: 33.61 (a), 21.64 (b) Deficit: [Data not specified]	Yield decreased with shading, but deficit irrigation improved water productivity.
Water Applied (m ³ /row)	Full Sun: 3.15 (a), 2.94 (b) Deficit: 2.02 (a), 1.82 (b)	Full Sun: [Data not specified] Deficit: 0.59–0.72	Full Sun: [Data not specified] Deficit: 0.65–0.70	Shaded areas required 55–80% less water than control.
Water Productivity (kg/m ³)	Deficit: ~40–45	Deficit: 93.11 (a) Full Sun: [Data not specified]	Deficit: 68.90 (a), 60.31 (b)	Deficit irrigation + shading doubled water productivity vs. control.
Microclimate	Higher air temp (22.3°C), soil temp (25.6°C), and wind speed (0.89 m/s).	Intermediate shading: air temp 21.5°C, soil temp 24.7°C.	Lowest air temp (19.8°C), soil temp (20°C).	Shading reduced evapotranspiration (ET) by 30%.
Soil Moisture	Lower due to higher ET.	Higher than control, but lower than below panels.	Highest moisture retention (9.4% increase).	Shading conserved soil moisture.
Irrigation Uniformity	DU: 47–85% UC: 69–99.5%	DU: 47–85% UC: 69–99.5%	DU: 47–85% UC: 69–99.5%	Variability in emitter performance affected water distribution.

4.2 India's Agrivoltaics Systems

Building on this successful integration of Agrivoltaics systems in the agricultural sector, India has taken the lead globally in the mainstreaming of Agrivoltaics, particularly in high solar irradiance and heat stress regions. A systematic review by Panda et al [60] reported that Agrivoltaics systems in India, particularly under semi-arid and arid conditions, can significantly improve land-use efficiency, crop performance, and water management. Dual-use "crop + PV" systems increased land productivity by 60–160% compared to separate land uses. Crop yields varied by species: leafy greens and berries tolerated partial shading well, with yields increasing up to 60%, whereas grain crops such as corn and wheat experienced reductions up to 30%, reflecting differences in shade tolerance. Microclimatic benefits included higher soil moisture (up to 9.4% increase) and reduced evapotranspiration, contributing to improved water-use efficiency. PV energy output in these systems reached 50–90% of conventional ground-mounted installations, providing a modest energy trade-off offset by agricultural gains. Economic analyses indicated income increases up to 75% for horticulture and 50% for livestock, while the levelized cost of energy remained comparable to standard PV. Environmental benefits included 10–50% lower greenhouse gas emissions, with overall resource use reduced except for mineral and metal consumption. Additionally, shading improved human comfort for workers by lowering wet bulb globe temperatures, mitigating heat stress during labor-intensive periods.

For Egypt, these results suggest that partial shading from elevated PV panels could stabilize yields for shade-tolerant crops in both Upper Egypt and the Nile Delta, while improving water-use efficiency in arid regions. Optimized panel spacing and height can balance crop productivity and energy generation, with additional revenue from electricity and reduced heat stress further supporting Agrivoltaics adoption. The Indian experience highlights that careful crop selection and microclimate management are critical for achieving dual benefits in high-sunlight, water-limited Egyptian climates.

4.3 Spain's Agrivoltaics Systems in Medical Plant Cultivation

Spain has also studied dynamic Agrivoltaics systems to grow high-value medicinal plants, such as sage, thyme, mint, and rosemary. In the aftermath of ongoing research conducted by the Disciglio group [61], plots were classified as T (Open Field/Full Sun), representing traditional farming with no PV panels; UP (Under Panels), permanently shaded by PV panels; and BP (Between Panels), receiving alternating shade and sunlight as the panels rotated. The UP plots received only 25–50 W/m² solar radiation, substantially lower than BP and T plots (1025–1228 W/m²), and had air temperatures 2–6°C cooler than full-sun conditions. These microclimatic modifications promoted taller and wider sage growth (+42.8% height, +58.9% width in UP) compared to full sun. Essential oil yields of sage, mint, rosemary, and lavender were 1.8–2.5% under AV shading, higher than 1.2–2.1% in T plots, indicating enhanced crop quality. Weed coverage was lower under UP and BP,

reducing competition and water stress, while dry matter content remained largely consistent across plots, with higher values in sage, rosemary, and thyme (45.9%) compared to oregano and lavender (29.8%).

These findings are particularly relevant to Egypt, where semi-arid conditions prevail in regions such as the northern coastal zone and Nile Delta. Partial shading under PV panels could mitigate excessive radiation, enhancing growth and essential oil accumulation for medicinal and aromatic crops while reducing water stress and weed competition. Implementing panel heights, row spacing, and dynamic shading similar to the Spanish system may optimize light exposure, crop performance, and PV energy generation. Overall, the Disciglio et al. study demonstrates that microclimatic modulation via dynamic Agrivoltaics can improve both yield quality and resource efficiency, offering a practical framework for high-sunlight, water-limited agricultural areas in Egypt.

4.4 Agrivoltaics Systems in Arid Middle Eastern Regions (Saudi Arabia)

Recent research in Saudi Arabia done by Ahmad et al group [62] has demonstrated the potential of Agrivoltaics systems to simultaneously optimize solar energy generation and agricultural productivity under arid conditions. They found that Elevated PV panels provide partial shading, moderating extreme temperatures and reducing soil evaporation. These microclimatic benefits allow drought-tolerant and shade-adapted crops, such as eggplant, leafy greens, and medicinal herbs, to maintain stable growth while water use is significantly reduced. Rainwater harvested from PV panels can further support irrigation, exemplified by an annual collection of 150,000 L for 0.4 hectares of crops, decreasing pumping energy requirements and overall water costs.

Their system achieves land-use efficiency ranging from 35–73%, with a land equivalent ratio (LER) between 1.04 and 2.05, depending on PV density. Approximately 85% of the land remains accessible for standard agricultural operations, demonstrating that Agrivoltaics can enhance both crop and energy output without major disruption to traditional farming practices. Economic analyses reveal that the levelized cost of electricity (LCOE) is reduced to \$0.048/kWh, compared to \$0.059/kWh for conventional PV, while crop production costs (LCOC) decrease from \$0.651/kg to \$0.50/kg. Net present value (NPV) analyses indicate profitability over a 15-year horizon, primarily driven by water savings, energy efficiency, and improved crop yield.

For Egypt, which shares climatic conditions similar to Eastern Saudi Arabia—including high solar irradiance, arid soils, and water scarcity—these findings are highly relevant. Partial shading under PV panels can stabilize yields of drought-sensitive and shade-tolerant crops while reducing irrigation demands. The dual-benefit model of energy production and water-efficient agriculture enhances land productivity and economic resilience. The crops used in the Saudi study (eggplant, leafy greens, and medicinal herbs) are comparable to Egyptian crops such as leafy vegetables, cucurbits, and medicinal or aromatic plants, making these findings directly applicable to Egypt's agricultural conditions.

4.5 USA's Agrivoltaics System for Tomato Production

Tomato cultivation in Agrivoltaics systems has been investigated in the USA for potential improvements in crop production and water-use efficiency. A case study by AL-agele [44] evaluated how tomato yields and water productivity were affected by partial shading from solar panels. While crop yields were lower in shaded areas compared to unshaded control plots, the reduction in

water demand created a distinct advantage for Agrivoltaics systems in water-scarce regions. Subplot identifiers "a" and "b" denote the northern and southern rows within the same treatment, with "a" generally receiving less shade and exhibiting higher yields than "b". Table 4 shows the detailed findings of the study.

The total yield was highest in the fully irrigated control plots (88.42 kg/row for "a" and 68.13 kg/row for "b") and decreased under shading: row full irrigated areas were 53.59 kg/row ("a") and 32.76 kg/row ("b"), while panel full irrigated areas were 33.61 kg/row ("a") and 21.64 kg/row ("b"). Water applied was highest in the control plots (up to 3.15 m³/row) and lowest under shaded deficit treatments (0.59–0.72 m³/row), corresponding with reductions of 55–80% relative to the control. Water productivity (WP) was markedly higher in shaded and deficit-irrigated plots, with the row deficit "a" treatment achieving 93.11 kg/m³, 53.98 kg/m³ greater than the T control, and the panel deficit "a" treatment reaching 68.90 kg/m³. Microclimate measurements indicated cooler soil temperatures under the panels (19.8°C) compared to the control (22.3°C), contributing to lower evapotranspiration and higher soil moisture retention. These results demonstrate that combining deficit irrigation with partial shading can double water productivity while significantly reducing water use.

For Egypt, which experiences high solar irradiance and water-limited conditions, these findings are directly relevant. The microclimatic benefits observed in the USA—reduced soil temperature, conserved moisture, and improved water productivity—can be leveraged to cultivate tomatoes and other shade-tolerant crops such as cucurbits and leafy vegetables. Using elevated PV panels with partial shading, similar to the U.S. configuration, could stabilize yields, reduce irrigation requirements, and enhance water-use efficiency, making Agrivoltaics systems a viable strategy for sustainable tomato production in Egyptian arid and semi-arid regions.

4.6 Italy's Agrivoltaics System for starchy vegetables.

Italy has explored Agrivoltaics systems to evaluate their impact on crop production and economic viability in Mediterranean climates. A case study conducted by Ademollo et al [63] in Sesto Fiorentino, Tuscany, examined potatoes as a representative starchy crop using elevated and widely spaced photovoltaic panels. In the simulation, the panels were positioned at a height of 3 m, spaced 5 m apart, and tilted at an angle of 30°. They covered approximately 40% of the land surface while maintaining nearly all of the ground area available for cultivation. High-resolution shading maps showed localized reductions in solar irradiance of up to 55% beneath the panels, particularly during March and April.

The simulations showed that moderate shading early in the season improved water-use efficiency and delayed soil moisture depletion, allowing tuber growth to continue under mild stress. Despite an average reduction of 15% in total potato yield compared to full-light cropping (26.8 t/ha vs. 31.5 t/ha), the land-equivalent ratio reached 1.58, demonstrating that combining PV energy generation with crop production increases overall land productivity. Yield variability within the field was substantial: beneath panels, yields dropped to 46% of full-light values, while at optimal shaded positions, yields peaked at 106% of full-light despite receiving only 85% of PAR. Over an 18-year simulation period (2008–2024), AV yields mirrored the declining trend of full-light conditions due to warming and drought stress, but the gap narrowed from a 15% penalty to 13%, indicating partial resilience under variable climatic conditions. Economic analysis revealed that AV systems, though

37% higher in CAPEX than conventional ground-mounted PV, could improve long-term net present value and internal rate of return when dual revenues from energy and crop production were considered.

For Egypt, particularly in regions with high solar radiation and water scarcity, moderate shading with elevated PV panels could

support the cultivation of key horticultural crops such as potatoes, eggplant, and peppers. Italy and Egypt share Mediterranean climates—hot, dry summers and mild, wet winters—making the Italian Agrivoltaics experience highly relevant not to mention that potatoes are one of Egypt's most important vegetable crops, contributing to both domestic consumption and exports.

Table 4 Study results by Al-agele conducted-on tomatoes [44].

Parameter	Under Panels (UP)	Between Panels (BP)	Full Sun (T)	Conclusion
Solar Radiation (W/m ²)	25–50 (98% lower than T)	1025–1228 (similar to T)	1025–1228	UP had near-total shading; BP matched full-sun radiation.
Air Temperature (°C)	28.1–32.2 (2–6°C cooler than T)	30.0–35.1	30.1–38.9	Shading lowered leaf temperatures, indicating less water stress.
Sage Growth (cm)	Height: +42.8%; Width: +58.9% (vs. T)	Height: +38.6%; Width: +42.3% (vs. T)	Baseline (no shading)	Shading promoted taller/wider growth in sage.
Dry Matter Content (%)	No significant difference across plots	No significant difference	No significant difference	Highest in sage, rosemary, thyme (~45.9%); lowest in lavender (~29.8%).
Essential Oil (EO) Yield (%)	Sage, mint, lavender, rosemary: 1.8–2.5% (higher)	Oregano, thyme: 1.4–2.3% (higher than T)	Sage, mint, lavender, rosemary: 1.2–2.1% (lower)	UP/BP plots enhanced EO yield in most species, likely due to microclimate.

Table 5 Summarizes the key findings of the six global Agrivoltaics studies.

Country / Study	Climatic Type	System Type	Crops Tested	Key Findings	Relevance / Lessons for Egypt
France [34]	Temperate	Semi-transparent, elevated, and tracking systems	Grapes, vegetables (lettuce, cucumber, durum wheat)	Lettuce and cucumber evapotranspiration reduced 62–81%, canopy cover increased up to 150%; wheat yield decreased 8–11%; microclimate moderated (2–3°C cooler, higher soil moisture); panel height and spacing influenced light distribution and crop performance	Upper Egypt could benefit from shading to reduce evapotranspiration and heat stress; Nile Delta suitable for leafy crops; careful optimization of panel height, tilt, and spacing can minimize yield reductions; dust may reduce PV output slightly but can be managed with cleaning
India [60]	Arid / Semi-arid	Elevated fixed-tilt and tracking systems	Leafy vegetables, pulses, berries, wheat	Water productivity increased 10–30%; soil moisture up to 9.4% higher; LER >1; PV energy output 50–90% of conventional; horticultural income increased up to 75%; partial shading reduced heat stress and moderated microclimate	Shade-tolerant crops in Upper Egypt benefit from reduced evapotranspiration and stabilized yields; dual-use land increases overall productivity; deficit irrigation combined with shading can enhance water-use efficiency; dust may reduce PV efficiency under high irradiance, but irrigation and cleaning can mitigate
Spain [61]	Mediterranean / Arid	Dynamic PV systems (UP / BP)	Medicinal and aromatic plants: sage, mint, rosemary, thyme, lavender	UP plots: radiation 25–50 W/m ² ; BP plots 1025–1228 W/m ² ; air temperature 2–6°C cooler under panels; sage height +42.8%, width +58.9%; essential oil yield 1.8–2.5% vs 1.2–2.1% in full sun; weed suppression; dry matter content stable	Partial shading can enhance growth and secondary metabolites of medicinal/aromatic crops in northern Egypt and Nile Delta; reduces heat and water stress; careful panel layout can optimize light distribution; dust may slightly reduce PV energy efficiency
Saudi Arabia [62]	Desert	Elevated PV panels; partial shading	Eggplant, leafy greens, medicinal herbs	Land-use efficiency 35–73%; LER 1.04–2.05; rainwater harvested 150,000 L/0.4 ha; shading reduced soil temperature and evapotranspiration; PV output sufficient for energy; dual-use increased net revenue	Upper Egypt, with desert-like climate, can adopt similar shading configurations to conserve soil moisture and reduce irrigation; suitable for shade-tolerant crops like leafy vegetables, eggplant, medicinal herbs; dust accumulation may slightly reduce PV output and requires maintenance
USA [44]	Desert	Vertical and elevated PV systems	Tomato, lettuce, forage crops	Shading reduced yield but increased water productivity up to 93.11 kg/m ³ with deficit irrigation; water applied reduced 55–80%; soil temperature under panels 19.8°C vs 22.3°C control; evapotranspiration reduced 30%	Upper Egypt can benefit from vertical or elevated shading systems for tomatoes and leafy crops; improves water productivity in arid regions; deficit irrigation combined with shading critical; dust may affect PV output and irrigation efficiency
Italy [63]	Mediterranean	Elevated PV panels, 3 m height, 5 m spacing, 40% coverage	Potatoes	Yield penalty 15% (26.8 t/ha vs 31.5 t/ha); LER 1.58; early-season shading improved soil moisture and delayed stress; CAPEX 37% higher, but long-term NPV improved; shading mitigated heat stress	Mediterranean climate similar to northern and central Egypt; potatoes are a major crop; shading improves soil moisture, reduces heat stress, and supports early growth stages; dual-use PV increases revenue; careful panel layout and crop selection essential; dust may reduce PV efficiency but manageable

4.7 Examples summery and relation to Egypt.

The compiled insights and findings from these global Agrivoltaics studies demonstrate that partial shading from elevated or dynamic PV systems consistently moderates microclimatic stress, enhances water-use efficiency, and can improve overall land productivity. Table 5 summarizes the key findings of the six global Agrivoltaics studies, detailing system configurations, crop responses, microclimatic effects, water-use efficiency, energy output, economic outcomes, and their relevance to Egyptian agricultural conditions. In Egypt, regions such as Upper Egypt and the Nile Delta exhibit climatic conditions comparable to those in the analyzed studies, including high direct normal irradiance (DNI), elevated ambient temperatures, and arid to semi-arid environments.

High DNI in Egypt can increase PV energy yield but may exacerbate heat stress on crops; shading designs similar to those in France, India, Spain, Saudi Arabia, the USA, and Italy can alleviate this by reducing leaf and soil temperatures. Water productivity improvements observed globally—from 10% in India to over 90 kg/m³ for tomatoes in the USA—indicate that combining partial shading with optimized irrigation could significantly reduce Egypt's water demands while maintaining crop yields. Crop selection plays a critical role: shade-tolerant or partially shade-adapted species such as leafy vegetables, cucurbits, medicinal herbs, tomatoes, and potatoes are likely to benefit most. Dust soiling, prevalent in Egypt's desert and semi-arid regions, may reduce PV output and slightly influence crop microclimate; however, regular panel cleaning and maintenance can mitigate these effects. Overall, the global evidence suggests that carefully designed Agrivoltaics systems can provide dual benefits in Egypt—maximizing energy generation, conserving water, and maintaining or enhancing crop productivity—while supporting sustainable and economically resilient agricultural practices under Mediterranean-type, high-irradiance conditions.

5. The Energy Sector in Egypt

Historically, fossil fuel especially natural gas and oil, which provide most of Egypt's electricity have dominated the country's energy scene. Egypt now struggles with energy security, sustainability, and environmental effects even if these resources have given a consistent energy foundation for decades. Along with industrial development, fast population increase has resulted in increasing energy consumption, therefore taxing the nation's infrastructure and stocks of fossil fuels.

5.1 Solar Radiation and PV Potential in Egypt

Egypt is in a region that experiences some of the highest levels of solar radiation in the world. This is primarily due to its geographical position within the Sun Belt, which results in high solar irradiance levels throughout much of the year. The country receives, on average, over 10 hours of sunlight per day, creating an ideal environment for solar power generation. Data from SOLARGIS indicates that areas in southern Egypt, such as Aswan, receive more than 2,000 kWh per square meter annually [64]. This high level of solar radiation makes Egypt one of the top global contenders for solar energy development. Table 6 shows the solar radiation data for various regions in Egypt, which demonstrates the uniformity of solar radiation across the country.

Recent regional assessments indicate that Egypt has substantial solar resources, with solar radiation not constituting a major limiting factor in broad assessments of agrivoltaic suitability.

Table 6 Annual solar radiation in Egypt by region (kWh/ m²/year) [64].

Region	Solar Radiation (kWh/m ² /year)
Northern Egypt	2045
Central Egypt	2191
Southern Egypt	2337
Aswan	2483

This widespread solar availability supports the potential for solar-energy production across the country, although local irradiance, land characteristics, and climatic conditions should be considered when evaluating individual sites [65]. Figure 6 Illustrated solar irradiance distribution throughout Egypt with the highest values are presented in southern regions.

Figure 7 presents the Photovoltaic Electricity Potential map. This figure shows the areas within Egypt with the highest potential for photovoltaic electricity generation, further supporting the argument for large-scale solar energy deployment. These favorable conditions have sparked numerous solar power projects, for example Benban Solar Park located near Aswan with a total installed capacity of 1.8 gigawatts [66]. Egypt has vast solar potential, especially in its deserts, allowing for solar power without using arable land. Agrivoltaics could boost land use efficiency [67].

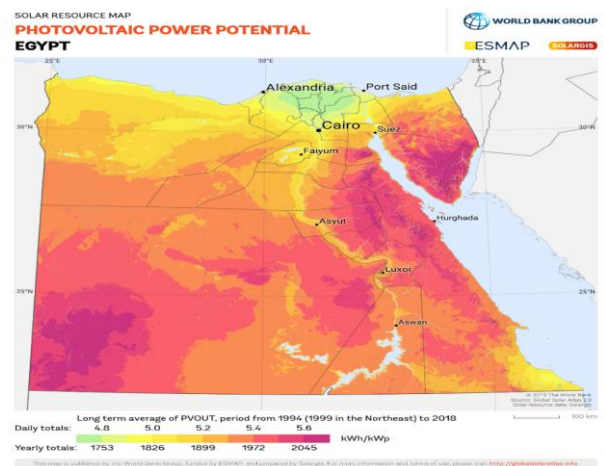


Fig. 6 Solar Irradiance Map of Egypt [64].

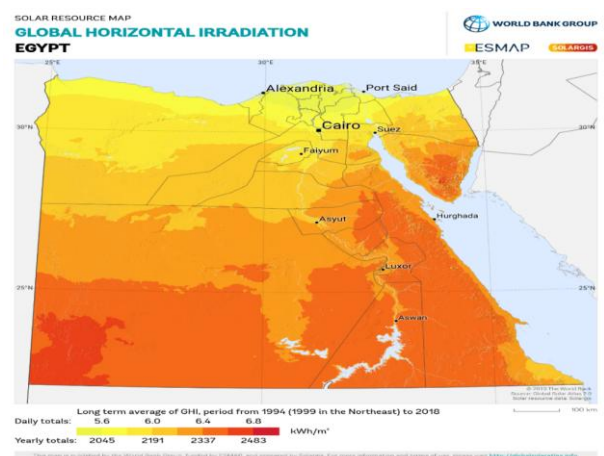


Fig. 7 Photovoltaic Electricity Potential Map of Egypt [64].

With high solar radiation and a goal to generate 42% of power from renewables by 2035, Agrivoltaics is key to Egypt's Vision 2030 [68].

5.2 Renewable Energy Goals and Vision 2030

Egypt is working to reduce its fossil fuel dependence by aiming to generate 42% of its electricity from renewables by 2035, as part of Vision 2030 [69]. This strategy focuses on reducing environmental impact, improving energy security, and cutting imports. Solar power plays a key role, with the 1.8 GW Benban Solar Park near Aswan being one of the largest in the world [70]. Wind energy is also crucial, with the Gulf of Suez offering high potential for large-scale production [60]. While hydroelectric power from the Aswan High Dam remains important, its share is decreasing as solar and wind energy grow [71, 72].

5.3 Energy Transition and Policy Support

To meet its ambitious renewable energy targets, Egypt has introduced various policies and incentives to attract private investment. The 2014 Feed-in Tariff (FiT) system, which encourages investment in solar and wind energy projects, has drawn significant international investment and helped expand Egypt's renewable energy capacity [73]. The government allows homes and businesses to sell excess solar energy via net metering, boosting decentralized energy and Egypt's renewable mix. Collaborations with the World Bank, EBRD, and IRENA provide financial and technical support for large-scale projects, advancing Egypt's sustainable energy goals [74]. These projects demonstrate Egypt's dedication to renewable energy, economic prosperity, and environmental sustainability.

5.4 Long-term Energy Sustainability

Long-term viability of Egypt depends on its drive toward renewable energy. Demand for power will only rise as the nation keeps seeing population increase and economic development. Egypt is setting itself to satisfy these needs by investing in solar, wind, and hydropower, therefore reducing the negative environmental consequences of fossil fuels [75]. Shifting to renewable energy will reduce Egypt's reliance on imported fossil fuels, enhancing energy security. A diverse energy mix will help Egypt weather price shocks and supply disruptions as global energy markets become more unpredictable [76]. In addition to improving security and finances, expanding the renewable energy sector will create jobs, particularly in rural areas where solar and wind farms are being built.

6. The Agriculture Sector in Egypt

Agriculture accounts for 11.3% of Egypt's GDP and employs about 25% of the workforce, making it vital to the economy [77]. The fertile Nile Valley and Delta, which make up less than 6% of the land, are the primary agricultural areas [77]. To address food security and water shortages, Egypt must explore innovative solutions to maximize agricultural productivity [78].

6.1 Water Scarcity and Climatic Constraints

With about 85% of Egypt's freshwater coming from the Nile, the nation's agriculture heavily relies on it. However, population growth, industrial development, and upstream projects like the Grand Ethiopian Renaissance Dam (GERD) are increasingly putting pressure on Egypt's water resources [79].

Around 80% of Egypt's water supply is used for agriculture, highlighting the urgent need for better water management. Rising temperatures and changing rainfall patterns, driven by climate change, are expected to further strain Egypt's agricultural sector [80]. Egypt has responded with contemporary irrigation

methods like sprinkler systems and drip irrigation to boost water efficiency and reduce waste. Still, more creative solutions are needed to handle the scope of the difficulty. By lowering soil evaporation, producing favorable microclimates, and increasing water-use efficiency, Agrivoltaics systems which mix solar energy generation with agriculture offer a possible answer [81].

6.2 Crop Diversity and Economic Impact

Egypt has a great variety of crops that are vital for both export and home use. Among the most fundamental staple crops are sugarcane, barley, wheat, maize, and rice. The main grain crop is wheat; Egypt imports the most of it worldwide to satisfy its own need. While rice is a mainstay in Egyptian cuisine, maize is very vital for cattle feed. Especially in the Nile Delta and Valley areas, these basic crops make up a significant share of Egypt's farmed land [82]. Apart from main crops, Egypt has valuable horticulture ones like cotton, oranges, grapes, strawberries, pomegranates, tomatoes, and potatoes. While oranges are among Egypt's most significant fruit exports and the nation ranks among the top orange exporters worldwide, Egyptian cotton is world-renowned for its quality and is a main export good. These crops provide rural jobs and generate foreign cash, therefore benefiting Egypt's economy [83].

In the context of Agrivoltaics, Egypt cultivates a wide array of nightshade plants (Solanaceae family), which play a critical role in both domestic consumption and export markets [84]. Key species include tomatoes (*Solanum Lycopersicon*), potatoes (*Solanum tuberosum*) and eggplants (*Solanum melongena*) grown extensively across the Nile Delta, Valley, and Upper Egypt [85]. Tomatoes and potatoes are particularly important; tomatoes are a dietary staple and a significant export commodity [86], while potatoes rank among the country's most vital vegetable crops for both domestic use and food security [87]. These crops share physiological traits—moderate shade tolerance, high sensitivity to heat and water stress, and responsiveness to microclimate—that make them ideal candidates for integration with Agrivoltaics systems [88, 89]. Partial shading from PV panels can reduce soil and leaf temperatures, lower evapotranspiration, and improve soil moisture retention, particularly during critical growth stages, thereby enhancing water-use efficiency and stabilizing yields under Egypt's high irradiance and water-limited conditions [90, 91]. The adoption of Agrivoltaics for nightshade crops can increase land-use efficiency, provide additional revenue from energy generation, support rural livelihoods, and contribute to agricultural diversification and climate resilience [61]. Together with the country's staple and horticultural crops, these high-value nightshade plants underline Egypt's potential to optimize both food security and economic returns through innovative, dual-use farming practices.

Table 7 summarizes the key characteristics of Egypt's major nightshade crops, highlighting their growing regions, seasonal cycles, average yields, and economic importance. It also presents their tolerance to partial shading and suitability for Agrivoltaics systems, along with their sensitivity to heat and water stress.

This overview illustrates how tomatoes, potatoes, eggplants, and peppers can be effectively integrated into Agrivoltaics layouts, optimizing water-use efficiency, stabilizing yields under high irradiance, and supporting both domestic consumption and export-oriented agriculture.

Table 7 characteristics of Egypt's major nightshade crops.

Crop	Major Growing Regions	Growing Season	Average Yield (t/ha)	Shade Tolerance / Agrivoltaics Suitability	Domestic vs Export Importance	Notes on Water and Heat Stress
Tomato [92]	Nile Delta, Valley, Upper Egypt	Nov–May (winter tomato), Mar–Jun (spring/summer)	40–43	Moderate shade tolerance; responds well to partial PV shading	High domestic consumption; significant export (fresh, processed)	Sensitive to high temperature and water deficit; shading improves water-use efficiency
Potato [93]	Nile Delta, Upper Egypt, Middle Egypt	Oct–Mar (winter crop), Feb–Jun (spring crop)	26–31	Moderate shade tolerance; benefits from early-season shading under PV	Domestic staple; high export potential	Heat stress can reduce tuber size; partial shading conserves soil moisture
Eggplant [94, 95]	Nile Delta, Upper Egypt	Mar–Aug	39.25	Moderate shade tolerance; can be grown under partial PV shade	Mainly domestic consumption; minor exports	Sensitive to water stress; shading reduces evapotranspiration and heat stress

7. Feasible Agrivoltaics System Designs for Egypt

This section provides a detailed examination of Agrivoltaics system configurations tailored to Egypt's climatic and agricultural conditions. It introduces the simulation framework used to evaluate photovoltaic (PV) system performance alongside crop productivity, with a focus on potato cultivation as a representative crop. By integrating both energy generation and agricultural productivity analyses, this section establishes a comprehensive basis for proposing feasible and efficient Agrivoltaics designs that maximize dual-use land benefits.

7.1 Study Area: Minya, Egypt

Minya, situated in Upper Egypt along the Nile, is selected as the study area due to its representative semi-arid climate, agricultural significance, and high solar potential. The climate and solar resource data for Minya were obtained using the Global Solar Atlas by the World Bank Group [96], focusing on a user-defined area of approximately 52,669 km² along the Nile Valley. This dataset provides detailed information forming the basis for both PV and Agrivoltaics simulations.

The region experiences abundant solar radiation, with global horizontal irradiation (GHI) ranging from 6.05 to 6.39 kWh/m²/day and direct normal irradiation (DNI) between 5.98 and 7.29 kWh/m²/day, making it particularly suitable for photovoltaic (PV) energy generation.

Average air temperatures range from 20.1 to 23.1°C, with a median of 21.8°C. The optimum tilt angle for PV modules ranges between 27° and 31°, with a median of 30°, providing the highest annual energy yield for fixed installations.

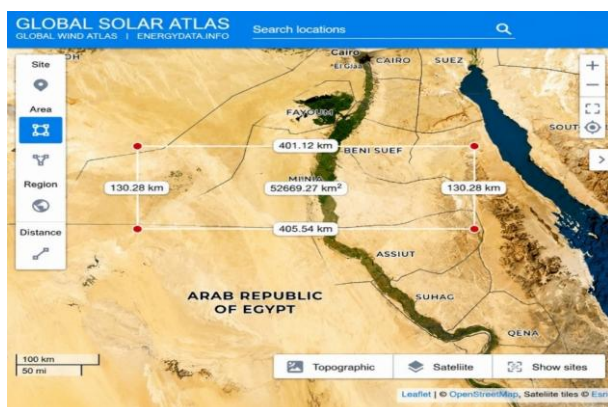


Fig. 8 Global Solar Atlas Area Map for Minya in Egypt [96].

Cumulative distribution function

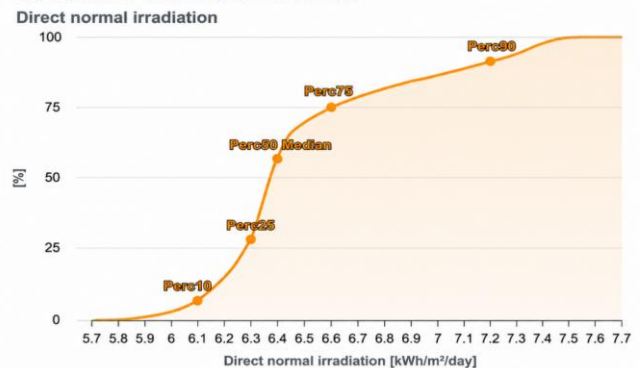


Fig. 9 DNI from the Global Solar Atlas Report [96].

Cumulative distribution function

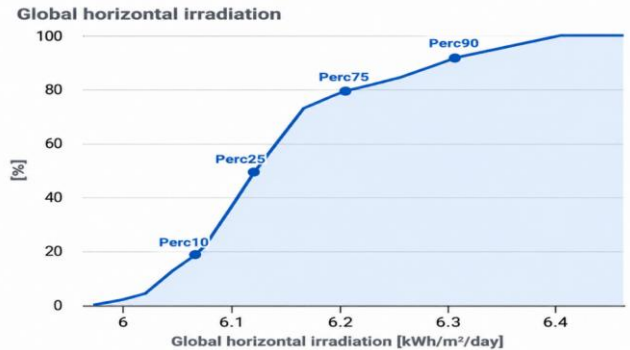


Fig. 10 GHI from the Global Solar Atlas Report [96].

Cumulative distribution function

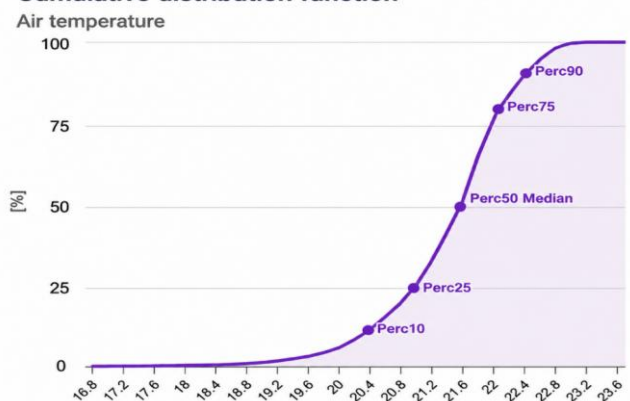


Fig. 11 Air Temp from the Global Solar Atlas Report [96].

Cumulative distribution function

Optimum tilt of PV modules

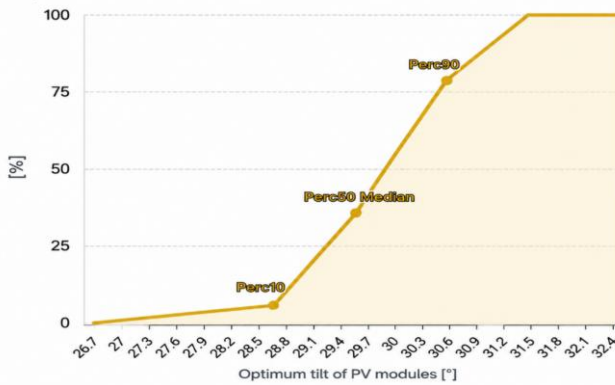


Fig. 12 Optimum Tilt Angle for PV Modules from the Global Solar Atlas Report [96].

7.2 PV System Simulation and LER

To evaluate photovoltaic energy production in Minya, a PV simulation was conducted using PVsyst software. The PV simulation employed LR5-72 HPH 550M mono-facial modules from Longi Solar [97], a high-efficiency monocrystalline silicon (Si) module designed for utility-scale applications. This module type is well-suited for regions with high solar irradiance, like Minya, due to its stable performance under elevated temperatures and its ability to maintain high energy conversion efficiency.

Table 8 LR5-72 HPH 550M specifications [97].

Parameter	Value and Unit
Nominal Power	550.1 Wp
Technology	Si-monocrystalline
Short-Circuit Current (Isc)	13.98 A
Maximum Power Point Current (Imp)	13.12 A
Open Circuit Voltage (Voc)	50.60 V
Maximum Power Point Voltage (Vmp)	41.95 V
Temperature Coefficient	-0.34%/°C
Efficiency	23.77 %

Table 9 Sungrow SG111 HV specifications [98].

Parameter	Value and Unit
Model Name	Sungrow SG111 HV
Max. DC Input Voltage	1500 V
Nominal DC Voltage	1015 V
Min. DC Startup Voltage	835 V
MPP Voltage Range	780 – 1450 V
Max. DC Current	146 A
Max. AC Output Power	111 kVA (@ 50 °C)
Nominal AC Voltage	540 V
AC Voltage Range	432 – 648 V
Max. AC Output Current	121 A
Efficiency (Max / Euro)	98.9 % / 98.7 %
Power Factor (Nominal)	> 0.99

The system was paired with a Sungrow SG111 HV inverter [98], which converts the generated DC power to AC for grid or local use while maintaining high conversion efficiency under variable load and irradiance conditions.

The photovoltaic coverage percentages used in the simulations (70 % for PV-only and 50 % for Agrivoltaics scenarios) are defined in terms of the ground coverage ratio (GCR), a widely recognized design metric for Agrivoltaics systems that quantifies the fraction of land

surface covered by PV panels and informs trade-offs between energy yield and crop performance in dual-use systems [99, 100].

The modules were set at a fixed tilt angle of 30°, matching the latitude of the region to maximize annual solar energy capture. The azimuth was set to 0°, corresponding to south-facing orientation in the northern hemisphere, which is optimal for solar irradiance reception. These settings were selected based on PVsyst's optimization for yearly energy yield, ensuring that both the PV-only and Agrivoltaics scenarios achieve maximum performance under local climatic conditions.

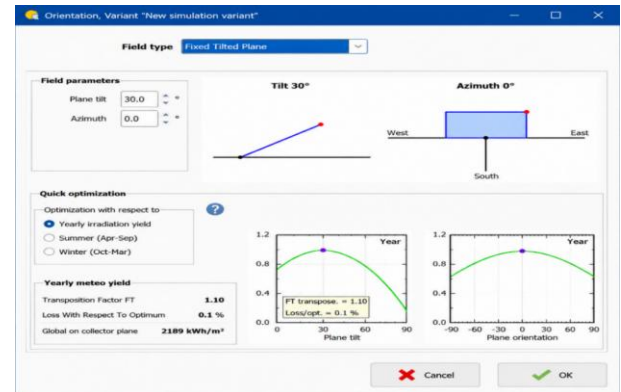


Fig. 13 Tilt Angle and Azimuth of the PVsyst Simulation.

a. PV-only scenario

The PV-only system for the 70 % coverage scenario will be composed of 2,727 modules and is paired with 11 Sungrow SG111 HV inverters, providing nominal AC power of 1,221 kW. The total array area is approximately 6,970 m², corresponding to a nominal DC capacity of 1,500 kWp.

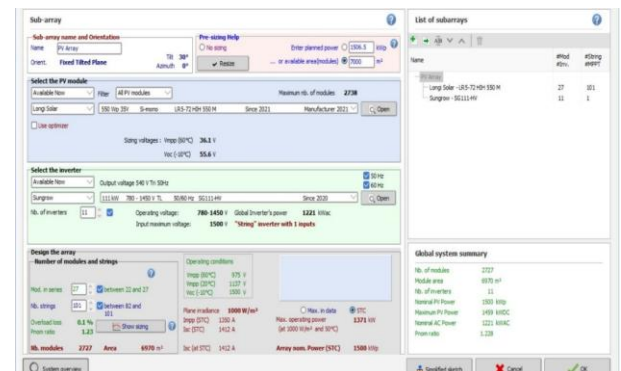


Fig. 14 Simulation Inputs for the PV-Only Scenario.

The Simulation produced a total of 2,803 MWh per year, corresponding to a specific production of 1,869 kWh/kWp per year. The normalized daily production was calculated at 5.12 kWh/kWp/day, while array losses and system losses were relatively low at 0.80 kWh/kWp/day and 0.06 kWh/kWp/day, respectively. The system achieved a performance ratio of 0.855, indicating efficient operation under the simulated climatic conditions.

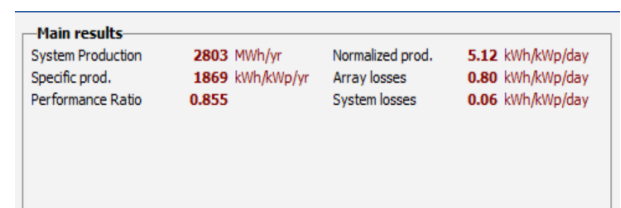


Fig. 15 Simulation Main Results for PV-Only Scenario.

These results demonstrate that the system is capable of delivering substantial annual energy output while maintaining high conversion efficiency, providing a solid baseline for subsequent Agrivoltaics simulations.

b. Agrivoltaics scenario

The system for the Agrivoltaics coverage scenario consists of 1,944 PV modules connected to 8 Sungrow SG111 HV inverters, providing a total nominal AC power of 888 kW. The total module area is approximately 4,969 m², corresponding to a nominal DC capacity of 1,069 kWp.

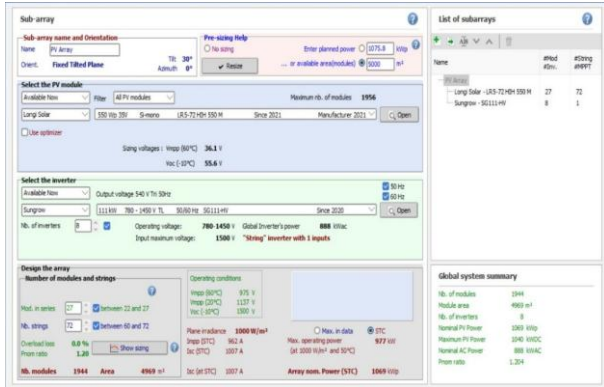


Fig. 16 Simulation Inputs for the Agrivoltaics Scenario.

The Agrivoltaics simulation produced a total of 2,001 MWh per year, corresponding to the specific production of 1,871 kWh/kWp per year. Normalized daily production was 5.13 kWh/kWp/day, while array losses and system losses remained low at 0.80 kWh/kWp/day and 0.06 kWh/kWp/day, respectively. The system achieved a performance ratio of 0.856, indicating efficient operation under the simulated conditions. These results demonstrate that, even with reduced land coverage to accommodate crop cultivation, the system can maintain high energy conversion efficiency while supporting dual-use objectives.

Main results			
System Production	2001 MWh/yr	Normalized prod.	5.13 kWh/kWp/day
Specific prod.	1871 kWh/kWp/yr	Array losses	0.80 kWh/kWp/day
Performance Ratio	0.856	System losses	0.06 kWh/kWp/day

Fig. 17 Simulation Results for the Agrivoltaics Scenario.

c. LER for nightshade plants in Egypt

Potatoes are a major irrigated crop in Egypt, cultivated primarily in the Nile Delta and Valley regions, including Gharbia, Minya, and other high-production areas. According to a recent study in Gharbia Governorate, summer and winter potato crops produced average yields of 12.74 t/feddan, equivalent to approximately 30.3 t/ha (1 feddan ≈ 0.42 ha) [93]. This yield represents above-average productivity compared with the national and regional averages for old lands, which typically range from 25–28 t/ha under conventional irrigated conditions [101, 102]. These baseline yields under full-sun, well-managed irrigation serve as a reference for evaluating potential relative yield impacts when potatoes are grown under partial shading in Agrivoltaics systems.

In the absence of long-term field data from Egypt, recent empirical and modeling studies on potato performance under Agrivoltaics shading were drawn to inform the yield reduction

assumptions. A process-based crop growth model applied to potatoes under Agrivoltaics shading in Sesto Fiorentino, Italy, found an average 15 % yield reduction compared to full-sun conditions, with shading beneath panels exceeding 50 % at times during the season [63]. Field experiments in Northern Italy likewise documented yield reductions from 12 % to over 30 % under different Agrivoltaics configurations [103]. Although these European sites differ climatically from Minya, the general pattern that moderate shading reduces potato yield by approximately 12–30 % is consistent across multiple studies and provides a reasonable basis for yield assumptions.

To evaluate the practical impact of Agrivoltaics on dual land use, the Land Equivalent Ratio (LER) for potatoes was calculated by the following equation [104].

$$LER = \frac{Y_{AV}}{Y_{ref}} + \frac{E_{AV}}{E_{ref}} \quad (1)$$

where Y_{AV} and Y_{ref} represent the potato yield under Agrivoltaics and conventional open-field conditions, respectively, while E_{AV} and E_{ref} denote the annual electricity outputs of the Agrivoltaics and PV-only reference systems.

Based on PVsyst simulations for Minya, Egypt, the Agrivoltaics configuration with approximately 50 % PV coverage generated 2,000.7 MWh/year, while the PV-only reference with approximately 70 % coverage generated 2,803.5 MWh/year, yielding an electricity ratio of:

$$\frac{E_{AV}}{E_{ref}} = \frac{2000.7}{2803.5} = 0.714 \quad (2)$$

Using the assumed scenario-based potato yield reduction of 12–30 %, based on empirical and modeling studies of Agrivoltaics shading [63, 103] the crop yield ratio becomes:

$$\frac{Y_{AV}}{Y_{ref}} = 0.70\text{--}0.88 \quad (3)$$

The resulting projected LER is therefore 1.41–1.60, indicating that one hectare of Agrivoltaics can provide the same combined food-and-energy output as approximately 1.41–1.60 hectares of separate conventional agriculture and PV-only land demonstrating a strong potential of Agrivoltaics to enhance land-use efficiency.

Tomatoes are one of Egypt's most widely cultivated vegetable crops, with production concentrated in the Nile Delta, including Sharqia and Dakahlia Governorates, and extending into Upper Egypt. Recent data indicate that total cultivated area reached approximately 414–416 thousand feddans in 2023–2024, with average yields of 16.82–18.03 t/feddan (≈40–43 t/ha) under conventional full-sun conditions, though total production faced a shortfall of roughly 501.34 thousand tons due to climatic stress factors [92]. A socio-economic study in Sharqia Governorate confirms similar yields and highlights the economic significance of tomato cultivation, including net and gross profits, marketing efficiency, and its role in sustaining rural livelihoods [105]. These baseline yields provide a reference for assessing potential impacts of partial shading under Agrivoltaics.

Since detailed field data on tomato yields in Egypt under partial shading are not available, studies from similar Mediterranean and hot, arid climates can be used as a reference. Agrivoltaics generally reduce total tomato yield by approximately 6–29%, depending on irrigation and shading intensity, while providing benefits such as improved water-use efficiency, moderated soil and canopy temperatures, and enhanced fruit quality [44, 106].

These reductions provide a practical basis for estimating potential impacts on tomato production under PV shading in Egypt.

Using the scenario-based tomato yield reduction of 6–29 %, based on empirical studies of Agrivoltaics shading [44, 106], the crop yield ratio becomes:

$$\frac{Y_{AV}}{Y_{ref}} = 0.71-0.94 \quad (4)$$

Combined with the PV energy ratio measured in the same Agrivoltaics setup:

$$\frac{E_{AV}}{E_{ref}} = 0.714 \quad (5)$$

The resulting projected LER for tomatoes is therefore approximately 1.42–1.65, indicating that one hectare of Agrivoltaics can provide the same combined food-and-energy output as roughly 1.42–1.65 hectares of separate conventional tomato cultivation and PV-only land. This demonstrates the strong potential of Agrivoltaics to enhance land-use efficiency for tomato production.

Eggplant (*Solanum melongena*) is a major irrigated vegetable crop in Egypt, cultivated primarily in the Nile Delta and Upper Egypt regions, including Giza, Minya, and other high-production areas. According to recent field studies, eggplant crops under full irrigation with black polyethylene mulch produced average yields of 15.7 t/feddan, equivalent to approximately 39.25 t/ha [94, 95]. These baseline yields under full-sun, well-managed irrigation serve as a reference for evaluating potential relative yield impacts when eggplants are grown under partial shading in Agrivoltaics.

Since detailed field data on eggplant yields under partial shading in Egypt are not yet available, empirical results from similar climates can serve as a reference. Studies on Agrivoltaics in tropical and Mediterranean-like environments indicate that partial shading can reduce eggplant yield by approximately 20–40 %, depending on the intensity of shading and irrigation regime [107, 108]. Heavy shading directly under PV panels causes the largest reductions, while plants grown in inter-row or moderately shaded areas experience much smaller yield penalties [109]. These reductions are accompanied by improved microclimate conditions, including lower soil and canopy temperatures, reduced evapotranspiration, and enhanced water-use efficiency, which partially offset the negative effects of shading. Given that Egypt's Nile Delta and Upper Egypt regions share high solar irradiance, hot temperatures, and arid to semi-arid conditions like the study sites, this yield reduction range can provide a realistic estimate for evaluating the potential impact of Agrivoltaics on eggplant production under partial shading in Egyptian agricultural systems.

Using the scenario-based eggplant yield reduction of 20–40 %, based on empirical studies of Agrivoltaics shading in climates similar to Egypt [107, 108], the crop yield ratio becomes:

$$\frac{Y_{AV}}{Y_{ref}} = 0.60 - 0.80 \quad (6)$$

Combined with the PV energy ratio measured in the same Agrivoltaics setup:

$$\frac{E_{AV}}{E_{ref}} = 0.714 \quad (7)$$

The resulting projected LER for eggplants is therefore approximately 1.31–1.51, indicating that one hectare of Agrivoltaics can provide the same combined food-and-energy output as roughly

1.31–1.51 hectares of separate conventional eggplant cultivation and PV-only land. This demonstrates the strong potential of Agrivoltaics to enhance land-use efficiency for eggplant production.

The analysis of Land Equivalent Ratios (LER) summarized in table 10 for Egypt's major nightshade crops—potatoes, tomatoes, and eggplants—demonstrates the strong potential of Agrivoltaics systems to enhance land-use efficiency. Yield reductions under partial shading range from 6–29 % for tomatoes, 12–30 % for potatoes, and 20–40 % for eggplants, based on empirical studies in similar climates. Across all three crops, the PV energy contribution was considered constant, with $E_{AV}/E_{ref} \approx 0.714$, reflecting the same Agrivoltaics configuration. The resulting LER values are 1.41–1.60 for potatoes, 1.42–1.65 for tomatoes, and 1.31–1.51 for eggplants, indicating that one hectare of land under an Agrivoltaics system can provide the combined food-and-energy output of approximately 1.31–1.65 hectares of separate conventional agriculture and PV-only land.

Table 10 Nightshades LER Data Summary.

Crop	Baseline Yield (t/ha)	Yield Reduction (%)	Crop Yield Ratio (Y_{AV}/Y_{ref})	LER Range
Potato	30.3	12–30	0.70–0.88	1.41–1.60
Tomato	40–43	6–29	0.71–0.94	1.42–1.65
Eggplant	39.25	20–40	0.60–0.80	1.31–1.51

This demonstrates the effectiveness of Agrivoltaics in simultaneously producing crops and electricity while optimizing land-use efficiency.

8. Opportunities and Challenges

By combining solar power generation with agricultural output, Agrivoltaics systems offer Egypt a major chance to address both her renewable energy and food security issues. Egypt's environmental and financial demands call especially for this dual-use approach. But various technological, financial, and policy-related issues must be resolved if Agrivoltaics systems are to be generally embraced.

8.1 Opportunities

Agrivoltaics technologies offer Egypt a huge opportunity to address its two challenges: food security and production of renewable electricity. Little arable land is exploited to its maximum as over 95% of the country is classified as desert. Agrivoltaics systems can also mitigate the food-energy tradeoff, because both vibrant crops and solar panel electricity are generated on the same land. Moreover, Egypt is positioned in the so-called Sun Belt which makes it an ideal place to produce solar power and by extension, through Agrivoltaics systems couple renewable energy production with agricultural services. With these technologies, Egypt can effectively achieve its Vision 2030 goals of minimizing dependence on fossil fuels, achieving food security and enhancing its energy mix.

In Egypt there is shortage in water availability for the purpose of agriculture and employing Agrivoltaics systems becomes a necessity. The shade of the solar panels reduce evaporation of soil and keeps a microclimate with better conditions to maintain the humidity, so that all these actions lead to saving water in general. Research has shown that Agrivoltaics systems can increase the water use efficiency of crops by around 30%, which is a significant advantage in dry Egypt. These systems not only conserve water but contribute to our environment sustainability as we help generate renewable power and decrease carbon emissions in support of climate

change solutions. The shaded areas beneath solar panels may also create habitat for various plant species, providing ecological resilience and supporting biodiversity.

Lastly, Agrivoltaics systems may be beneficial for rural development by generating jobs in agriculture and renewable energy. There are jobs in installing and maintaining solar panels and maximizing productivity in agriculture. These systems improve rural infrastructure and contribute to economic development, supporting Egypt in meeting its Vision 2030 goals of poverty reduction and sustainable growth. According to the performance of Agrivoltaics systems in Egypt, i.e. providing jobs, getting profit from Agrivoltaics systems and finally improving environment and economy, Agrivoltaics systems can lead to solving development problems in Egypt.

8.2 Challenges

High front end capital costs associated with deployment of Agrivoltaics systems are limiting their adoption, especially by small farms. Solar plants are expensive to install and to integrate with farming as costs are not yet being subsidized. Enterprises barred from the market: Governments should subsidize (or make low interest loans to reduce) these entry barriers. Thus, Agrivoltaics systems won't be easily adopted by smallholder farmers, and this would make impossible to scale them up to address the agro-ecological and energy issues facing Egypt.

Other than financial obstacles, there are technical challenges to the installation of Agrivoltaics. Predicting the panel height, spacing and orientation required for optimal land use is still quite challenging since the trade-off between energy production and agricultural yields is not trivial. There are other crops that do well in certain shades, so there is some adaptation to the particularities of Egypt. It also requires R&D to keep solar panels from getting buried under harsh desert conditions and harming agriculture yields. Surmounting these technical challenges and implementing Agrivoltaics systems involves a combination of targeted solutions and innovation.

Desert soiling is an important challenge for Agrivoltaics deployment in Egypt, particularly in Upper Egypt and reclaimed desert areas, because dust accumulation on photovoltaic modules acts as an additional shading layer that reduces solar transmittance and electrical output. Egyptian evidence has shown that the impact of soiling can vary even within the same country depending on local aridity and dust conditions; for example, a comparison between Cairo and Beni-Suef found that, after three weeks of natural dust accumulation without cleaning, the module exposed in Beni-Suef produced 15% lower maximum power than the module exposed in Cairo [110]. Studies from semi-arid and desert climates also indicate that soiling is not a one-time loss but a cumulative process, with reported soiling rates of about 0.25-0.35% per day during dry periods [111, 112]. This means that the technical and economic performance of Agrivoltaics in Egypt will depend not only on land-use efficiency and crop response, but also on cleaning frequency, maintenance strategy, and water availability. In desert conditions, power losses can rise from about 3% after 10 days to 13% after 90 days without cleaning, and one desert-climate study suggested that a cleaning interval of around 15 days may provide a reasonable balance between energy recovery and cleaning cost [113]. Because Egypt is also water-scarce, mitigation options such as dry cleaning, robotic cleaning, and anti-soiling coatings should be considered in the design of Agrivoltaics systems intended for desert or semi-arid regions [114].

A further challenge for Agrivoltaics deployment in Egypt is the legal status of photovoltaic structures on old agricultural land, particularly in the Nile Delta and Valley. Egyptian agricultural land is subject to strict protection against encroachment and construction, and recent amendments have further strengthened penalties for building on such land [115]. At the same time, Egypt's renewable-energy land-allocation framework has mainly focused on state-owned and desert land through the New and Renewable Energy Authority (NREA), rather than on dual-use systems installed on long-established cultivated land [116]. In this context, Agrivoltaics systems may face a significant administrative barrier unless their support structures are explicitly classified as permissible agricultural infrastructure or tools rather than prohibited buildings. Therefore, the deployment of Agrivoltaics on old agricultural land may require a dedicated legal definition, clear permitting procedures, and coordination among the authorities responsible for agriculture, electricity, and local administration.

Bridging the knowledge gap among farmers is crucial for adopting Agrivoltaics systems. These systems, which combine energy and agriculture, can be difficult for small-scale farmers to grasp. Without proper training and experience, farmers may be reluctant to adopt the technology. Training programs and technical support are essential to help farmers build the skills and confidence needed to operate Agrivoltaics systems effectively.

Market uncertainty is another challenge that affects the economic viability of Agrivoltaics. These systems are most effective when energy prices are stable, and there's a reliable market for selling solar-generated electricity. To foster long-term investment and wider adoption, it's essential to establish a stable policy framework that reduces market risks and offers incentives for Agrivoltaics development.

9. Future Work and Policy Recommendations

As Egypt moves toward adopting Agrivoltaics systems, several key steps are needed to address both technological and social aspects. These include pilot projects, policy development, stakeholder participation, and capacity building for farmers and local communities. By adapting global lessons to local conditions, Egypt can implement best practices for sustainable agriculture and energy, ensuring alignment with Vision 2030.

9.1 Pilot Projects and Demonstration Farms

Pilot agrivoltaic systems are essential for assessing and optimizing system designs across Egypt's diverse agricultural regions. Well-designed pilot projects should focus on major crops such as wheat, cotton, citrus fruits and grapes, as well as high-value fruits and vegetables. Demonstration farms should be established in regions with different soil and climatic conditions, including Aswan, Fayoum, and the Nile Delta. These projects should incorporate expertise in agricultural engineering, soil science, and land management. Water consumption, energy generation and crop productivity may also be quantified to identify optimal systems' configurations, panel postures and crops varieties to maximize the land use in Egypt. This information will also support the creation of programs that can be scaled across the country.

9.2 Policy Framework and Financial Incentives

A strong policy framework is needed to promote the uptake of Agrivoltaics systems in Egypt. The government must also develop economic motives for farmers to set up Agrivoltaics

structures through subsidies, tax discounts and feed-in tariffs. These "promotions" should be focused on reducing the significant up-front costs of installation (which continues to be a substantial barrier, particularly for small-holder farmers). Furthermore, low interest loan and grant programs are needed to enable the access of Agrivoltaics technology by farmers in rural and underserved regions. A transparent regulatory regime will make the approval system easier for Agrivoltaics projects and will help to attract domestic as well as international investors, contributing towards sector development.

9.3 Farmer Training and Capacity Building

Farmers' education and training are key to make Agrivoltaics systems successful. Training should focus on technical skills such as the maintenance of systems, crop selection under partial shading and efficient irrigation. Finally, extension services ought to be developed with a cadre of experts who can provide in-field experiential education and troubleshooting support when farmers are installing Agrivoltaics systems and throughout their operation.

Collaboration between agricultural institutions and non-governmental organizations (NGOs) through public-private partnerships (PPPs) could facilitate the efficient scaling of these training programs. Farmers can realize the maximum advantage from culture crops, by being trained on practicing and managing the Agrivoltaics systems in Egypt for a long time.

9.4 Research and Development

Scientific investigation should be concentrated towards the creation of climate-resilient Agrivoltaics technologies suitable for Egypt's particular climatic environment. Further research is needed to assess the impact of solar shading on crop health, water-use efficiency and yield response to extreme temperature and high-dry environments.

Working with international bodies, such as those from India, Spain and the US can allow for shared expertise and best practices. Furthermore, enhanced efficiency of bifacial and semi-transparent modules will be crucial to the country, that will facilitate maximum production of solar power without harming crop health. Investing in domestic production of these Agrivoltaics components would lower costs and generate jobs while increasing Egypt's capability to install and maintain such systems.

9.5 Long-term Economic and Environmental Assessments

Long-term economic and environmental evaluations are crucial for Agrivoltaics systems' success. These should track costs, energy prices, crop yields, water savings, and environmental impacts like carbon sequestration and soil health. The data will help refine policies and demonstrate Agrivoltaics as a viable solution for Egypt's agriculture and energy needs.

10. Conclusion

Agrivoltaics present a promising strategy for simultaneously producing renewable energy and cultivating crops in Egypt, particularly in regions characterized by high solar irradiance, limited arable land, and water scarcity. Global case studies demonstrate that various configurations—fixed-tilt, dynamic/tracking, vertical bifacial, and semi-transparent panels—can optimize the balance between energy production and crop growth, while moderating microclimatic conditions such as soil and canopy temperature and evapotranspiration.

For Egypt, nightshade crops such as potatoes, tomatoes, and eggplants exhibit varying tolerance to partial shading, with yield reductions ranging from 6–40% depending on crop type, shading intensity, and irrigation management. When combined with the PV energy output in Agrivoltaics setups, these reductions result in Land Equivalent Ratios (LERs) of 1.31–1.65, indicating that one hectare of Agrivoltaics land can deliver the combined food-and-energy output of approximately 1.31–1.65 hectares of separate conventional agriculture and PV-only land. These findings underscore the dual-use potential of Agrivoltaics to enhance land-use efficiency, optimize water use, and support climate-resilient crop production.

In addition to productivity gains, Agrivoltaics systems offer economic and environmental co-benefits, including increased farmer income from energy sales, reduced irrigation demand, and mitigation of heat stress on crops. While challenges such as upfront investment, maintenance, and crop selection remain, careful system design and appropriate crop choice can maximize benefits. Overall, Agrivoltaics provides a viable, sustainable solution for integrating renewable energy and agriculture in Egypt, offering both food security and energy generation in a complementary and efficient manner.

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