AgriVoltaics World Conference 2024

Plant & Crop Physiology

https://doi.org/10.52825/agripv.v3i.1356

Published: 18 Jul. 2025

A Study of Agrivoltaics Peanut Production With Single-Axis Tracking Systems

Milena Chanes de Souza[1,*], Ricardo Nery de Castro[1], Benhur Azambuja Possato[1], Matthias B. Krause[2], and Sol Hutson[2]

[1]Flextronics Institute of Technology (FIT), Brazil

[2]Nextracker, United States

*Correspondence: Milena Chanes de Souza, milena.souza@fit-tecnologia.org.br

Abstract. This study investigates the application of single-axis solar tracking systems in peanut production, a crucial crop for global food security and economic sustainability. The experiment was conducted at the FIT Solar Laboratory in Sorocaba, Brazil, from May to September 2023. Peanut plants were cultivated under two conditions: an Agrivoltaic system with bifacial solar modules with a single axis tracking system, and in a conventional agricultural setup. Key findings indicate that peanut biomass yield under Agrivoltaic systems was 17.02% lower than in traditional agricultural systems, primarily due to shading effects inherent to the dual-use configuration. Despite this reduction, the morpho-physiological parameters of peanut plants, including plant height (31.2 ± 1.5 cm), stem diameter (5.3 ± 0.3 mm), stomatal conductivity (0.24 ± 0.02 mol/m²·s), and chlorophyll index (34.6 ± 2.1 SPAD units), remained stable under the Agrivoltaic system, demonstrating the adaptability of peanut plants to lower light conditions. Photosynthetically active radiation (PAR) measurements varied significantly depending on the position under the trackers, with values ranging from 150 to 1,200 μmol/m²·s, reflecting the heterogeneity of light distribution. The Agrivoltaic system achieved an energy production of 2,354.82 kWh/kWp, reflecting a minimal deviation of 4.36% compared to the PV-only control system, which recorded 2,462.26 kWh/kWp. The Energy Performance Index (EPI) for the Agrivoltaic system was calculated at 0.96, demonstrating its efficiency in converting available solar energy under real-world conditions. This performance aligns with industry standards, underscoring the efficiency of single axis tracking systems in balancing agricultural and energy outputs.

Keywords: Sustainability, Dual-Use, Photovoltaic Efficiency

1. Introduction

The increasing global demand for energy has prompted the development of renewable energy technologies like solar photovoltaics (PV). Solar energy is highlighted as one of the most abundant and promising renewable energy sources, with approximately $1.2 * 10^5$ TW of solar radiation reaching the Earth's surface [1]. Solar radiation represents a significant opportunity for green technologies due to its abundance, cleanliness, cost-effectiveness, and inexhaustibility [2]. However, large-scale PV installations compete for land-use, e.g. agriculture. Agrivoltaic (APV) systems enable dual land use by integrating agriculture and PV production, enhancing land-use efficiency. On the other hand, solar radiation is also crucial for plant growth, particularly for photosynthesis. The availability and intensity of light significantly influences plant growth and yield, acting as a limiting factor [3]. Plants tolerant to shading or low light intensity are important for intercropping and agroforestry systems, as well as optimizing land use efficiency, especially in regions with limited agricultural land [4].

1.1 Dual use of the land: Photovoltaic with Agriculture

The development of renewable energy sources to meet global energy demands and combat climate change is a critical societal challenge. PV systems are highly efficient in capturing solar energy [5]. However, large-scale ground-mounted PV installations can lead to conflicts with agricultural land use, especially in regions with limited space [6]. To address this conflict, APV systems combine PV and food production on the same land area [7]. Commercial APV plants and research facilities have been established globally to show how APV can increase land efficiency [8].

The concept of APV was initially proposed in 1981 by Goetzberger and Zastrow to modify solar power plants to allow for additional crop production on the same area [9] and its success of APV systems hinges on maintaining crop productivity alongside energy production. Field experiments demonstrate improved land and water use efficiency with combined PV and crops compared to separate production, but the increase in PV module density can reduce crop radiation and yield [9,10,11].

1.2 Single axis solar tracking systems.

Traditionally, fixed, or static solar systems were common, but advancements in technology have led to the adoption of single-axis solar tracking systems, which can dynamically adjust the position of solar panels according to the sun's position throughout the day and across seasons. Although fixed racking systems are more durable in harsh environmental conditions and require less site preparation, solar tracking systems have become increasingly popular due to their ability to significantly enhance energy extraction efficiency and optimize the overall PV production process [12].

Single-axis solar tracking systems involve rotation around a single axis to align solar panels as perpendicular as possible to the sun's radiation. The most effective orientation for these systems is typically alongside the north-south meridian axis, using predefined algorithms based on mathematical calculations about the sun’s trajectory to determine the sun’s position at a particular time to orient the PV panels accordingly [13]. Understanding the advancements in solar tracking technology not only highlights the efficiency of energy production but also sets the stage for exploring how these innovations can positively impact agricultural practices, particularly in the cultivation of important crops like peanuts between the tracker systems.

1.3 Peanuts production

Peanuts (*Arachis hypogeaea L.*) are an important edible oil crop, second only to soybean in terms of the world production and trade. It plays an important role in ensuring the security of edible oil production, China being the world's largest producer [14], [15]. In 2021, global peanut production reached 53.6 million tons. The top ten peanut-producing countries in 2022 are as follows:

1º **China:** Leading with 18.4 million tons, nearly one-third of global production, primarily from Henan, Jiangsu, Guangdong, and Shandong provinces.

2º **India:** The second-largest producer at 10.2 million tons, accounting for 21% of total production. Major regions include Orissa, Karnataka, Gujarat, Maharashtra, Andhra Pradesh, and Tamil Nadu, with significant exports to Pakistan, Malaysia, and Indonesia.

3º **Nigeria:** The third-largest producer, contributing 30% of Africa's peanut output, mainly from the dry regions including Kaduna and Kano.

4º **United States:** Producing about 2.9 million tons in 2021, with Alabama leading production among 13 states.

5º **Sudan:** Fifth in production with approximately 2.4 million tons, benefiting from favorable climates in Kordofan, Darfur, and Gedaref.

6º **Senegal:** Producing 1.7 million tons, with the majority exported to China.
7º **Myanmar:** Producing 1.6 million tons annually, despite political instability, serving as a significant income source.
8º **Argentina:** Known for high-quality "Golden peanuts," producing around 1.3 million tons on over 35,000 hectares.
9º **Guinea:** Contributing about 907 thousand tons, essential for food security and local economies, primarily grown by smallholder farmers.
10º **Chad:** Producing 798 thousand tons, making peanuts a key income source and agricultural foundation, with exports through international trade routes [15,16.17].

The Figure 1 shows the map of the distribution of peanut cultivation worldwide, highlighting mainly China and India [16]. However, when comparing the data in Figure 2, it is possible to notice that the yield productivity (kg/ha) is quite different between countries [15,16,17]. Countries such as Israel, United States, China, Brazil, and Argentina manage to produce more in a smaller area of land. This can be due to several factors such as climate, soil quality, sunlight incidence, irrigation, type of management, type of seed, among other factors [18,19,20,21,22].

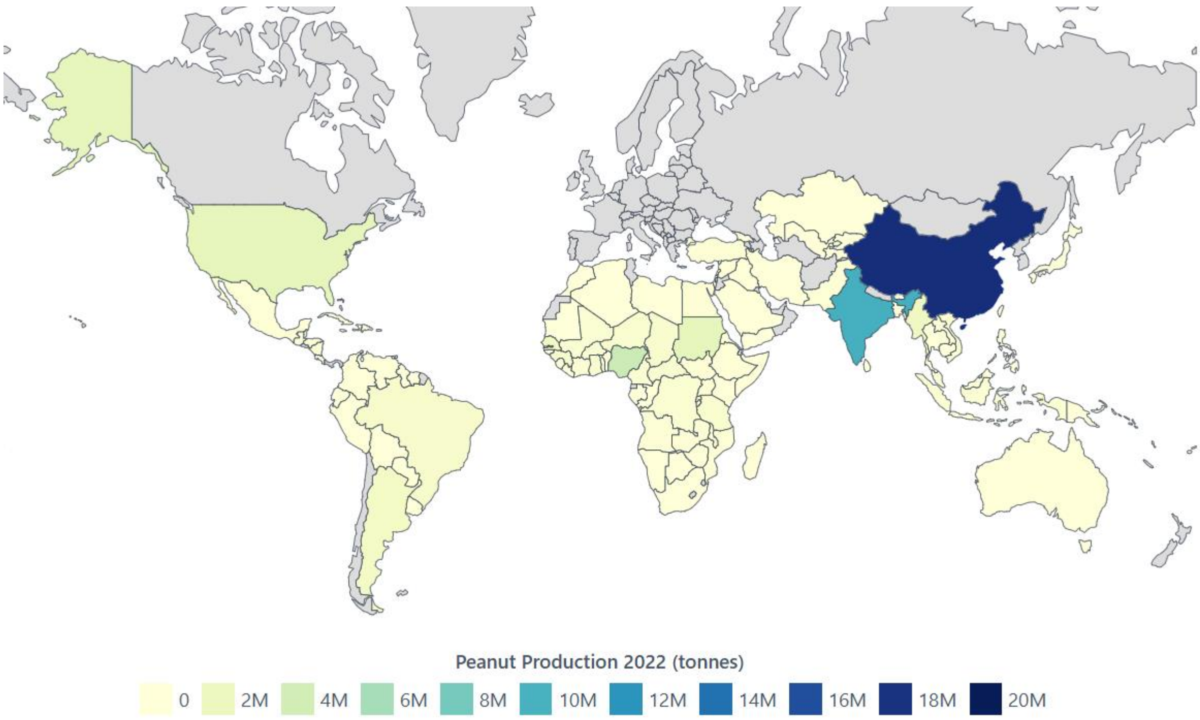

Figure 1. *Distribution map of peanut cultivation worldwide.*

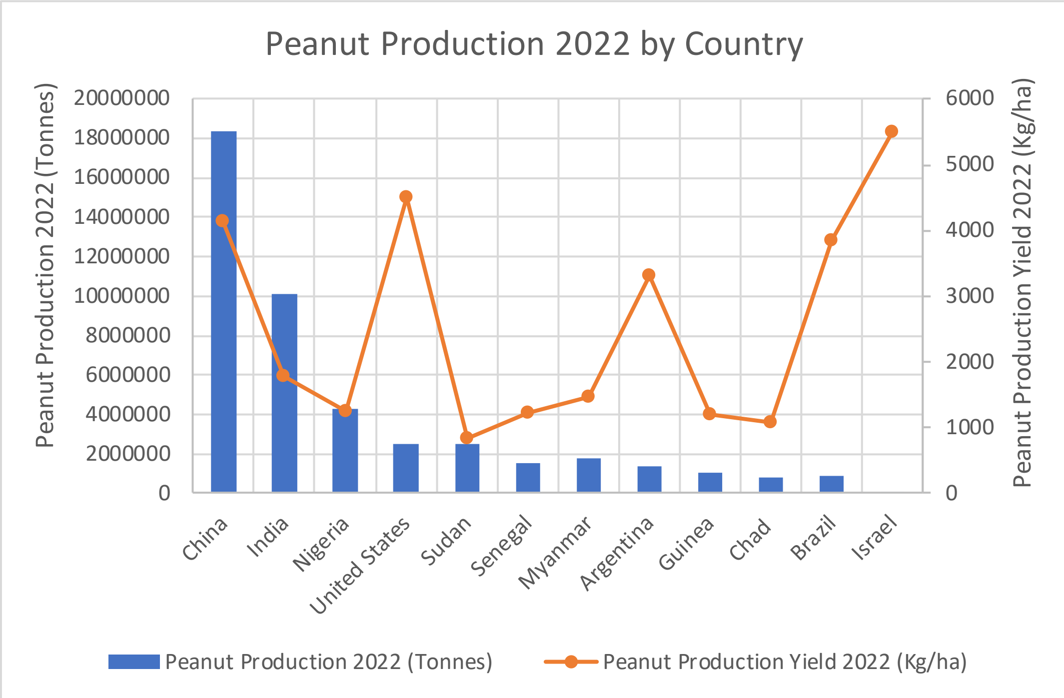

Figure 2. *Production versus production yield shown by country.*

Although there are large differences between the climates of the countries that grow peanuts, the optimal temperature range for peanut cultivation is between 25°C and 30°C. Below 15,5°C or above 35°C, plant growth significantly slows down. Maximum leaf and stem weights are typically achieved around 90 to 100 days after planting (DAP), and good branche production is essential for high pod yield in peanuts. For optimal yields, it is crucial to avoid drought stress and extreme temperatures during the critical period of 60-100 DAP. Maintaining optimal environmental conditions during this growth stage is key to maximizing peanut productivity [23].

Studies on peanut cultivation in APV systems have been found; however, there was not much productivity data available. Japan and China have conducted studies on peanut planting in APV systems, but they utilized PV systems with different characteristics. Japan used a special structure that is very similar to a pergola in a garden. The structures it created are tall, made of tubes and rows of photovoltaic panels, which are arranged with certain intervals to allow sufficient sunlight to reach the ground for photosynthesis [24,25]. In China, it was observed that peanut cultivation in an APV system (Fixed PV with a minimum height of 2.5 meters from the ground) led to a greater improvement in soil quality and multifunctionality than ryegrass. This approach significantly increased soil moisture, organic carbon, nitrogen, phosphorus, potassium nutrients, microbial biomass, and urease activity. However, this study does not provide data on peanut productivity [26]. In China, another study investigated the spectral separated concentrated agricultural photovoltaic (SCAPV) systems compared to the conventional agricultural system. It was noted that the SCAPV system achieved a peanut production productivity that was 6.5% higher than the reference, which was 4,3 kg/ha [27]. Seeking to improve more efficient and sustainable land use, this study evaluates the impact of APV systems with single axis tracking on peanut yield and energy production.

2. Material and Methods

The experiment was conducted from May 22 to September 15, 2023, at the FIT Solar Laboratory in Sorocaba, SP, Brazil (23.425°S, 47.367°W). Peanuts (IAC-385 Mojave) where cultivated under the following conditions:

1. **Agrivoltaics System (APV)**: 500 m² with 6 rows of single-axis Nextracker Horizon trackers (1.5 m torque tube height, 6.1 m pitch, GCR 31.47%, Canadian 385 bifacial modules).
2. **Agricultural Control (AGRI)**: 500 m² of unshaded agriculture.
3. **Photovoltaic Control (PV)**: 1 row of single-axis Nextracker Horizon trackers (1.5 m torque tube height, 6.1 m pitch, GCR 31.47% (parameter considered by the tracking algorithm)).

The peanut study was part of a larger study that included a total of 10 crops. Planting beds were arranged perpendicular to the trackers, with 10 beds per row and a total of 6 rows. Therefore, it was possible to create six replicates of each crop in a randomized manner, with at least one crop per row, see Figure 3. So, the peanut planting beds were aligned perpendicular to the trackers, ensuring consistent distance from the panels. Plant morpho-physiological data (plant height, stem diameter, stomatal conductivity, chlorophyll index) were collected at 70 DAP. Photosynthetically Active Radiation (PAR) was measured daily with a 1-minute interval using Apogee Quantum Sensor SQ-422X, positioned beneath the tracker, at the drip end, and in the middle of the alley. Within the 6-meter by 1-meter planting bed, measurements were taken at three positions, each with a sample size of 1 meter by 1 meter. At the end, the average was computed.

Figure 3. *Design of Experiment (DOE) and positioning of the planting beds.*

The Energy Performance Index (EPI), as defined by IEC 61724, is a standardized metric used to evaluate the performance of PV plants. It compares the actual energy output of the plant to the expected energy output based on computational modeling of the "as-built" project, adjusted for real-world environmental conditions such as solar irradiance and ambient temperature. The EPI is calculated as the ratio of measured energy to expected energy. In this study, the EPI was extrapolated for a 10,000 m² area, incorporating the Ground Coverage Ratio (GCR) into the energy production analysis. The PV modules used were Canadian Solar CS3W-385PB-AG bifacial modules, each with a nominal capacity of 385 W, and the inverters deployed were Sungrow SG20RT models, rated at 20 kW.

To account for differing inverter overload factors, performance estimates were generated using the System Advisor Model (SAM), version 2023.12.17. The simulations utilized 1-minute granularity data, including measurements of direct normal irradiance (DNI), global horizontal irradiance (GHI), and diffuse horizontal irradiance (DHI), as well as ambient temperature. These measurements were performed using high-precision sensors (EKO MS80 and MS57), ensuring the accuracy and reliability of input data for the computational modeling process.

3. Results and Discussion

The morpho-physiological data collected at 70 DAP, including plant height, stem diameter, stomatal conductivity, and chlorophyll index, are presented in Table 1. The results showed an increase in plant height (etiolation) in the APV system due to shade, while other morpho-physiological parameters were similar between APV and AGRI systems. This is attributed to the ability of peanut plants, like C3 crops, to adapt to lower light conditions.

Peanut biomass yield in the APV system (Middle Tracker) was 17.87% lower than in the AGRI control. Biomass production was influenced by reduced radiation, particularly beneath the trackers. APV system Beneath Tracker was 34.91% lower than in the AGRI control. The perpendicular alignment of the planting beds ensured consistent sampling positions, and yield measurements were taken at multiple positions (under the tracker, at the drip end, and in the middle of the alley). This method allowed a comprehensive analysis of peanut yield at various light exposure levels.

The peanut biomass yield in the AgriPV system (Middle Tracker) showed a 17.87% lower production than in the control (Fig. 4A). This finding aligns with previous studies by Neto *et al.* (2011) [28] and Adjahossou *et al*. (2008) [29], that finds lower production with peanuts cultivated in greenhouses in different shade depths.

Table 1*. Morpho physiologic parameters of peanut, average with standard deviations, in Agrivoltaics System and Agriculture (different letters at rows indicate statistical difference on Tukey test with p<0,05).*

Morpho physiologic parameters	APV	AGRI
Plant Height (cm)	a 21.43 ± 5.23	b 13.73 ± 3.31
Stem Diameter (mm)	a 4.32 ± 0.89	a 4.26 ± 0.70
Stomatal Conductivity (mmol/cm^{2}s)	a 24.90 ± 13.82	a 22.23 ± 7.32
Chlorophyl Index	a 0.57 ± 0.18	a 0.49 ± 0.13
Biomass yield (g/m^2)	a 184.97 ± 44.08	a 225.21 ± 42.04

3.1 Radiation, APV yield, and PV performance

Significant reduction in radiation beneath the trackers is showed on figure 4B, consistent with the operation of a full solar tracking system. The data indicate that direct solar radiation is almost entirely obstructed directly beneath the tracker. In contrast, PAR measurements in the middle of the alley revealed minimal shading, highlighting a phenomenon that warrants further analysis to assess the consistency of light distribution across the experimental area. This reduction in radiation diminishes the rate of photosynthetic activity, inducing etiolation, which reallocates photoassimilates towards leaf and stem growth at the expense of pod development, ultimately reducing overall yield.

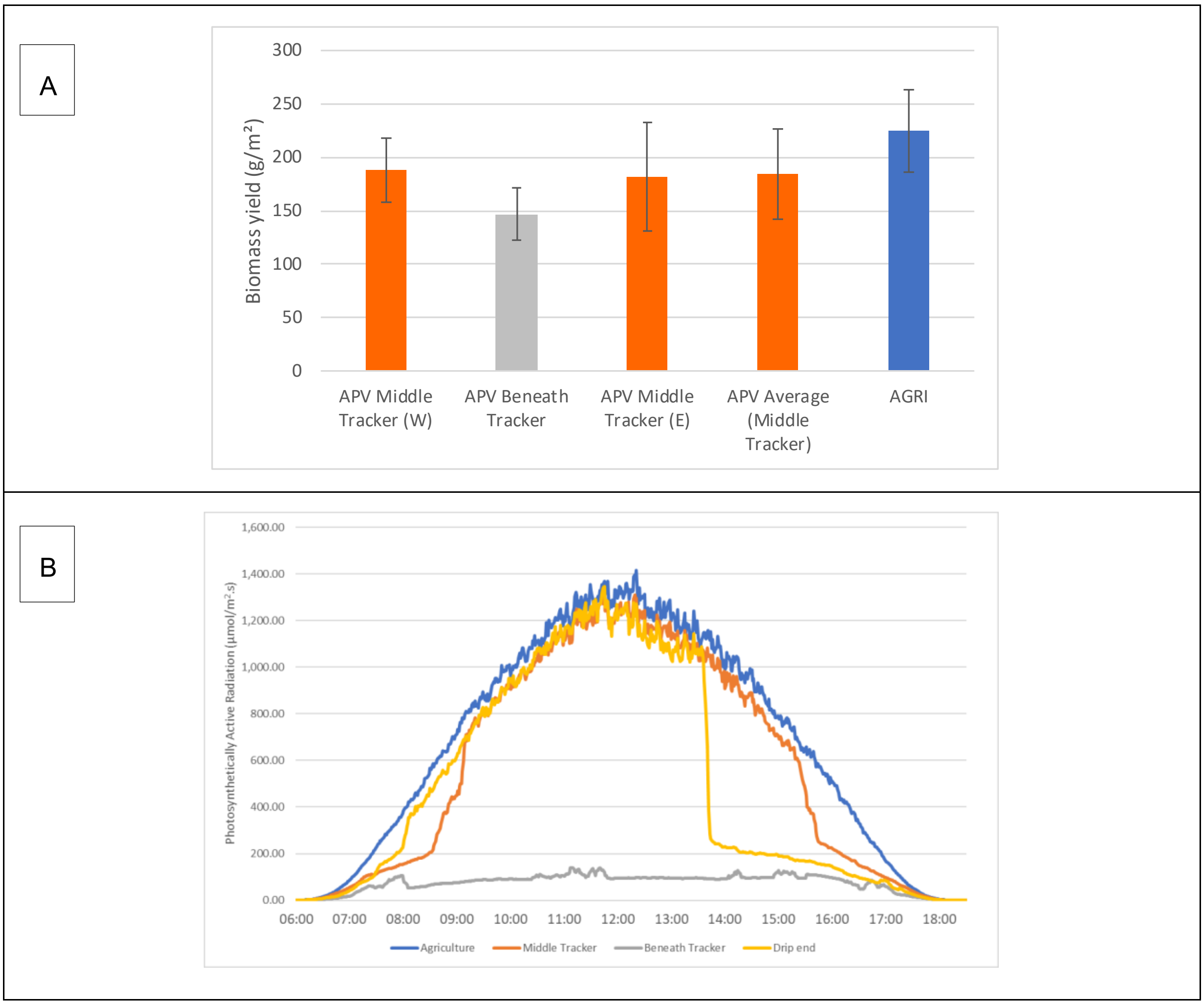

Figure 4. *(A) Peanut productivity (g.m^{-2}) on the APV vs AGRI with Standard Deviation (different letters indicate statistical difference on Tukey test with p<0,05). (B) Average PAR (μmol/m^2.s), (July 7th to September 15th, 2023) in the APV system (middle tracker, drip end, and beneath tracker) versus AGRI.*

On the PV performance side, the measures (extrapolated to areas of 10,000m²) on the inverters were 2,462.26 kWh/kWp for the reference area and 2,354.82 kWh/kWp for the APV area. The observed 4.36% deviation in measurements is negligible, considering the typical error range of 1% to 3% for the inverters' built-in sensors, as specified by manufacturers, and flash tests and IV curve tracers used for module qualification also exhibit error margins of 1% to 3%, contributing to minor discrepancies in rated performance values. Additionally, edge effects, which were not accounted (larger in the PV because the tracker is far from the others), can introduce minor deviations in irradiance and energy production. Moreover, the reduction in albedo within the APV system could also have contributed to the slightly lower energy production, as less reflected solar irradiance reaches the modules.

4. Conclusions

If we consider the production across all measured areas (Middle and Beneath Tracker), the decrease in biomass productivity rises to 23.55%. However, it is important to note that the areas Beneath Tracker are not suitable for planting, particularly for the Trackers in this study, which are 1.5 meters high. Therefore, peanut production under APV systems - Only considering data from the Middle Tracker - with full solar tracking showed a 17.87% reduction in yield compared to traditional agriculture. While peanut plants exhibit etiolation due to shading, their morpho-physiological parameters remain stable. The deviation in energy production from the APV system compared to the PV control was minimal and well within the typical error range of the inverters and module characterizations. Measurements at different positions provided a more comprehensive understanding of yield variability. These results suggest that APV systems can support peanut production while maintaining a reasonable energy yield.

Data availability statement

The data presented in this paper is restricted by legal constraints.

Author contributions

The author's contribution of this paper are Ricardo Nery de Castro, Milena Chanes de Souza, Benhur Azambuja Possatto, and Matthias Krause: Methodology, Investigation, Supervision and Writing – review & Editing.

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

Nextracker and FIT – Flextronics Institute of Technology.

References

[1] G. W. Crabtree; N. S. Lewis. "Solar energy conversion," in Physics Today, 2007, vol.60, no.3, pp.37-42, doi: https://doi.org/10.1063/1.2718755

[2] A. O. M. Maka; J. M. Alabid. "Solar energy technology and its roles in sustainable development," in Clean Energy, 2022, vol.6, no.3, pp. 476-483, doi: https://doi.org/10.1093/ce/zkac023

[3] C. Campillo; R. Fortes; M. H. Prieto. "Solar Radiation Effect on Crop Production," in Solar Radiation. InTech, 2012, doi: http://dx.doi.org/10.5772/34796

[4] A. C. Noertjahyani; A. Komariah, H. Mulyana. "Shade effect on growth, yield, and shade tolerance of three peanut cultivars," in Journal Agro, 2020, vol.7, no.1, pp. 102-111, doi: https://doi.org/10.15575/6273

[5] R. E. Blankenship, *et al.* "Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement," in Science, 2011, vol.332, no.6031, pp. 805-809, doi: https://doi.org/10.1126/science.1200165

[6] S. Nonhebel, "Renewable energy and food supply: Will there be enough land?," in Renewable Energy, 2005, vol.30, no.13, pp. 2283-2301, doi: https://doi.org/10.1016/j.rser.2004.02.003

[7] M. Wagner, *et al.* "Agrivoltaics: The Environmental Impacts of Combining Food Crop Cultivation and Solar Energy Generation," in Agronomy, 2023, vol.13, no.2, doi: https://doi.org/10.3390/agronomy13020299

[8] S. Schindele *et al.* "Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications," in Applied Energy, 2020, vol.265, doi: https://doi.org/10.1016/j.apenergy.2020.114737

[9] A. Weselek, *et al*. "Agrophotovoltaic systems: applications, challenges, and opportunities. A review," in Agronomy for Sustainable Development, 2019, vol.39, no. 35, doi: https://doi.org/10.1007/s13593-019-0581-3

[10] S. N. Bhandari, *et al.* "Economic Feasibility of Agrivoltaic Systems in Food-Energy Nexus Context: Modelling and a Case Study in Niger," Agronomy, 2021, vol.11, no.10, doi: https://doi.org/10.3390/agronomy11101906

[11] G. Dinesh; J. M. Pearce. “The potential of Agrivoltaic systems. Renewable and Sustainable,” in Energy Reviews, 2016, vol.54, pp. 299-308, doi: https://doi.org/10.1016/j.rser.2015.10.024
[12] A. Anshul, *et al.* “Review on Sun Tracking Technology in Solar PV System,” in Energy Reports, 2020, vol.6, pp. 392-405, doi: https://doi.org/10.1016/j.egyr.2020.02.004
[13] H. Mousazadeh, *et al.* “A review of principle and sun-tracking methods for maximizing solar systems output,” in Renewable and Sustainable Energy Reviews, 2009, vol.13, no.8, pp. 1800-1818, doi: https://doi.org/10.1016/j.rser.2009.01.022
[14] W. Shenying, *et al.* “Integration of Agricultural Machinery and Agronomy for Mechanised Peanut Production Using the Vine for Animal Feed,” in Biosystems Engineering, 2022, pp. 135-152, doi: https://doi.org/10.1016/j.biosystemseng.2022.04.011
[15] Food and Agriculture Organization of the United Nations (FAO). “Crops and livestock products,” 2024, https://www.fao.org/faostat/en/#data/QCL (February 20th, 2025)
[16] World Population Review. “Peanut Production by Country 2024,” https://worldpopulationreview.com/country-rankings/peanut-production-by-country (February 20th, 2025)
[17] Atlas Big. “World Peanut Production by Country,” https://www.atlasbig.com/en-us/countries-peanut-production (February 20th, 2025)
[18] C. S. Henderson, *et al.* “Productivity in the peanut under salt stress in soil with a cover of plant mulch,” in Revista Ciência Agronômica, 2023, vol.54, https://doi.org/10.5935/1806-6690.20230043
[19] R. A. M, Bruno, *et al.* “Advancements in peanut mechanization: Implications for sustainable agriculture,” in Agricultural Systems, 2024, vol.215, doi: https://doi.org/10.1016/j.agsy.2024.103868
[20] L. S. Gerald. “Response of Peanut (Arachis hypogea L.) to Cultivation Methods and Boron and Calcium Application,” in International Journal of Biosciences, 2024, vol.25, no.1, pp. 75-92, doi: http://dx.doi.org/10.12692/ijb/25.1.75-92
[21] G. Yohannes: L. Huaiyong. “Optimizing Peanut (*Arachis hypogaea* L.) Production: Genetic Insights, Climate Adaptation, and Efficient Management Practices: Systematic Review,” in Plants, 2024, vol.13, no.21, doi: https://doi.org/10.3390/plants13212988
[22] D. Jianshu, *et al.* “Irrigation and Fertilization Scheduling for Peanut Cultivation under Mulched Drip Irrigation in a Desert–Oasis Area,” in Plants, 2024, vol.13, no.1, doi: https://doi.org/10.3390/plants13010144
[23] N. Puppala, *et al.* “Sustaining yield and nutritional quality of peanuts in harsh environments: Physiological and molecular basis of drought and heat stress tolerance,” in Frontiers in Genetics, 2023, vol.14, doi: https://doi.org/10.3389/fgene.2023.1121462
[24] S. Asa’a, *et al.* “A multidisciplinary view on agrivoltaics: Future of energy and agriculture,” in Renewable and Sustainable Energy Reviews, 2024, vol.200, doi: https://doi.org/10.1016/j.rser.2024.114515
[25] M. Junko. “Japan Next-Generation Farmers Cultivate Crops and Solar Energy”, 2013, https://www.renewableenergyworld.com/solar/japan-next-generation-farmers-cultivate-agriculture-and-solar-energy/#gref (February 20th, 2025)
[26] L. Jiufu, *et al.* “The Early Effects of an Agrivoltaic System within a Different Crop Cultivation on Soil Quality in Dry–Hot Valley Eco-Fragile Areas,” in Agronomy., 2024, vol.14, no.3, doi: https://doi.org/10.3390/agronomy14030584
[27] Z. Fangxin, *et al.* “Large-scale and cost-efficient agrivoltaics system by spectral separation,” in iScience. 2023, vol.26, doi: https://doi.org/10.1016/j.isci.2023.108129
[28] F. S. N. Augusto. *et al*. “Influência do sombreamento sobre o crescimento do amendoim,” in XI Jornada de ensino, pesquisa e extensão, 2011, https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/907494/1/InfluenciadosombreamentosobreocrescimentodoamendoimJEPEX2011.pdf (February 20th, 2025)
[29] S. B. Adjahossou, *et al*. “Ecophysiological responses of peanut (Arachis hypogea) to shading due to maize (Zea mays) in intercropping systems,” in Cameroon Journal of Experimental Biology, 2008, vol.04, no.01, pp. 29-38, doi: https://doi.org/10.4314/cajeb.v4i1.37972