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Research article

Agrivoltaic systems for sustainable energy and agriculture integration in Turkey

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ABSTRACT

In recent years, the use of solar photovoltaic (PV) energy, which is one of the leading renewable energy sources, has become increasingly widespread around the world due to its numerous advantages. However, PV-based electricity generation necessitates a large amount of land. Agrivoltaic (AV) systems, an innovative approach to combining agricultural and electricity production in the same area through solar modules positioned several meters above the surface of the ground, are growing rapidly in renewable energy and farming communities. This study explores Turkey's solar power generation and agricultural activities, combining crop cultivation and electricity generation for sustainable development on the same land. Furthermore, the AV potential for the most agriculture ten cities in different climate zones in Turkey is investigated using the PVsyst program. A list of the most commonly grown crops in the ten selected cities and the types of AV systems that can be employed with these crops is provided. The results show that AV systems present a great opportunity for the optimal integration of solar power generation with food production, especially for the cities of Konya, Kayseri, and Manisa, with the most ideal conditions for agricultural and solar power production. By combining the solar power potential of the country with the production capacity of arable lands, the increasing energy needs can be met and more efficient agricultural production can be provided. This study is expected to demonstrate that in specific regions of Turkey, AV farming will be suitable for certain crops.

1. Introduction

The regional conflicts, extreme weather events, and COVID-19 pandemic we have experienced in recent years have shown that the use of energy resources is of great importance for countries [1]. Climate change mitigation necessitates a reduction in greenhouse gas emissions and increased use of low-carbon renewable energy sources. Renewable energy sources, which are abundantly available and derived mainly from the sun, are continually replaced by nature and emit no greenhouse gases or air pollution. Developments in renewable energy are made to meet the rapidly growing energy demand with the increase in the world population. The use of solar photovoltaic (PV) energy, which is one of the leading renewable energy sources, plays a major role in generating electric power around the world. Recently, PV technology has made considerable progress in utilizing a large, clean, and sustainable source of energy to meet society's electricity demands. However, the installation of the PV systems necessitates a significant amount of land [2–5].

While solar modules generate electrical energy using sunlight, the area in which they are located cannot be used for agriculture. In

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Nomenclature

AV	Agrivoltaic
PV	Photovoltaic
N	North
S	South
kW	Kilowatt (unit: W)
MW	Megawatt (unit: W)
GW	Gigawatt (unit: W)
TWh	Terawatt hour (unit: Wh)

many countries, the continuous installation of large-scale PV systems has resulted in increased concerns over the loss of agricultural land to more economic PV energy generation. While the rapid growth of the world population increases global energy demand, climate change affects agricultural production negatively. Rising temperatures dramatically reduce the ideal agricultural yields while causing the expansion of weeds and pests on the farmland. For this reason, the effective use of agricultural lands gains more and more importance [6].

For many years, PV technology has been used in agriculture to offer long-term, sustainable electricity for agricultural production activities [7]. Numerous studies have been conducted on the use of land for solar energy. According to some research, PV energy falls into the "no-risk" category, as determined by the risk classification, thus solar energy is expected to be between 20 % and 60 % of the global electrical supply by 2050 [7–9]. Another research shows that solar power facilities might use up to 5–10 % of all available land. The optimal conditions and site factors for installing solar modules on agricultural land are analyzed [10]. Based on a ground-mounted PV system, a potential conflict between food production and renewable energy generation is tested. Besides, the effects of PV systems on the environment are studied [11]. Agriculture which provides most of the global food production is negatively impacted by human-caused environmental pollution. Taking world population growth into account, agricultural production has to expand continuously. This can only be achieved by increasing agricultural output and refining agricultural technologies [12]. More than three decades ago, the idea of agrivoltaic (AV) systems was proposed [13]. AV stands for combining PV energy and agricultural production in an efficient way on farmland. It is the ideal combination of PV modules and plants on the same piece of land. The main challenge is to produce energy and crops at the same time while avoiding conflict. PV modules and crops coexisting indicate that sunlight is shared between the two forms of production. Many commercial AV plants and small-scale research facilities have been already constructed around the world. This strategy is very effective in growing vegetables with leafy greens such as lettuce, cabbage, and spinach, as well as with root crops such as potatoes, carrots, radishes, and beets [14–16]. In Ref. [14], findings from a systematic review of 98 studies on AV systems were presented, with a focus on engineering aspects and factors influencing power yield. However, there is a lack of comprehensive financial models for AV systems, and limited investigation into large-scale facilities integrating livestock grazing, which is a notable gap given that regions with high PV potential often involve significant grazing areas. A study investigated Turkish farmers' perspectives on AV system through interviews and desk research. Pioneering farmers value the synergistic potential of these systems, but concerns about bureaucratic difficulties and legislative deficiencies hinder their implementation [17]. Another study [18] explores the potential of AV systems in Turkey, focusing on the three provinces with the highest agricultural production. The research uses Geographic Information System (GIS) and the fuzzy analytic hierarchy process (FAHP) to investigate the capabilities of these systems. Besides, it contributes to practitioners deciding on target locations to produce solar energy sustainably while allowing for crop production. In Ref. [19], the economic performance of AV system in Turkey was evaluated, focusing on the Ayaş pilot project. Findings suggest that electricity price policies, farmer welfare, suitable finance models, cost reductions in irrigation, and increased income through electricity sales can significantly improve the system's economic performance. In Ref. [20], researchers developed an experimental 0.675 kW AV system using artificial intelligence tools to optimize energy and food production. The model predicts

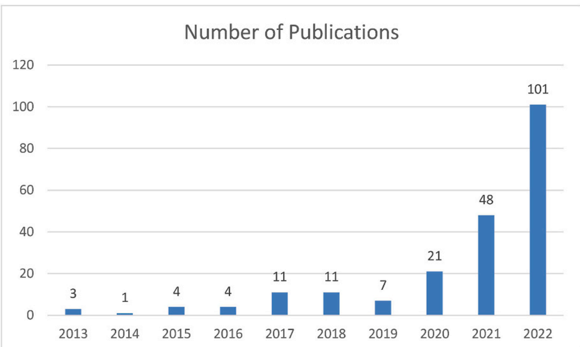


Fig. 1. Number of published articles on the topic "Agrivoltaic systems" since 2013. Source: Web of Science.

optimal conditions of 104.9097 kWh energy and 9.0955 kg of food, with a land equivalent ratio and payback period of 1.73 and 9.49 respectively. Another study suggests that integrating AV systems in Mediterranean olive groves could increase global PV capacity by 2.5 %, increase electricity demand by 1.8 %, prevent CO_2 emissions, and create around 560,000 jobs if installed on 1 % of the olive surface area [21].

There are a great number of studies on AV systems that can be found in published works. Based on the "Web of Science" results, Fig. 1 shows the number of articles about AV from 2013 to 2022. It is clear that publications are gradually increasing, indicating that this field is receiving more attention globally. Between 2013 and 2022, studies on AV systems in the literature cover various aspects such as optimal system design, crop selection, microclimate effects, and water use efficiency. Some key topics explored in the literature include; System design: Research is centered on designing and optimizing AV systems to increase energy production while reducing the shading impact on crops. Factors relevant to design criteria in studies include panel orientation, spacing, and elevation [22–24]. Crop selection: The studies have taken care of crops suitable for AV systems, taking into account characteristics such as shade tolerance, water requirement, and economic value [25]. Microclimate effects: Researchers have studied the impact of AV systems on microclimate conditions in agricultural areas, such as temperature, humidity, etc. [22,26]. Water Use Efficiency: Researchers have investigated less water use and mutual efficiency increases in AV systems due to the importance of water for agriculture [27].

Many countries lack clear guidelines and policies against AV systems, possibly due to climate-specific agricultural activity studies and traditional farming practices. Turkey has recently included AV systems in political legislation, based on the cities where PV systems are most installed. Therefore, this study is significant in providing insights into radiation values, city location, and plant diversity to introduce AV systems in Turkey. Considering the limited number of studies conducted in the context of Turkey, the present study was carried out to address this gap in the literature accordingly [14,30]. This paper explores Turkey's potential for sustainable food and energy supply using AV systems that integrate solar power generation in agricultural production. Choosing the most agriculture ten cities in different climate zones in Turkey, the AV potential of the country is assessed using the PVsyst program. In addition to Turkey's solar power generation and agricultural activities, the paper aimed to find out which of the agricultural ten cities in different climate zones in Turkey was most suitable for AV systems and which types of AV systems can be employed with the crops grown in these cities. The findings are crucial for policymakers, energy planners, and agricultural stakeholders, guiding investment decisions and promoting sustainable development in Turkey's energy and agriculture sectors. The data of this study were obtained from the Ministry of Energy and Natural Resources, the Ministry of Agriculture and Forestry, the Food and Agriculture Organization, and the World Bank Group.

The rest of the paper is organized as follows; Section 2 and Section 3 present the materials and methods and the features of AV systems respectively. Section 4 describes the potential of Turkey's solar energy and agricultural production. In Section 5, the evaluation of the AV possibility for the most agriculture ten cities in different climate zones in Turkey is performed using the PVsyst program. Section 6 provides recommendations for future research and conclusions.

2. Materials and methods

During the literature review process, relevant terms such as "agrivoltaic systems," "agrivoltaic systems in Turkey," "Turkey's solar energy potential," "agriculture in Turkey," and "crops grown in Turkey" were systematically searched in Web of Science and Scopus. The focus was on studies conducted in English and Turkish languages. In this study, the PVsyst tool was used to simulate the performance of solar energy potential for the most agriculture ten cities (Konya, Ankara, Şanlıurfa, Sivas, Yozgat, Diyarbakır, Eskişehir, Kayseri, Çorum, and Manisa) in different climate zones in Turkey. Analyzing solar energy potential performance through PVsyst involves a systematic approach to maximize the efficiency and effectiveness of PV systems. It involves setting parameters like location coordinates and system configurations, preparing the groundwork for accurate results, and using meteorological data to simulate solar radiation and environmental factors. For this purpose, the Metenorm database, which contains the most up-to-date data among the databases in the program (Meteonorm, NASA-SSE, PVGIS, Solcast, and SolarAnywhere), was used. Thus, by drawing a solar path, the sunshine duration and solar movements of the cities were obtained, and the potential of the specified cities in terms of energy production was reached. Additionally, a list of the most commonly grown crops in the ten selected cities is given and different types of AV systems are presented to determine which types of AV systems can be employed with the crops grown in these cities.

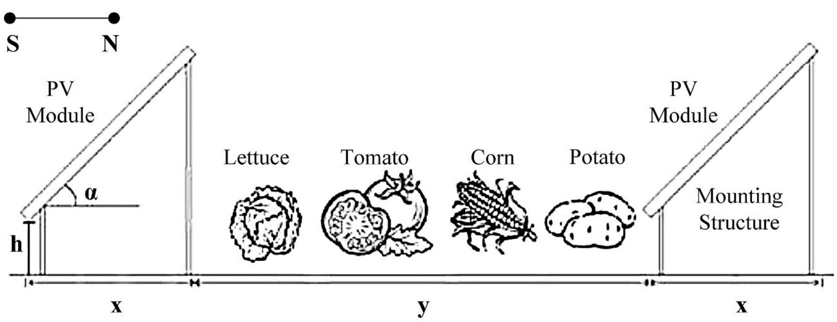


Fig. 2. The main schematic of an AV system.

3. Agrivoltaic systems

Since the turn of the twentieth century, the global population has risen from 1 billion to 8 billion, leading to higher levels of agricultural consumption per person. Expanding agricultural production and improving agricultural technologies are required to meet the growing consumption. The idea of an AV system was first introduced by two German scientists Goetzberger and Zastrow in 1982 to realize the dual use of farmlands for PV energy generation and plant growth [13]. The primary objective of the AV system is to generate electricity while simultaneously cultivating plants in the same area, especially in arid regions where water, energy, and food supplies are limited. Although the idea was initially proposed more than three decades ago, it took several years before the term “agrivoltaic” was developed and the various advantages of this technology were fully realized [28,29]. AV is the technique of integrating agricultural and renewable energy production, such as growing crops and solar modules on the same piece of property. The solar modules are raised roughly a few meters above the ground using fixed support systems so that farm equipment can access the crops below [30]. The main schematic of an AV system is presented in Fig. 2.

Fig. 2 represents the horizontal projection of PV, the distance between rows of agricultural PV arrays, the tilt angle, and the height of steel structures. These parameters are denoted by x, y, α, and h respectively. Farming machines must be able to pass between PV rows, thus the height of the steel structures and the distance between them must be appropriate. Typical PV plants in AV systems have a distance of 5–10 m between each pair of PV array rows. The purpose of this gap is to avoid PV shadows on the next row, and it must be ideal for crop harvesting.

The advantages of AV systems can be summarized as follows: The potential use of solar energy is maximized; it is beneficial to the cultivation of some crops due to the shade effect; PV modules installed on top of crops have higher efficiency; it increases the productivity of the land based on the mutual common use; and it has a favorable environmental impact [31]. In recent years, there has been a significant increase in the amount of AV systems that have been installed all over the world, and an increasing number of countries are following this trend. In 2012, AV system installations across the globe were only 5 MW, but as of 2020, that number has reached 2.9 GW [32].

4. The potential of Turkey’s solar energy and agricultural production

Turkey’s economy is experiencing rapid growth, making it one of the world’s fastest-growing economies [33]. Over the past ten years, Turkey’s yearly primary energy consumption has climbed by roughly 10 %. When compared to the previous year, the gross annual electricity consumption in 2021 increased by 8.74 %–332.9 TWh. The amount of generated electricity increased by 9.14 %–334.7 TWh. According to the Turkey Electricity Demand Projection Report covering the years 2020–2040, it is expected that the country’s annual electricity consumption will be 370 TWh in 2025 and 591 TWh in 2040. As of the end of November 2022, the total installed electric generation capacity of Turkey reached 103.541 GW and the installed capacity of PV energy is 8.479 GW, thus its ratio to total installed capacity is 8.35 % [34]. There have been recent studies in the literature that discuss Turkey’s agricultural and electricity production. In Ref. [35], Geographical Information Systems (GIS) technology was employed to identify optimal locations for a solar power plant in the Malatya Province of Turkey, considering various factors such as solar energy potential, infrastructure, topography, and environmental features using the Analytical Hierarchy Process method. In Ref. [36], various renewable energy sources, including solar, biomass, geothermal, wind, and hydropower in Turkey, through a SWOT analysis were systematically evaluated. The study [37] examines incentive systems for PV systems by analyzing policies in selected countries from Europe, America, Asia, South America, and Africa. It specifically focuses on Turkey, assessing its current PV situation and the potential to propose improvements in the field of incentives and policies for PV systems in Turkey. Researchers [38] evaluated Turkey’s renewable energy capacity to identify key priorities for the country’s energy policy. It discusses Turkey’s renewable energy potential and regulatory conditions, drawing comparisons with the European Union. Considering the studies conducted in the agricultural field [39], examines

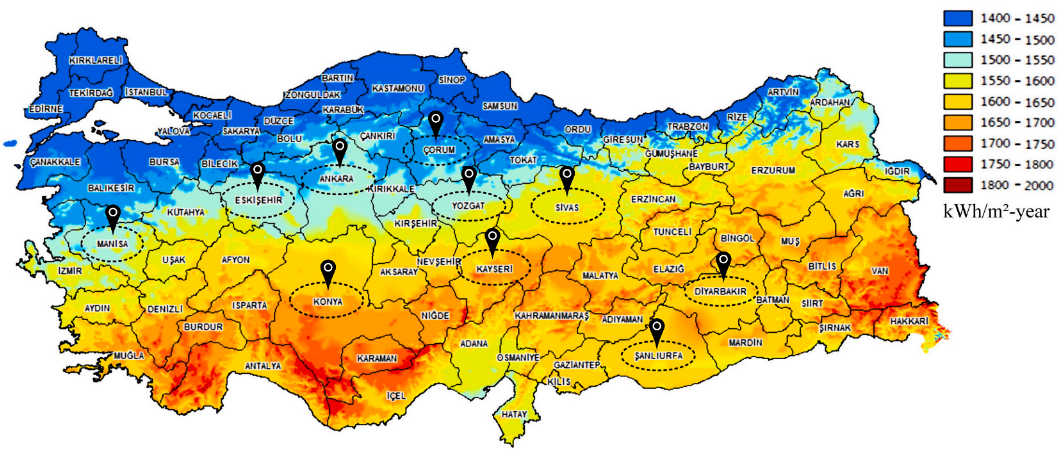


Fig. 3. Monthly average solar radiation (kWh/m^2-month) of Turkey [42].

the impact of agriculture, renewable energy production, and globalization on CO_2 emissions in Turkey from 1970 to 2017. Results indicate that the considered factors contribute to increased environmental pollution, confirming their undesirable impact on CO_2 emissions. In another study [40], the global and Turkish agricultural production and food supply systems' effects of COVID-19, including reduced supplies, labor shortages, increased prices, decreased demand, and changing consumer attitudes are assessed. This study [41] explores the feasibility of employing renewable energies in agricultural activities, examining solar energy, biomass energy, wind energy, geothermal energy, and hydropower through application examples in Turkey. The conclusion offers proposals and recommendations, advocating for the adoption of alternative energy sources over fossil fuels in agriculture. Turkey, which is located in the geographical coordinates of 39.1667° N latitude and 35.6667° E longitude in the continent of Asia, has one of the longest daily sunshine durations in the world with roughly 7.5 h of sunlight every day. The country has a significant solar energy potential due to its geographical location in the northern hemisphere. According to the Turkey Solar Energy Potential Atlas (GEPA), the average annual total sunshine duration and radiation density are 2741 h and 1527.46 kWh/m^2 [42]. Figs. 3 and 4 display the monthly average solar radiation and the solar energy potential map of Turkey respectively. July receives the highest amount of solar radiation, as shown in Fig. 3, with a maximum value of 175.38 kWh/m^2-month. On the other hand, December has the lowest solar radiation, at 46.87 kWh/m^2-month. Due to the sunlight angle, the peak value occurs in July rather than in the hottest month of August. As can be seen from Fig. 4, solar radiation is abundant in Turkey, particularly in the south, east and inland regions. The southeast and southwest regions appear to have the maximum solar radiation potential, with a value of 1800–2000 kWh/m^2 per year. Northwestern and northeastern coastal regions receive the least sunlight due to their geographical location [42].

Geographically, Manisa is located in the Aegean region, Ankara, Eskişehir, Konya, Yozgat, Kayseri, and Sivas in the Central Anatolia region, Çorum in the Black Sea region, Şanlıurfa and Diyarbakır in the Southeastern Anatolia region. These cities are generally located in various climatic regions of Turkey, but they all have sufficient sunlight throughout the year. Table 1 lists the total annual solar energy potential and sunshine duration by region in Turkey. As can be noticed, total annual solar energy potential and the levels of sunshine radiation drop from the South to the North. Southeastern Anatolia is the region in Turkey that receives the most amounts of solar radiation and sunshine duration, while the Black Sea region comes in last place due to its geographical location [42]. In addition to having a significant potential for solar electricity, Turkey is also one of the leading countries in the world in terms of agricultural production. The agricultural potential of Turkey is greater than that of any other country in Europe due to its larger land area. As a result, the agricultural sector of the Turkish economy is the eighth largest in the world [43].

Agriculture is the main traditional activity of the Turkish population, with industrial and service sectors expanding rapidly. As indicated in Fig. 5, the number of people living in rural areas has been increasing continuously from 1990 until 2021 due to agricultural development. Fig. 6 shows the evolution of agricultural areas in Turkey between 1961 and 2020. As can be noticed, the ratio of arable land and the land under permanent crops has remained almost unchanged, while the ratio of the land under permanent meadows and pastures has slightly increased. Turkey's landforms and climate allowed for the formation of many geographic regions and microclimates. Therefore, almost everywhere in Turkey farming can be conducted [44,45]. Turkey can grow any kind of crop due to the ideal climate conditions, fertile soil, and sufficient rainfall [46]. Turkey exports 1827 various farm products to 193 nations, making the country's food and agriculture self-sufficient. As of 2020, agriculture employs 18 % of the Turkish workforce, accounts for 10 % of exports, and 7 % of the gross domestic product. Wheat, sugar beets, milk, cotton, tomatoes, and a variety of other fruits and vegetables are among Turkey's most important agricultural exports. In Turkey, where more than half of the land area is used for agricultural purposes, the agricultural production value is close to 50 billion dollars [47]. Turkey's Anatolian region exhibits agricultural diversity through specialized crop production in different cities, highlighting the region's richness and productivity. Each city's focus enhances the nation's agricultural output and economic resilience, contributing to the overall agricultural landscape [48].

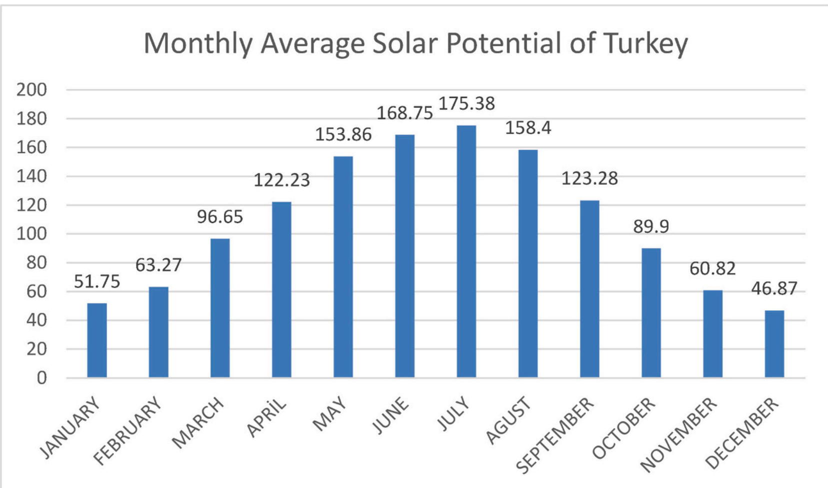


Fig. 4. Turkey solar energy potential map [42].

Table 1
Turkey's total annual solar energy potential and sunshine duration by region [42].

Regions	Total Energy (kWh/m^2-year)	Sunshine Duration (hour/year)
Southeastern Anatolia	1460	2993
Mediterranean	1390	2956
Eastern Anatolia	1365	2664
Central Anatolia	1314	2628
Aegean	1304	2738
Marmara	1168	2409
Black Sea	1120	1971

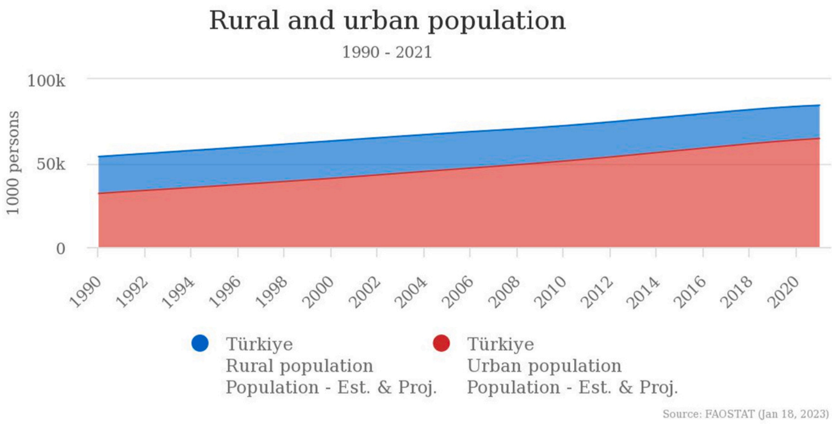


Fig. 5. Rural and urban population change in Turkey from 1990 until 2021 [44].

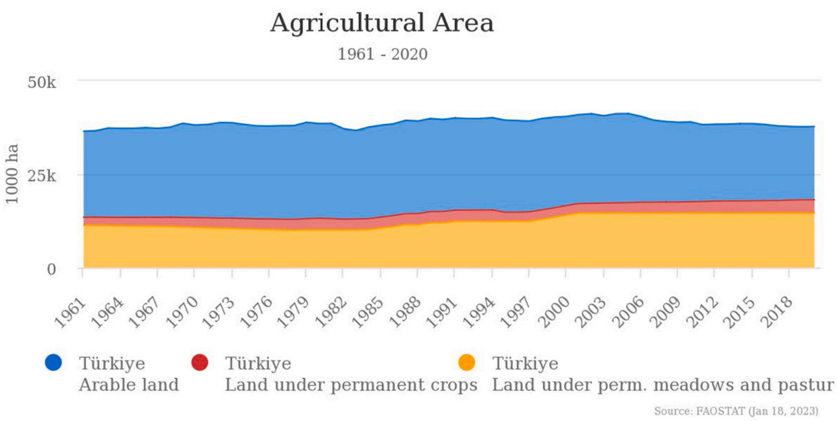


Fig. 6. Evolution of agricultural areas in Turkey between 1961 and 2020 [45].

5. Evaluation of the agrivoltaic possibility of Turkey

5.1. Types of agrivoltaic systems

AV systems can be categorized according to the crop cultivation location and the type of PV modules being used as illustrated in Fig. 7.

Crops that can tolerate some shade are grown in the solar PV plant's inter-row space and ground clearance (Fig. 7A and B). While the crops grown in the inter-row area are exposed to both beam and diffused radiations throughout the day, the crops grown beneath solar PV modules are only exposed to diffused radiations and marginal beam radiations. Besides, the usage of semi-transparent solar PV modules is a different type of AV system (Fig. 7C). Due to its light permeable feature, some of the solar radiation can reach the back of the module. In addition, the utilization of hydroponics, which is one of the cutting-edge setups, can be applied in the AV system (Fig. 7D). Using aqueous solvents and nutrient solutions, the hydroponic technology allows for the cultivation of crops without the use

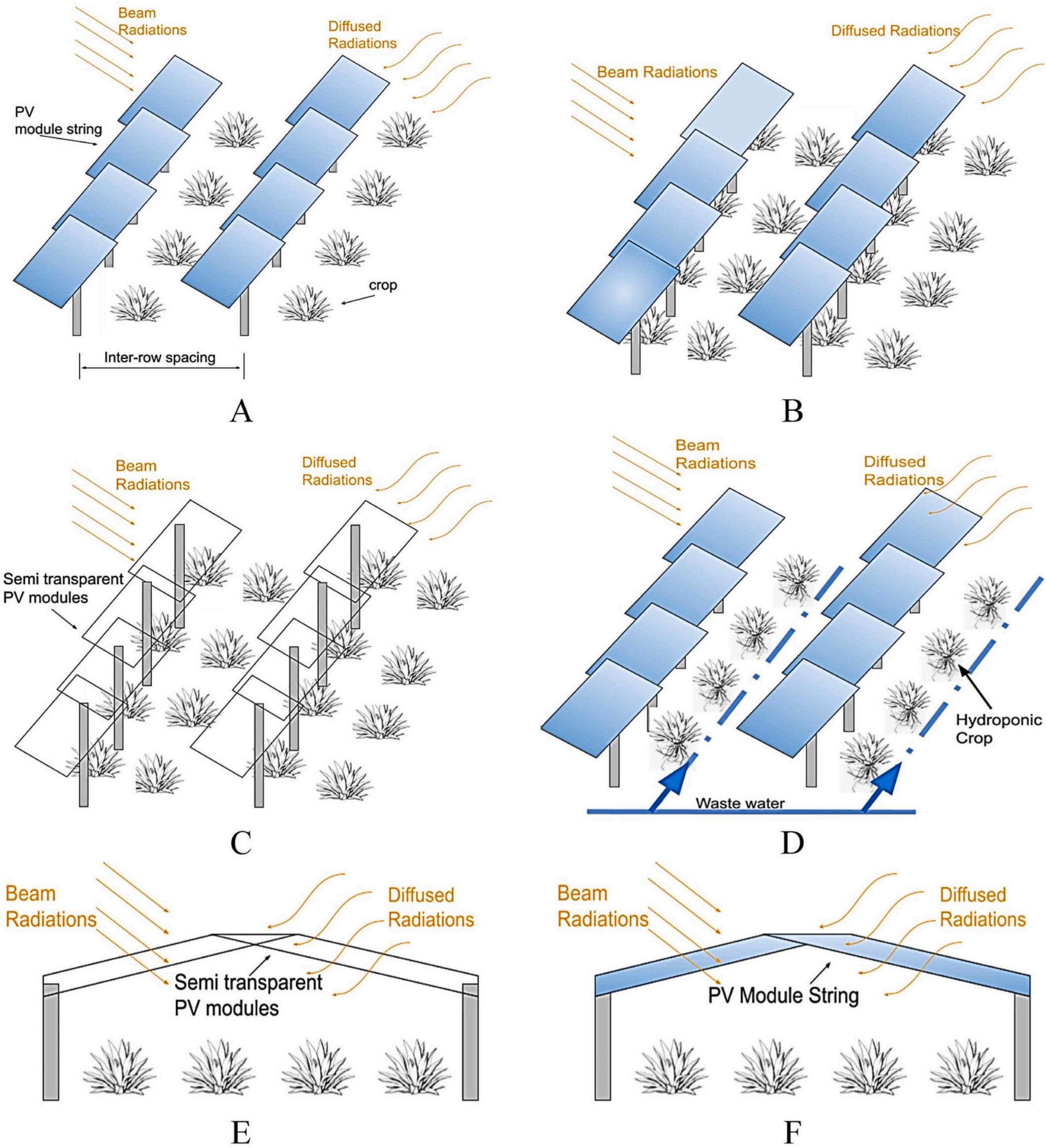


Fig. 7. Types of AV systems used in the agricultural field.

of soil. The aim behind hydroponic AV is to grow shade-tolerant hydroponic crops in the spaces between the rows and directly below the solar PV modules. This kind of AV system would be more suited for rooftop solar PV plants since hydroponic crops do not require soil. Another design would cover the roof of the greenhouse with semi-transparent solar PV modules (Fig. 7E), allowing more light to enter the building. Thus, it is possible to grow greenhouse food and power plants in the same greenhouse. In a different case, the crops might be grown in a greenhouse setting with a regular PV module partially covering the top surface. In this case, the partially covered greenhouse top allows solar radiation to enter the greenhouse (Fig. 7F). One of the most important components of the AV systems is the choice of suitable crops. Because when the studies in the literature were examined, it was seen that the crop productivity in the experimental group was lower than the crops in the control group, between 3.98 % and 91.30 % [49–51]. There may be a solution in fewer PV modules or wider spacing between modules, but some studies have shown the opposite [52,53]. Therefore, as was already indicated, choosing the right crop and order of PV modules is crucial. The following points include the key criteria for choosing AV crops.

- Climatic factors: The temperature of the environment has a significant impact on plant growth [54]. The predominant global atmospheric circulation patterns and physical geography traits have a significant impact on Turkey's climate. Even when just the country's physical location is taken into account, it becomes clear that the temperature gradually drops from south to north while the summer's sunshine duration is higher than in the winter. This is especially true of slopes facing the north, where direct solar radiation is less absorbed. On the south-facing slopes, however, it decreases drastically. Because of this, Turkey's climate, including its temperature, precipitation, and vegetation distribution, varies significantly [55].

- Height of the crop: The ideal structure height is important for the PV systems' improved structural stability and minimal wind resistance. Therefore, choosing crops that provide the best ground clearance is necessary [54].
- Requirement of water and direct sunlight: Plants with a high water requirement may cause corrosion under the modules and in the structures holding the modules. By adjusting their photosynthetic rate or changing the growth of their leaves, plants respond to shading with species-specific physiological adaptations and avoid acute sunshine shortage [53].
- Sufficient solar exposure: Solar exposure is crucial for the growth and development of crops. Sufficient solar exposure can positively affect crop growth in several ways such as the photosynthesis process by which plants convert light energy into chemical energy, which is used for growth and development. The more sunlight a crop receives, the more energy it can produce through photosynthesis, leading to increased plant growth and yield [56].
- Temperature regulation: Solar radiation helps regulate the temperature of the crop's environment. The warmth generated by sunlight can help increase the rate of biochemical reactions in plants, leading to increased growth [57].
- Water absorption: Solar exposure to a plant can increase the rate of transpiration due to providing a decrement in its temperature. Hence, the rate at which plants absorb water from the soil and release it into the atmosphere can change. With evapotranspiration, plants can maintain the ideal water balance in their root zone in addition to controlling temperature [58].
- Flowering and fruiting: Solar exposure can play a critical role in the timing and success of flowering and fruiting in crops. Proper exposure to sunlight can help trigger the plant's reproductive processes, leading to the development of flowers and fruits. However, excessive sun exposure can also have negative effects on crops. For example, prolonged exposure to direct sunlight can cause heat stress and damage to the plant, leading to reduced growth and yield [59]. It is important to balance the amount of solar exposure with other environmental factors like temperature, humidity, and water availability to optimize crop growth and yield. For ideal plants, the AV system provides optimum improvement.

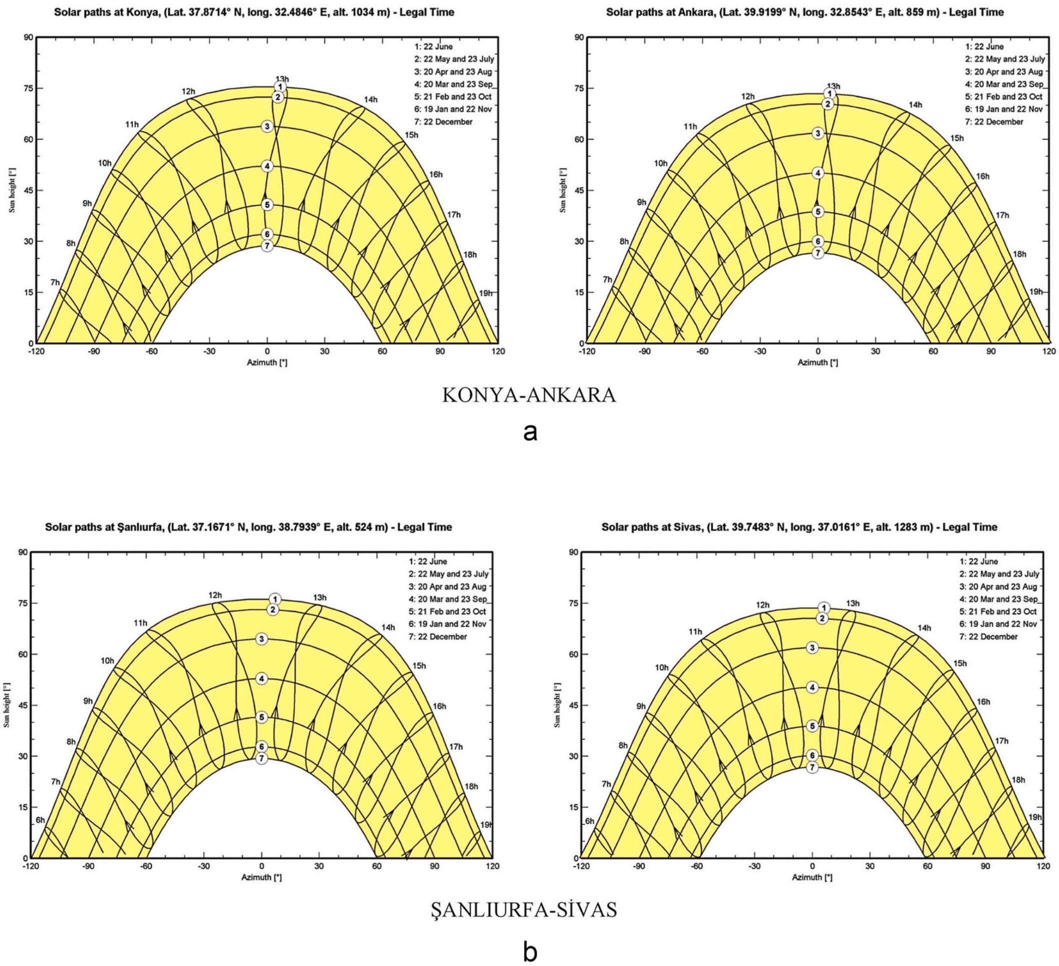
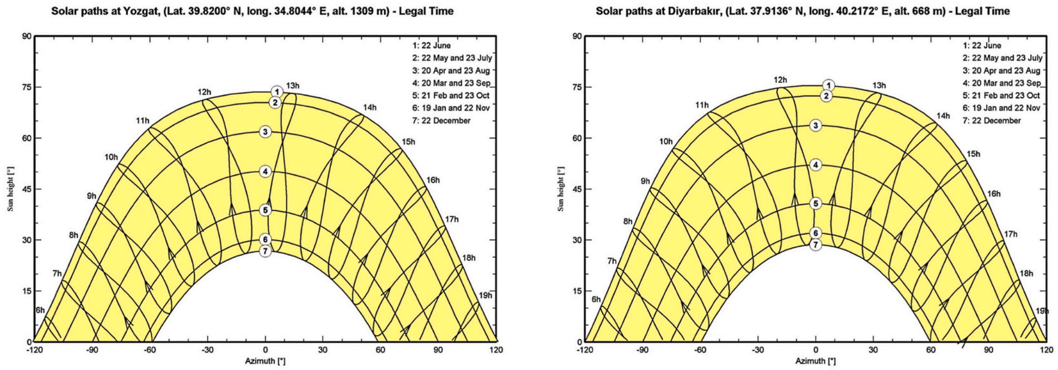


Fig. 8. Sun path diagrams for the most agriculture ten cities in Turkey.



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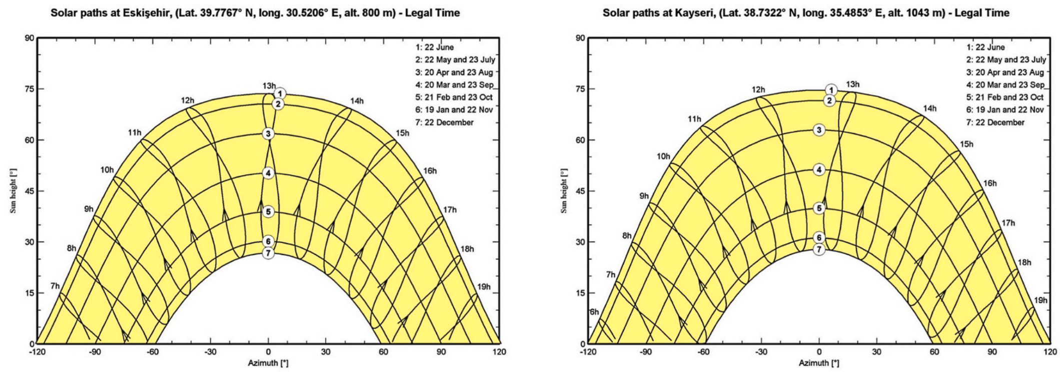

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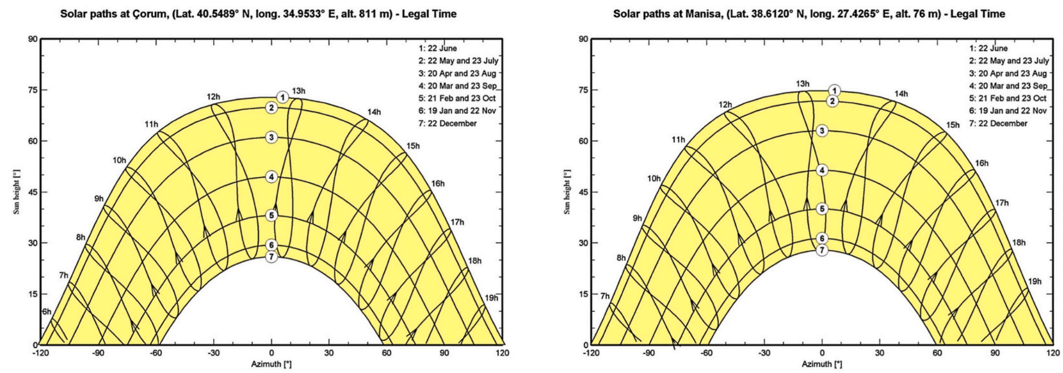


ÇORUM-MANİSA

e

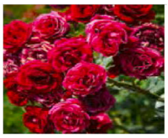
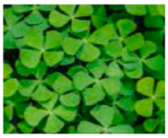
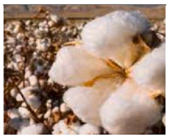
Fig. 8. (*continued*).

- Sufficient land: This is crucial for AV system practical applications. From this perspective, Turkey has an abundance of land that is suitable for agricultural use. With around 19 million hectares of agricultural land, Konya surpassed all other 80 cities in Turkey as of 2021 to become the country's most important agricultural city. This achievement was based on the size of the agricultural land.

5.2. *Suggesting potential AV systems in Turkey*

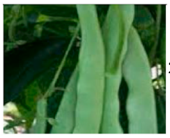
Turkey is still in the early stages of implementing AV systems. However, depending on the country's location, there are numerous opportunities. This location of the country brings some advantages such as plant diversity and electricity generation density. Turkey is

Table 2
The list of the most grown products in Turkey.

#	Name of the crop	Appearance	Suitable soil	Height of crop	Special features
1	AleoVera		sandy and humus soil	60–100 cm	need direct sunlight
2	Lavender		prefers neutral (6.4) to slightly alkaline pH (8.2)	50 cm	appropriate water drainage, air currents, and solar exposure
3	Rose (for oil)		quite fresh, clay loam and organic material-rich soils	60–110 cm	long duration and high-intensity light
4	Nettle		rich in nutrients, heavy, humous, and moist	80–400 cm	Partial shade
5	Alfalfa		most loamy, not very sandy, containing sufficient lime lands	50–80 cm	needs temperature
6	Poppy		all kinds of soil, alluvial soil	80–110 cm	needs temperature and sunlight
7	Cotton		all kinds of soil, alluvial soil	60–120 cm	needs temperature and sunlight
8	Sugar beets		rich in organic matter	80–185 cm	needs sunlight and water
9	Sunflower		all kinds of soil, neutral PH (6.5–7.5) soil	150–200 cm	needs sunlight and water

(*continued on next page*)

Table 2 (*continued*)

#	Name of the crop	Appearance	Suitable soil	Height of crop	Special features
10	Potatoes	 0	sandy loam soils	100 cm	cooler climates
11	Chickpea	 1	calcareous sandy soils	15–60 cm	cooler climates
12	Dry beans	 2	a good amount of organic matter, deep, loamy, or silty, slightly acidic soil	33–105 cm	needs sunlight, the ideal temperature 18–20 °C
13	Lentil (red)	 3	grows in a wide range of soil types	30–40 cm	cannot be grown at very low temperatures
14	Wheat	 4	deep-structured, clayey, sandy-loam soils rich in organic matter, containing phosphorus and lime	95–105 cm	cooler climate, don't need much water
15	Maize	 5	in deep, warm, loamy soils rich in organic matter and plant nutrients, with good drainage and aeration	100–300 cm	cooler climate, the ideal temperature 24–32 °C
16	Barley		rich in organic matter, pH (5–8)	35–100 cm	cooler climate, relative humidity of 70–80 % is very suitable
17	Rice in the husk	 7	deep, loamy, and nutrient-rich soils with low permeability	50–150 cm	ideal temperature 18–23 °C

one of the most important countries in the world with variable ecological environmental conditions with approximately 12,000 plant taxa of one-third are endemic which is a taxon limited to a small geographic area [60]. As already mentioned, the country is rich in agriculture and has many sunny days a year. Germany, a member of Europe, has a solar energy potential that is less than half that of Turkey. However, as of 2019, it is known that the country produces about six times more electricity than Turkey based on solar energy [30]. Turkey has very significant potential in this respect and is one of the countries with a high number of sunny days [30]. As indicated in Fig. 8, the annual sun path diagrams for the most agriculture ten cities in Turkey are given. All of these cities are located in the inner part of the country, where agricultural activities are conducted with great intensity. Besides, these cities generally have a high amount of solar energy potential. The x-axis of Fig. 8 shows the solar azimuth angle, while the y-axis represents the solar elevation angle in degrees. Drawing a solar path allowed for the assessment of the cities' sunshine duration and solar movements, ultimately revealing their potential in terms of energy production. Sun path diagrams are crucial for designing and optimizing AV systems, providing insights into sun radiation patterns, shading impacts, and seasonal fluctuations. They help estimate the annual energy output of a solar energy system in a specific region, enabling sustainable energy generation and agricultural efficiency in integrated systems. This information is essential for achieving these goals.

According to the data of the Turkish Statistical Institution, the most commonly grown crops in the ten selected cities in Turkey are listed in Table 2 [61–68]. The types of AV systems that can be employed with these crops are listed in Table 3. The optimum temperature is the most suitable temperature for plant life, and every plant needs a certain amount of temperature to grow. In an AV production system, altered microclimate conditions can have several implications on crop productivity and the quality of the harvestable products. However, for a huge number of crop species, there are no statistics available. Furthermore, the data applicability to AV systems is constrained because they primarily come from netting and agroforestry trials [15]. In an AV system, a small fraction of incident solar radiation is converted into electricity, the remaining is absorbed by the module, making it hotter than its surroundings. The air beneath the PV module will typically be warmer than the surroundings if the structures are not designed properly, which will result in heat being trapped beneath it. In this case, choosing warm-season crops would be preferable. Other than this, shade-tolerant crops may also be considered.

Although AV systems offer numerous advantages, their implementation presents certain drawbacks and challenges such as initial costs, maintenance, crop selection, and technical difficulties. Research and development efforts are addressing these challenges in AV systems, aiming to improve efficiency and accessibility for farmers. AV systems optimize agricultural and solar energy production, requiring continuous collaboration between researchers, policymakers, and farmers for widespread adoption. The suitability of implementing AV systems in Turkey can be assessed based on climate characteristics, farming techniques, and local conditions. Considering these key factors together, Turkey possesses a highly advantageous climate and agricultural diversity for AV systems [17,30].

According to simulation findings by PVsyst, the annual solar irradiation levels and sunshine duration of the ten selected cities are listed in Table 4. The determined irradiance values are different and vary between 1588 kWh/m^2 and 1886 kWh/m^2 respectively. While Table 1 provides an overview of the regions in Turkey based on the empirical data, Table 4 shows data for the ten selected cities in these regions obtained from PVsyst simulations. The total annual solar energy potential and sunshine duration in Tables 1 and 4 differ since the listed values in Table 1 are from Turkey's geographical regions, which include other cities, whereas Table 4 presents only the values of the 10 cities selected in this study.

A comparison of the ten selected cities reveals differences in agricultural activities, climate, simulation results, sun path, solar irradiation, and crops. In Turkey, mountain ranges span from the western to the eastern regions, extending in a parallel manner to the northern and southern coastlines. The elevation steadily ascends from the west to the east. Due to this geomorphological characteristic, various climate zones are present throughout the country. These are the Mediterranean Climate Zone, Black Sea Climate Zone, Marmara Transition Zone, and lastly which encompasses over 50 % of the country is the continental climatic zone. All selected cities, except for Manisa, fall within the continental climate zone, Manisa exhibits characteristics of a Mediterranean climate [30,46]. Areas with favorable climates and sufficient water supplies have often exhibited greater agricultural output such as Konya, Kayseri, and Manisa. Cities located closer to the equator, such as Şanlıurfa, Konya, Kayseri, and Diyarbakır, have greater levels of solar irradiation; however, Konya, Kayseri, and Manisa have stable climatic conditions and diverse agriculture sectors, which is advantageous for these places. These criteria, in addition to crop diversity and geographical characteristics, determine the eligibility of each city for AV systems.

As can be seen from the sun path diagrams in Fig. 8, Konya, Kayseri, and Manisa, in particular, stand out among other cities due to their higher solar irradiation and sunshine duration values. Based on the PVsyst simulation results as listed in Table 4, Konya, Kayseri, and Manisa record annual solar irradiation values of 1764 kWh/m^2, 1746 kWh/m^2, and 1760 kWh/m^2, respectively. Although Şanlıurfa and Diyarbakır receive comparable or even greater solar radiation, they struggle with agricultural productivity due to limited opportunities such as inefficient water management and limited agricultural irrigation, insufficient adoption of modern agricultural technologies, and local economic conditions. Konya, Kayseri, and Manisa play crucial roles in Turkey's agricultural landscape, contributing significantly to the country's food production and economy. Konya, also known as the "grain silo of Turkey," is one of the country's leading agricultural centers. Its vast plains and fertile soil make it ideal for cultivating grains such as wheat, barley, corn, and oats. Kayseri, located in central Anatolia, is another important agricultural region in Turkey. The city's agricultural economy is diverse, with a focus on crops like wheat, barley, and sugar beets. Manisa, located in western Turkey, is known for its fertile soil and favorable climate, making it suitable for a wide range of agricultural activities such as tomato, cucumber, lettuce, sunflower, pepper, grape, and potato. In addition to receiving a huge amount of sunlight and for their diverse agricultural industries, Konya, Kayseri, and Manisa possess superior access to water resources. Moreover, consistent weather conditions in these regions reduce severe weather events, while the Mediterranean climate in Manisa, Konya's wide basin, and Kayseri's high altitude enhance the practicality of establishing AV systems. Therefore, these cities demonstrate remarkable potential for AV systems, particularly for cultivating various crops. The AV systems depicted in Fig. 7 can be implemented in types A and B for Konya and Kayseri provinces, and in types E and F for Manisa province, considering the specific land area and topography of these regions.

Table 3
Optimum AV system categories for different crops in the ten selected cities in Turkey.

Types of AV systems	Crops grown in the ten selected cities
(A), (B), (D), and (F)	There will be full shading under the module due to the module-mount shapes. Shade-tolerant plants can be grown under the PV modules such as Alfalfa, Potato, Rose, Barley, Wheat, Dry bean, Lentil, Poppy
(A), (C) and (E)	There will be solar radiation between the modules. Shade-intolerant plants can be grown in inter-row spacing and under transparent solar PV modules such as Sunflower, Rice in the husk, Maize, Aleo Vera, Cotton, Dry bean, Chickpea, Sugar beet, Nettle, Lavander
(F)	They could be opaque, which would reduce the amount of solar radiation that passes through them. It can be ideal for plants that like warmth such as Rose, Aleo Vera, Dry Bean

Table 4
Solar radiation values and sunshine duration of the ten selected cities.

Cities	Total Energy (kWh/m^2-year)	Sunshine Duration (hour/year)
Manisa	1760	2840
Ankara	1687	2611
Eskişehir	1588	2479
Konya	1764	2898
Yozgat	1724	2683
Kayseri	1746	2842
Sivas	1692	2653
Çorum	1645	2511
Şanlıurfa	1886	3033
Diyarbakır	1760	2613

6. Conclusion

This research offers a comprehensive perspective on the integration of solar energy production and agriculture, which have gained significant popularity worldwide in recent years, in the context of Turkey. The agricultural sector, which accounts for a significant portion of the country's energy consumption, is growing due to population growth, making it a prime location for sustainable energy solutions. AV systems have tremendous potential in Turkey for several reasons.

- Abundant sunlight: Turkey receives significant amounts of sunlight, making it an ideal location for solar energy production.
- Growing energy demand: Turkey's energy demand is increasing, and AV systems can help to meet this demand while also supporting the agricultural sector.
- Agricultural land availability: Turkey has a large amount of agricultural land, which can be used for AV systems, providing an opportunity to increase food production and energy generation.
- Climate benefits: AV systems can provide shade and cooling to crops, improving their growth and reducing the risk of water evaporation, which is especially beneficial in regions with high temperatures.

Turkey's diverse climates and geographical features make it an attractive case study for AV systems due to its renewable energy potential. Overall, the potential for AV systems in Turkey is significant, and the optimal use of AV systems can play a key role in supporting both the energy and agricultural sectors in the country. The main limitations of the presented study are that it is mainly based on the simulation results and data from the different organizations. To support the findings in this study, future work will be to test AV systems on a small-scale real application.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Atıl Emre Coşgun: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Mustafa Sacid Endiz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Hasan Demir:** Resources. **Muciz Özcan:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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