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Deploying Agrivoltaics in Sub-Saharan Africa: A Sustainable Pathway Towards Energy-Food Security-Challenges and Opportunities: A Review

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ABSTRACT Agrivoltaics (APV) offer an innovative solution to the pressing energy and food security challenges in Sub-Saharan Africa (SSA). Over 600 million people in this region lack access to energy, and food insecurity remains pervasive. By combining photovoltaic (PV) systems with agricultural production, APV optimizes land-use efficiency, enabling concurrent renewable energy generation and enhancing agricultural productivity. This review critically evaluates the potential of APV systems to address these dual challenges, focusing on SSA's unique socioeconomic and environmental contexts. Key findings highlight the APV's ability to mitigate agricultural constraints, such as water scarcity and climate variability, while providing decentralized energy solutions to rural communities. The analysis emphasizes strategic APV design considerations, including panel height, spacing, and crop compatibility, which are essential for optimizing energy and crop yields. However, challenges such as high initial costs, limited technical capacity, and sociocultural acceptance pose significant barriers to its widespread adoption. This review discusses policy recommendations for addressing these barriers, including financial incentives, technology transfer frameworks, and stakeholder engagement strategies. The novelty of this work lies in its tailored approach to SSA, integrating evidence from global APV case studies and proposing localized implementation strategies that align with the region's development priorities. This study advances the understanding of APV as a pathway to achieving Sustainable Development Goals (SDGs) in SSA by offering a dual-purpose model for energy access and food security. Overcoming adoption barriers through innovative governance, research, and community engagement will be pivotal to unlocking the transformative potential of APV in SSA's energy-food landscape.

INDEX TERMS Solar Energy, Agrivoltaics, PV Plants, Sub-Saharan Africa, Sustainable Development Goals

I. INTRODUCTION

Sub-Saharan Africa (SSA) confronts the interlinked challenges of energy poverty, food insecurity, and climate change [1], [2], [3], with over 600 million people lacking reliable access to energy [4] and agriculture, and nearly 60% of the population being vulnerable to erratic rainfall, land degradation, and limited technological advancement [5]. These overlapping crises not only exacerbate poverty and limit economic opportunities but also pose significant barriers to achieving key Sustainable Development Goals

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(SDGs) [5], [6], [7]. Integrated solutions that simultaneously address energy generation, agricultural productivity, and environmental sustainability are essential for long-term development of the region. Agrivoltaics (APV), the dual use of land for photovoltaic (PV) energy generation and agricultural production, offers a promising pathway for reconciling these challenges. By enhancing land-use efficiency, APV systems provide decentralized, clean electricity, while supporting agricultural resilience [8], [9]. Globally, APV have demonstrated substantial benefits, including improved crop yields, increased water-use efficiency, and enhanced renewable energy generation [10], [11], [12]. However, deploying APV in SSA entails unique challenges owing to the region's distinct climatic, socioeconomic, and infrastructural constraints. Limited research has critically analysed the feasibility and adaptability of APV systems to these diverse contexts [1], [13], [14].

The novelty of this study lies in its tailored approach to SSA, integrating evidence from global APV case studies, such as Kenya's Malindi Solar Plant and Ghana's solar-hydro hybrid projects, with localized implementation strategies that align with the SSA region's development priorities. This review advances the understanding of APV as a pathway toward achieving the SDGs in SSA by offering a dual-purpose model for enhancing both energy access and food security. In this review, key design parameters such as the panel tilt angle, height, and spacing are rigorously examined. For instance, the optimal tilt angle, calculated using $\theta_t = \emptyset + \beta$ where $\emptyset$ denotes latitude and β an adjustment angle for seasonal variation, is critical for maximizing irradiance capture while minimizing crop shading. Furthermore, partial shading—a common challenge in APV installations due to dynamic crop growth and varying sun angles—can induce multiple local power maxima, thereby complicating maximum power point tracking (MPPT) [15]. Recent studies [15], [16], [17] have demonstrated that dynamic MPPT algorithms, which leverage iterative voltage and current sampling for real-time adaptation, are essential for reliably extracting the maximum power under such conditions.

This review also presents a comprehensive socioeconomic evaluation of APV in SSA. It examines crop-specific considerations, policy barriers, and financial instruments, including concrete fiscal mechanisms such as feed-in tariffs (FITs) tailored for agrivoltaics, to support local and scalable APV solutions. By critically analysing key technical design elements alongside policy frameworks and community acceptance factors, this study provides a practical roadmap for leveraging APV systems as a decentralized, sustainable development model. The opportunities presented here aim to stimulate local investment, promote climate resilience, and facilitate rural electrification in SSA, thereby offering a transformative solution to the region's pursuit of sustainable development.

II. LITERATURE REVIEW

A. AGRIVOLTAICS CONCEPT

The term 'Agrivoltaic' (APV) first appeared in the 1980s [18]. According to [18] and [16], the attribution of the term APV is ascribed to Adolf Goetzberger of the Fraunhofer Institute, who conceptualized the dual use of arable land for both agricultural and solar energy purposes. As noted in Reference [18], Goetzberger understood the saturation level of light in plants and recognized that any additional light beyond this saturation point does not enhance photosynthesis [18]. Consequently, it was considered unnecessary to maintain large open spaces above plants when these areas could accommodate solar panels [16], [18], [19]. The installation of solar panels above crops should be executed in a manner that allows the crops to assimilate the optimal amount of light required for effective photosynthesis [13], [18], [19]. Although these systems remain the subject of extensive research to determine their full potential, three APV systems have been identified, as shown in Figure 1. The first system consists of arranging solar arrays with interspaces among the crops to be cultivated [18], [19]. In the second system, elevated solar arrays ensure adequate spacing for light penetration into the crops [19].

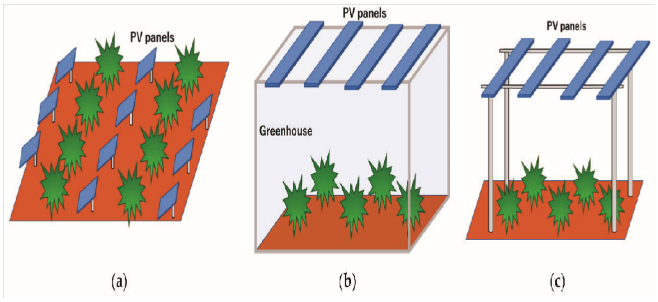

FIGURE 1. Three types of APV systems: (a) crops grown in the area between PV panels, (b) a PV greenhouse, and (c) a stilt-mounted system. Redrawn from [20] **.**

Additionally, the greenhouse solar array features PV cells positioned above the greenhouse to fully enclose crops while allowing moderate light [10], [18], [19]. All three APV systems aim to optimize the solar energy absorption by both solar panels and crops. As elucidated by [16], [20], [21], the primary consideration in implementing APV systems is the tilt angle of the solar panels to maximize light capture by the panels and penetration into the crops [20], [22]. Furthermore, factors including the type of crop cultivated, solar availability in the location, and height of the panels are pertinent to the deployment of APV systems [22], [23].

B. DESIGNING APV SYSTEMS

The design of an APV presents challenges in the absence of adequate engineering expertise [18]. As reported in [18], three distinct APV designs have been formulated and implemented in various contexts. The most prevalent of these designs involves the installation of fixed solar panels on greenhouses as well as between or above open fields of crops [16], [18]. The intensity and efficiency of the field panels can be modified by increasing the number of panels per unit area or adjusting the inclination of the panels to optimize the absorption of solar radiation [18]. The tilt angle (θ_t) of the solar panels is a pivotal factor influencing the quantity of solar radiation captured by the panels and the extent of shading cast on crops [18], [19]. The optimal tilt angle for a specific location can be calculated using the following formula[16]:

$$\theta_t = \emptyset + \beta \quad (1)$$

where ϕ represents the latitude of the location and β is an adjustment angle based on seasonal variations. For example, regions near the equator in SSA may require minimal seasonal adjustments. Incorporating optimal tilt angles maximizes energy generation and ensures that adequate light reaches the crops below, particularly for shade-tolerant species [16].

MPPT under partial shading conditions is a critical issue that directly affects APV efficiency. However, this critical factor has been addressed less frequently in studies under partial shading conditions, particularly in the SSA region. Partial shading, which is inherent in APV installations owing to crop growth and varying sun angles, leads to non-uniform irradiance across the PV modules. This variability can cause the PV array's power–voltage characteristics to exhibit multiple local maxima, making it difficult for conventional MPPT algorithms to consistently track the true global maximum power point. Recent reviews have demonstrated that advanced dynamic MPPT algorithms are essential under such conditions [15], [17]. These dynamic approaches utilize iterative voltage and current sampling along with adaptive search techniques to constantly adjust the operating point in real time, thereby maximizing energy extraction, even when shading conditions fluctuate.

Integrating such MPPT strategies into APV designs is crucial not only for improving the overall energy yield, but also for ensuring system stability under the dynamic shading patterns typical in agricultural settings. While optimizing the panel tilt for maximum irradiance and minimal crop shading is fundamental to APV design, addressing the challenges of MPPT under partial shading is equally important. The adoption of dynamic MPPT techniques, as recommended by recent studies [15], [17], offers a solution for improving energy generation and system performance in APV deployments.

The initial application of APV systems in Japan has been relatively rare. Reference [19] elucidates how these systems employ a light assembly of panels supported by thin pipes. These configurations are characterized by their light weight and ease of disassembly. Furthermore, the panels can be relocated and adjusted frequently. These adjustments were executed manually, particularly during planting seasons, owing to potential obstructions posed by the presence of farmers [19], [20], [22]. To enhance stability, early APV systems incorporated more substantial spaces between panels, thereby diminishing wind resistance[18]. Advancements in design have subsequently been integrated to bolster the efficacy of APV [7], [20], [24]. For instance, contemporary APVs are equipped with tracking systems that permit the automatic optimization of panel positioning [6], [23]. This tracking technology augments the systems' capabilities for electricity generation and agricultural output without necessarily requiring on-site engineering interventions [23]. Certain companies in France pioneered the development of single-axis tracking systems that can seamlessly adapt to the requirements of plant cultivation [19]. An example is SunR's system, which features an east-west tracking mechanism that integrates weather forecasting, plant growth measurements, and optimization software to establish conducive conditions for plants while maximizing solar energy production [6], [25].

The amount of light available for photosynthesis is another critical consideration in APV design. The percentage of Photosynthetic Adsorption Ratio (PAR) transmitted to crops can be evaluated using Equation (2) [6]

$$PAR_t = \frac{I_t}{I_O} \text{ x } 100 \qquad (2)$$

where I_t is the radiation transmitted through the panels and I_0 is the incident solar radiation. Modern translucent or bifacial panels can be designed to optimize PAR transmission, ensuring that sufficient light reaches crops while maintaining high-energy yields. This is particularly relevant for SSA, where intense sunlight can sometimes exceed the photosynthetic saturation point of the crops [26].

A system developed by the APV utilizes south-facing panels that can be removed through a sliding mechanism. In Switzerland, an enterprise has engineered translucent solar modules that, while remaining static, can concentrate light onto solar cells [18], [20]. This Swiss model can adjust to the requirements of plants, specifically the solar intensity needed at various times of the day [22]. Additionally, Artigianfer has created a greenhouse endowed with solar panels that track the movement of the sun along the east-west axis [6], [27]. This advancement allows the panels to absorb the maximum amount of solar energy throughout the day. Current APV systems frequently employ single- or dual-axis tracking to dynamically optimize panel positioning [23], [25]. Such systems utilize real-time data regarding sunlight direction, and plants need to modulate panel orientation, as evidenced by Sun's east–west tracking mechanisms [6]. By maximizing solar energy capture, these systems also mitigate variability in light distribution to crops, thereby enhancing both energy and agricultural yields [6].

The shading ratio (S_r), which quantifies the fraction of land shaded by solar panels, is another important design parameter [20]

$$S_r = \frac{A_p}{A_t} \quad (3)$$

where A_p is the area covered by the panels, and A_t is the total land area. Proper spacing between panels can mitigate excessive shading, which is critical for sun-loving crops such as maize or wheat. On the other hand, tighter spacing may benefit shade-tolerant crops, such as spinach and lettuce. This flexibility allows APV systems to be tailored to the specific agricultural needs of the SSA regions [22].

Perhaps the latest documented developments in APV system design occurred in 2017 in China. The University of Science and Technology in Hefei conceptualized curved glass panels canvassed with dichroitic polymer films. The design allows the panels to absorb selective wavelengths from the sun (red and blue wavelengths) to scale up plant photosynthesis, instead of burdening plants with the selection process [23], [25]. Moreover, the design concentrates a great deal of solar radiation to boost the electricity generation capacity of curved panels compared with flat panels [23]. The design can also eliminate unwanted shadows, allowing continuous absorption of blue and red wavelengths [25], [28]. In other words, this technology helps plants grow faster by providing the correct light elements necessary for photosynthesis [29]. It also generates more electricity than conventional panels.

A key metric for evaluating the efficiency of APV systems is the Land Equivalent Ratio (LER), which measures the combined productivity of land for energy and agriculture [8].

$$LER = \frac{Crop\ Yield_{APV}}{Crop\ Yield_{conventional}} + \frac{Energy\ Output_{APV}}{Energy\ Output_{conventional}} \quad (4)$$

An LER greater than one indicates that APV systems are more efficient than standalone agricultural or solar systems [30]. For instance, [30]observed that the LER values for certain shade-tolerant crops under APV systems ranged between 1.6 and 1.7, representing a 60-70% improvement in land-use efficiency. Incorporating such metrics provides quantitative evidence supporting the adoption of APV in SSA [26], [30].

Economic considerations such as initial costs, long-term benefits, and return on investment are crucial for the scalability of APV systems. The Net Present Value (NPV) formula is often used to evaluate economic feasibility [19]

$$NPV = \sum_{t=0}^{T} \frac{(R_t - C_t)}{(1+r)^t} \quad (5)$$

where R_t represents the revenue generated, C_t represents the costs, r is the discount rate, and T is the project lifetime. For APV systems in SSA, this equation can help to assess the economic trade-offs between upfront installation costs and long-term gains in energy and agricultural productivity [26].

C. ADVANTAGES OF APV

The dual use of land for energy production and agriculture eliminates competition for scarce land resources and enhances sustainability. Reference [31] showed that the rapid growth of the global population has increased contention over land. Countries require energy for their economies and food for their populations, making competition between these essential needs unavoidable. [32] APV offers a promising solution by enabling dual-use land to meet energy and food demands [7], [12], [32], [33].

Research has shown that APV improves land-use efficiency [7], [34], [35], [36], [37]. Reference [38] found that implementing APV systems can increase land use efficiency by 60% to 70%. This makes APV an attractive option for farmers who can simultaneously generate energy and grow crops. Once installed, these systems remain operational for several years with regular maintenance, allowing farming activities to continue seasonally, while energy production occurs year-round [39], [40].

APV also enhances the economic value of the crop yield [33], [41], [42]. [41] discovered that shade-tolerant crops grown under APV systems, combined with solar-generated electricity, can increase crop value by up to 30% compared with conventional farming [41]. Crops suited to greenhouse environments perform even better under APV [12], [43]. Furthermore, summer crops often thrive in these systems because of the improved sunlight regulation and transmission [42], [43], [44].

Another significant advantage is the creation of a microclimate. References [10], [18] highlight that APV generates localized conditions to sustain food production, even in adverse weather conditions. These systems regulate heat and water flow, ensuring optimal growth conditions. For example, solar panels can shield crops from excessive sunlight while retaining soil moisture, thereby leading to more sustainable farming practices [18], [45], [46].

APV also provide clean, renewable energy that can power core farming operations [47], [48], [49]. References [6], [32] identified key farm activities such as water pumping, crop spraying, harvesting, pest control, and security as energy-intensive tasks. Commercial farms typically rely on expensive, non-renewable energy sources such as diesel and hydroelectric power [31]. By generating electricity from solar panels, farmers can significantly reduce operational costs by adopting cleaner energy alternatives [12], [50]. Solar power, which is free and highly reliable in sunny regions, offers a cost-effective and sustainable solution for powering farm operations.

D. DISADVANTAGES OF APV

Although APV presents promising benefits, it also faces notable challenges. A primary concern is the potential competition between solar panels and crops for sunlight. Critics argue that the shade created by solar panels can reduce sunlight reaching crops during critical growth periods, potentially diminishing yields [6], [37]. As observed by [51] shade-tolerant crops are more suitable for APV systems, but these represent only a small fraction of the crops needed for national food sustainability [14], [52]. For example, wheat, a staple crop grown globally, performs poorly under low light conditions, making it less compatible with APV[14], [53]. However, this challenge can be mitigated by carefully selecting crop types and strategically placing panels to optimize the sunlight distribution [53].

Studies on crop performance in APV systems have yielded mixed results [11], [18], [54]. While some crops, such as lettuce, have shown yields similar to those of conventional farming methods [46], [55], others have experienced significant reductions. A reference [43] study on APV greenhouses revealed a 64% drop in crop yields when roofs were half-covered by solar panels, and an 84% reduction in electricity output [43]. These findings underscore the importance of tailoring system design for specific crops and environments [7], [43]. For instance, elevated panel installations could improve crop production and energy generation compared to greenhouse designs [40].

Economic considerations also pose challenges: the high upfront costs of installing APV systems, including the infrastructure for ploughing, weeding, and managing farms under solar panels, can be prohibitive [12], [40]. Reference [18] research in Germany highlighted annual losses of up to 80,000 per acre for APV investments, attributed to the high costs of installation and maintenance [18], [41]. Mitigation strategies such as government subsidies, low-interest loans, and shared financing models can help alleviate these financial burdens [18]. Additionally, integrating less expensive materials and streamlining system designs may lower farmers' costs [18].

APV systems also require specialized expertise, which many farmers lack [41]. Installing and maintaining solar panels involves complex connections and fixtures that can only be handled by trained professionals [41], [56]. Labor costs for maintenance have increased in some regions, as highlighted in a German study that found a 3% increase in expenses related to panel upkeep [41]. These costs can be mitigated by providing training programs for farmers and local electricians, thereby reducing dependence on external service providers and promoting self-sufficiency [12], [46].

Social and environmental concerns warrant further attention. Large-scale installations can disrupt the aesthetic appeal of landscapes, leading to resistance from the local communities. As noted in [9], the visual impact of solar panels and their potential interference with natural surroundings can spark protests. Cleaning chemicals used for panel maintenance may also leave toxic residues, potentially harming nearby ecosystems [9], [12]. Addressing these issues requires community engagement during project planning and the use of environmentally friendly cleaning solutions to minimize ecological damage [9], [12].

Another concern is the potential health risks associated with the electromagnetic waves emitted by solar panels, although these claims remain primarily unverified[9]. Further research is needed to evaluate APV' long-term social and environmental impacts of APV and develop guidelines to mitigate potential risks.

Although APV faces challenges related to crop compatibility, costs, technical complexity, and social acceptance, these can be addressed through strategic planning, targeted subsidies, technological innovation, and community engagement [18], [45].

E. ENERGY SCARCITY IN SSA

SSA faces critical energy access and reliability challenges that hinder economic growth and social development [42], [48]. According to [57] data from 2022, an estimated 600 million people in the region will lack access to energy, leaving the electrification rate at just 48% despite population growth (see Table 1) [40], [57]. In addition, 83% of the population relies on traditional biomass for cooking, which highlights a significant deficit in access to clean energy sources [40], [46], [57].

TABLE I
THE TOP TEN COUNTRIES IN SSA HAVE THE HIGHEST POPULATION WITHOUT ELECTRICITY (%) AND THE RURAL POPULATION WITHOUT ELECTRICITY (%) [4].

Country	Population without Access to Electricity [%]	Rural Population without Access to Electricity [%]
Burundi	77.2	63.3
Central African Republic	74.9	59.2
Chad	73.9	58.2
Congo, Democratic Republic	73.2	54.9
Angola	72.5	56.8
Comoros	72.5	56.8
Gabon	71.7	50.4
Sudan	71.1	55.4
Mali	68.6	52.8
Eswatini	66.1	50.4

SSA's existing electrical grid infrastructure suffers from reliability issues with frequent and prolonged outages. As a result, over 45% of the industrial and commercial electricity demands are met by costly and polluting diesel generators [40], [57], [58]. Moreover, key sectors, such as transport, industry, and buildings, exhibit extremely low energy access rates of 1%, 26%, and 4%, respectively, significantly impeding economic progress [46].

Geographic disparities have exacerbated this issue. Southern African countries, such as South Africa, Botswana, and Mauritius, show relatively higher electricity access rates, nearing 50%, with 37% of their energy transitioning to renewable sources [42], [46]. In contrast, Central and East African nations face electricity access rates between 17% and 32% and have minimal access to clean cooking fuels [46]. West Africa's situation lies between these extremes, emphasizing uneven progress across the region [46], [59].

Despite progress, the electrification rate in SSA remains insufficient to keep pace with population growth, as illustrated in Figure 2. Innovative solutions, such as APV, present a promising opportunity to address energy and agricultural challenges simultaneously [46], [60].

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The solar energy potential varies across SSA, but many regions receive sufficient sunlight to support APV systems. Southern and Northern Africa have high solar potential, with annual average sunlight exceeding 2,000 kWh/m², whereas East and Central Africa also receive adequate sunlight for such initiatives [46], [59]. Figure 3 highlights the solar irradiation potential across different regions, demonstrating the feasibility of solar-based solutions, such as APV.

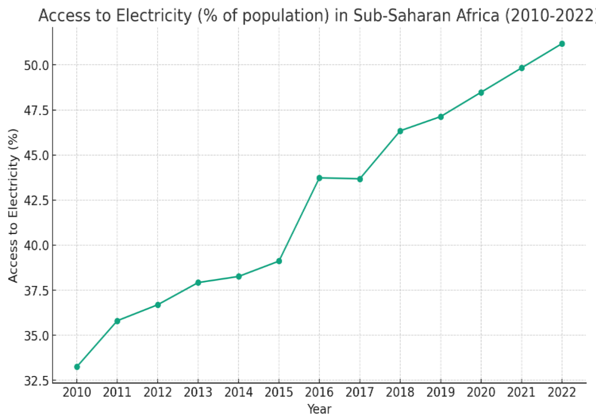

FIGURE 2. Access to electricity (% of the population) in SSA from 2010 to 2022 [61]

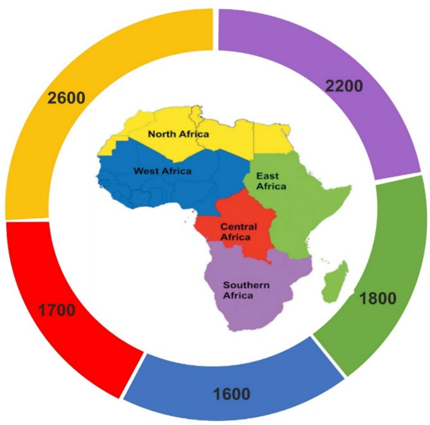

FIGURE 3. Average Annual Solar Irradiation (kWh/m²/year) in the African Regions. Redrawn from [60]

A comprehensive approach involving governments, development agencies, and stakeholders is necessary to address the energy deficit and promote the adoption of APVs in SSA. A critical step is the development of robust policies and regulatory frameworks. These should include incentives such as subsidies or tax breaks to encourage renewable energy investments, particularly for APV projects [59], [62]. Additionally, streamlined approval processes can attract private sector participation by reducing bureaucratic hurdles and ensuring quicker project implementations [18], [19].

Capacity building and education are essential for the success of APV systems. Local communities, farmers, and technicians must be trained to install and maintain these systems to promote local ownership and to create employment opportunities [14], [19]. This approach ensures that the necessary technical expertise is available locally, reducing dependency on external support and enhancing the sustainability of APV initiatives [12], [36], [62]. Targeted deployment strategies should focus on regions with favourable solar potential and significant agricultural activities, such as Southern and Northern Africa [19], [42]. These areas provide optimal conditions for initial implementation, ensuring higher success rates. Gradually, deployment can be expanded to less-accessible regions using portable or modular APV solutions that adapt to varying environmental and infrastructural conditions [36], [42], [48].

Innovative financing models are essential for scaling APV projects. Public-private partnerships (PPPs) and international development funds can be leveraged to secure the required capital [42], [48]. Microloans and pay-as-you-go schemes can also make solar home systems more affordable for rural households, thus enabling wider access and adoption [22]. Integrating APV systems with existing infrastructure such as rural electrification projects can further enhance energy access [22], [48]. Combining these efforts with ongoing grid expansion initiatives allows for efficient use of resources while addressing energy needs in underserved areas [42], [48], [60]. Such integration ensures that the APV complements rather than competes with existing renewable energy efforts [18].

Finally, the implementation of pilot projects with precise monitoring and evaluation frameworks is crucial. These projects should assess the socioeconomic impact of APV systems and provide data-driven insights to refine the deployment strategies [18]. Continuous evaluation ensures that challenges are addressed proactively, and successful approaches are scaled effectively to benefit more communities [40].

By adopting these actionable recommendations, SSA can unlock the full potential of APV, bridging the energy access gap, while promoting sustainable agricultural practices and economic development [6], [46].

The successful implementation of APV can advance progress toward achieving United Nations Sustainable Development Goal 7 by enhancing energy access, food security, and climate resilience in SSA [46]. Case studies, such as Ghana's Bui Power Authority solar-hydro hybrid project and Kenya's Malindi Solar Plant, provide compelling evidence of the potential for renewable energy solutions in the region [58], [59]. In Kenya, the Malindi Solar Plant, a 40 MW installation developed by Globeleq, not only exports substantial power to the national grid but also serves as a catalyst for socioeconomic development in its surrounding communities [63]. Technically, the plant's robust design with high-efficiency PV modules and innovative grid-integration strategies demonstrate how large-scale renewable projects can achieve high performance under diverse climatic conditions [63], [64]. Its ability to reliably deliver energy, even during partial shading events, underscores the importance of integrating advanced MPPT algorithms, as discussed earlier, to optimize yields in dynamically changing environments.

From a socioeconomic perspective, the Malindi Solar Plant has set a benchmark for scalable and sustainable renewable energy projects in SSA [21], [63]. By exporting 40 MW to the national grid, the plant not only alleviates energy poverty but also contributes to national energy security, supports industrial growth, and improves access to electricity for thousands of households [63], [64]. Moreover, the project generated significant local job opportunities during both the construction and operational phases, stimulating economic development in the region [63]. Additionally, the strategic location of the plant and its alignment with government renewable energy policies enable favourable financing conditions and risk mitigation, which are critical factors for scaling up such initiatives across the continent.

The integrated approach demonstrated by the Malindi project, coupling technical innovation with socioeconomic benefits, serves as a blueprint for future APV deployment [21], [63]. By linking optimized energy generation through dynamic MPPT and optimal tilt strategies with resilient agronomic practices, APV systems can be designed to satisfy the dual demands of renewable energy production and sustainable agriculture. Scaling these initiatives across SSA could lead to significant greenhouse gas reduction, enhanced water-use efficiency (through reduced evaporation in shaded areas), and broader improvements in regional climate resilience. Hence, the successful operation of projects such as the Malindi Solar Plant validates that innovative renewable energy solutions, when combined with agrivoltaics, can drive sustainable development and deliver tangible benefits to local communities [21], [63], [65].

F. APV POTENTIAL IN SSA

In rural SSA, more than 600 million people lack stable and affordable energy, highlighting a severe energy access crisis [19], [38], [39]. APV systems provide a promising decentralized solution to address this gap by harnessing abundant solar energy (Figure 4 and Table 2). These systems offer clean energy to off-grid areas, thereby meeting the substantial unmet demand for electricity. The generated electricity can be used for critical agricultural operations such as cold storage, irrigation, and crop processing. Additionally, it can support community-benefiting services such as machinery rentals, which are often inaccessible owing to high costs or lack of infrastructure [19], [40]. By reducing the dependency on diesel-powered generators, APV systems can yield significant cost savings for farmers, thereby enabling sustainable agricultural practices [4], [41].

Beyond energy generation, APV systems have the potential to diversify income streams for farmers by allowing them to sell surplus electricity back to the grid or to local communities. This additional revenue could facilitate the transition to more commercialized farming practices, enabling smallholder farmers to invest in better equipment and farming techniques [33], [67]. Another critical advantage of APV systems is their ability to address water-management challenges. Agriculture consumes 72% of global freshwater resources, a demand that is more acute in sub-Saharan countries due to water scarcity and the exacerbating effects of climate change [43], [44], [45]. APV installations help mitigate water stress by reducing evaporation through the partial shade created by solar panels, with water savings ranging from 20% to 40% [4], [46].

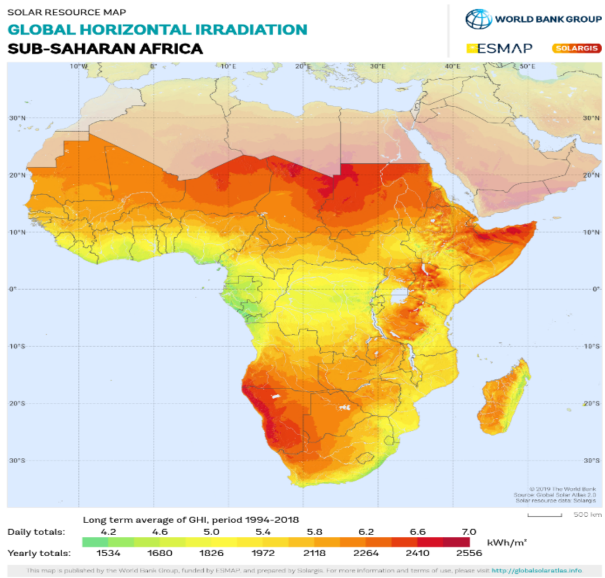

FIGURE 4. Map of the Global Horizontal Irradiance in SSA [66]

TABLE II
SOLAR ENERGY POTENTIAL WITH APV IN KEY SSA REGIONS. DATA FROM [46], [68], [69], [70].

Region	Countries	Solar Irradiation ($kWh/m^2/yr$)	Cropped Area (Million ha)	APV Potential (GWh/yr)
Southern Africa	South Africa, Botswana	2200	12.5	27,500
East Africa	Kenya, Ethiopia, Tanzania	1800	45	81,000
West Africa	Nigeria, Ghana, Ivory Coast, Mali, Gambia	1600	75	120,000
Central Africa	DR Congo, Cameroon, Chad	1700	35	59,500
Total			167.5	288,000

Moreover, the infrastructure of APV systems can be leveraged for rainwater harvesting, thus enhancing the availability of renewable water resources [47], [71]. Harvested rainwater can be used efficiently in precision irrigation systems, providing a sustainable alternative to groundwater extraction, which is often unsustainable in many SSA regions [19], [68]. APV systems also reduce irrigation costs and protect crop yields from extreme weather events by creating controlled microclimate. These microclimates help maintain stable growing conditions, even

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in unfavourable external environments, and support high-value crop production, thereby increasing revenue for farmers [72], [73], [74]. Integrating livestock into APV systems further diversifies farming operations and enhances resilience, enabling farmers to maximize land use while supporting multiple agricultural outputs [49], [56]. The potential of APV systems extends beyond the farm level, addressing key SDGs, such as energy access, water conservation, food security, and climate resilience. As multifunctional systems, they provide a holistic approach to tackling a region's energy and food challenges while promoting environmental sustainability. However, realizing the full potential of APV systems requires comprehensive feasibility assessments tailored to the SSA's diverse socioeconomic and environmental contexts. These assessments must address the technical, financial, social, and policy aspects to ensure that the systems are technically feasible, socially acceptable, and economically viable.

Although APV systems offer immense promise, significant gaps need to be addressed. Maintaining a balance between maximizing energy production and ensuring plant productivity remains a critical challenge [10], [48], [75], [76]. Current designs often prioritize solar energy generation, sometimes at the expense of crop yield and socioeconomic considerations [10], [48]. For example, research has highlighted that the impact of shading and selecting suitable crops under APV systems varies significantly, underscoring the need for region-specific solutions [8], [72]. Additionally, the social and environmental impacts of large-scale installations, such as changes in land use and neighbourhood aesthetics, must be carefully managed to ensure community acceptance and long-term sustainability.

Despite these challenges, APV systems represent a transformative opportunity for SSA [42], [48]. The region's abundant solar resources, innovative APV designs, and tailored deployment strategies can simultaneously address the energy and food security challenges [42], [48]. APV systems can unlock a sustainable path toward economic and environmental resilience in SSA by advancing research and promoting government and stakeholder support [19], [42].

However, the success of APV systems depends heavily on local factors such as agroclimatic conditions, soil types, and crop selection [77], [78], [79]. For example, West Africa, with an average solar irradiation of 1600 kWh/m²/year and a vast cropped area of 75 million hectares, has remarkable APV potential of 120,000 GWh/year [11], [80]. These figures underscore the significant opportunity for SSA to tap into its renewable energy potential, while maintaining and even enhancing agricultural productivity. In addition to improving land-use efficiency, APV systems can also improve agricultural productivity by creating microclimates that reduce water demand and evapotranspiration rates [11], [67]. The shading effect of solar panels helps to conserve soil moisture, particularly in arid regions such as East Africa, which experience high temperatures and limited rainfall [70], [81]. As shown in Table 2, East Africa could harness 81,000 GWh/year from an APV system spread across 45 million hectares of cropland [70], [81]. By combining rainwater harvesting and precision irrigation powered by on-site solar energy, APV systems can further bolster water use efficiency and support sustainable agriculture in areas facing frequent droughts [55], [57], [70].

Moreover, APV systems, which rely entirely on renewable energy, help reduce the carbon footprint of agricultural activities by decreasing the need for fossil fuels [82]. In Central Africa, the APV potential is estimated at 59,500 GWh/year across 35 million hectares of cropped land, despite the region's relatively low solar irradiation levels of 1700 kWh/m²/year [57], [83]. This reinforces the need to adapt APV design and implementation strategies to the specific environmental conditions of each region. With a total cropped area of 167.5 million hectares, SSA can generate 288,000 GWh/year through APV systems, representing a significant opportunity to address food and energy security challenges [55], [82], [83]. However, to fully realize this potential, APV systems must be tailored to each region's local land-use patterns, environmental conditions, and cultural practices.

III. REVIEW METHODOLOGY: SYNTHESIS OF AGRIVOLTAICS IN SSA

This study adopts a narrative and systematic review approach to synthesize the existing body of knowledge on APV, mainly focusing on its potential, challenges, and opportunities in SSA and nearby regions. A narrative review was chosen for its flexibility in synthesizing interdisciplinary research, allowing the integration of findings from diverse studies to provide a comprehensive understanding of APV in SSA.

A. SEARCH STRATEGY

A comprehensive literature search was conducted using Google Scholar, PubMed, Scopus, and the Web of Science to gather relevant studies on APV and its role in enhancing energy and food security in SSA. The search targeted publications from 2000 to 2024, capturing foundational research and recent advances. A combination of Boolean operators and specific keywords such as "Agrivoltaics," "Agriphotovoltaics," "energy-food nexus," "solar energy in agriculture," "dual land-use systems," and "renewable energy in SSA" ensured the inclusion of a diverse range of studies. Literature selection followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, focusing on peer-reviewed journal articles, conference proceedings, and case studies.

The literature was categorized into three key areas to facilitate a structured analysis. Table 3: Technical, Energy, and Agricultural Aspects of APV Systems include studies that explore system design, PV shading effects, bifacial panel optimization, and crop yield responses under different APV configurations. These studies provide insights into the energy generation efficiency, microclimatic influences, and resource management strategies in APV farming.

Table 4: Economic, Environmental, and Policy Considerations in APV Systems presents research assessing the economic viability of APV systems, including cost-benefit analysis, return on investment (ROI), financial risk mitigation, and Levelized Cost of Electricity (LCOE). Additionally, it covers environmental sustainability metrics such as carbon footprint reduction, climate resilience, and Land Equivalent Ratio (LER), which measures land-use efficiency under APV configurations. Policy-focused studies in this section examine government incentives, regulatory frameworks, and strategies for scaling APV adoption in SSA.

Table 5: Social and Community Engagement in APV Systems focuses on stakeholder perspectives, adoption barriers, and the socioeconomic impact of APV. Research in this section highlights community-driven projects, farmer perceptions of APV technology, and the role of policy incentives in encouraging APV adoption. It also explores the broader social and economic benefits of APV systems, including employment generation, food security improvements, and rural electrification.

TABLE III
TECHNICAL, ENERGY, AND AGRICULTURAL ASPECTS OF APV SYSTEMS

Authors	Year	Country	Methodology	Research Focus
[1], [84]	2019	US	Empirical research	APV in drylands
[1], [46], [83], [84]	2024	Global	Theoretical simulation	Estimation of cultivable space in PV installations
[78], [85]	2024	Global	Simulation study	Designing and energy estimation of PV systems
[86], [87], [88], [89]	2022	Global	Multi-scale modelling	Integration of bifacial PVs
[19], [90], [91], [92]	2023	Global	Simulation study	Optimized energy generation
[40], [46], [49], [77], [93]	2024	Global	Conceptual study	Integration of PVs with agricultural tunnels
[8], [10], [18], [56], [78]	2022	Global	Field experiments	Agricultural productivity
[11], [18], [45], [94], [95], [96]	2021	Global	Case studies	Climate-smart agriculture
[11], [57], [92], [97]	2023	Benin	Desk study	Water-Energy-Food-Land (WEFL) needs assessment
[40], [92], [98], [99], [100], [101]	2024	Global	Systematic review	Fruit crop integration

TABLE IV
ECONOMIC, ENVIRONMENTAL, AND POLICY CONSIDERATIONS IN APV SYSTEMS

Authors	Year	Country	Methodology	Research Focus
[2], [3], [31], [102], [103], [104], [105]	2017	India	Techno-economic analysis	APV systems on grape farms
[18], [106], [107]	2021	Germany	Economic framework	FEADPLUS framework development
[95], [108], [109], [110]	2021	Global	Economic analysis	Financial risk mitigation
[2], [83], [111], [112], [113], [114], [115]	2024	Jordan	Simulation study	Feasibility assessment
[6], [98], [99], [116], [117]	2023	UK	Literature review	Sustainable Development Goals (SDGs)
[3], [41], [77], [118], [119]	2021	Various	Mixed methods	Climate resilience
[119], [120], [121], [122]	2023	Global	Environmental assessment	Environmental impacts
[46], [123], [124], [125]	2024	Global	Remote sensing	Environmental impacts of solar farms
[10], [18], [126], [127], [128]	2023	Global	Literature review	Environmental and energetic impacts
[55], [129], [130]	2021	Global	Policy analysis	Regulatory frameworks
[100], [131], [132], [133]	2022	Global	Policy analysis	Policy frameworks

TABLE V
SOCIAL AND COMMUNITY ENGAGEMENT IN APV SYSTEMS

Authors	Year	Country	Methodology	Research Focus
[1], [3], [9], [84], [92]	2023	Global	Qualitative study	Social acceptance of APV
[2], [19], [22], [70], [81]	2022	Global	Participatory research	Community-based projects
[9], [67], [128], [134], [135]	2023	South Africa	Qualitative study	Farmers' perspectives on APV
[11],[52], [82],[83], [122], [125]	2024	SSA	Participatory approach	Stakeholder engagement
[10],[11], [17], [20],[21], [28], [95]	2022	Global	Field experiments	Renewable energy integration
[37], [136], [137]	2024	Global	Case study	Hybrid systems operation

By structuring the literature review into these three sections, this study provides a comprehensive, evidence-based evaluation of the technical, economic, and social dimensions of APV deployment in SSA. This categorization supports a systematic assessment of challenges and opportunities and provides a solid foundation for future research and policy recommendations. To ensure the

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relevance and reliability of the literature, the search was limited to peer-reviewed journal articles, conference proceedings, and reports from reputable institutions. Gray literature, including government reports and unpublished studies, was excluded to maintain a rigorous standard of evidence. Again, the references cited in the key studies were manually reviewed to identify additional relevant works that may have been missed in the initial search.

B. INCLUSION AND EXCLUSION CRITERIA

Carefully defined inclusion and exclusion criteria were used to ensure the relevance and rigor of the review. Studies were included to determine whether they addressed APV, solar energy, or dual land-use systems, focusing on SSA or regions with comparable socioeconomic and climatic conditions. Priority was given to analysing APV's impact of APVs on energy generation, food security, land-use efficiency, and socioeconomic factors. Only English-language publications were considered for consistency in the analysis.

Conversely, studies focusing exclusively on PV technology without agricultural integration were excluded as they fell outside the scope of this review. Research unrelated to SSA or lacking transferability to similar socioeconomic and climatic contexts was also omitted. These criteria ensured that the review focused on exploring the nexus between energy and food security through the lens of APV in SSA.

C. DATA EXTRACTION AND ANALYSIS

Carefully defined inclusion and exclusion criteria were used to ensure the relevance and rigor of the review. Studies were included to determine whether they addressed APV, solar energy, or dual land-use systems, focusing on SSA or regions with comparable socioeconomic and climatic conditions. Priority was given to analysing APV's impact of APVs on energy generation, food security, land-use efficiency, and socioeconomic factors. Only English-language publications were considered for consistency in the analysis.

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D. THEMES AND TRENDS IN APV RESEARCH

Understanding the evolution of APV research requires in-depth exploration of its geographical reach, temporal progression, and thematic focus [92]. By analysing patterns and trends in the literature, this section provides insights into the field's development and contributions to global sustainability efforts. Visual tools such as heat maps, bar charts, and keyword analyses offer a comprehensive perspective, highlighting areas of growth, regional disparities, and recurring themes. This examination not only underscores progress, but also identifies gaps and opportunities for future research, particularly in regions and topics that remain underexplored.

1. Geographical Patterns in Research

The highlights of countries where APV research is most active are shown in Figure 5, revealing significant contributions from regions such as Europe, Asia, and North America. Sub-Saharan African (SSA) countries are underrepresented, emphasizing the need for expanded research efforts in these areas to address local challenges.

The bar chart (Figure 5) complements this analysis by providing a detailed frequency distribution of the countries covered in the search. It illustrates the dominance of certain nations in APV research, with a significant skew towards countries such as Germany and India [50], [98], [138]. The findings reveal a disparity in research activity across regions and indicate opportunities for future studies to focus on underrepresented areas, particularly in SSA.

2. Temporal Evolution of APV Literature

The annual publication trend indicates a sharp rise in APV research post-2015, reflecting growing global awareness of dual land-use systems and their role in sustainable energy and food production [98], [99]. The growth of APV research is evident in the distribution of publications over the years (Figure 6). This figure highlights the number of papers published annually from 2009 to 2024, demonstrating the increasing attention that this field has received over time [50], [98], [99].

The early years (2009–2018) saw limited activity with only a handful of publications. This reflects the nascent stage of APV as a research field in which the concept was primarily theoretical or undergoing initial explorations. From 2019 onward, the pace of publications began to accelerate, with a significant surge in 2021 and a peak in 2022, with over 30 papers published [98], [99].

This spike coincides with the growing global interest in renewable energy solutions and sustainable agriculture, driven by the urgent need to combat climate change and optimize land-use practices. The subsequent decline in 2023 and 2024 may be attributed to shifts in funding priorities or maturity of the field, reaching a plateau in specific research areas [98], [99].

Figure 6 clearly represents the expanding academic focus on APV, emphasizing its growing relevance in the global sustainability agenda. It also suggests the potential for future growth, particularly in unexplored regions, and interdisciplinary applications, which remain fertile ground for innovation and research.

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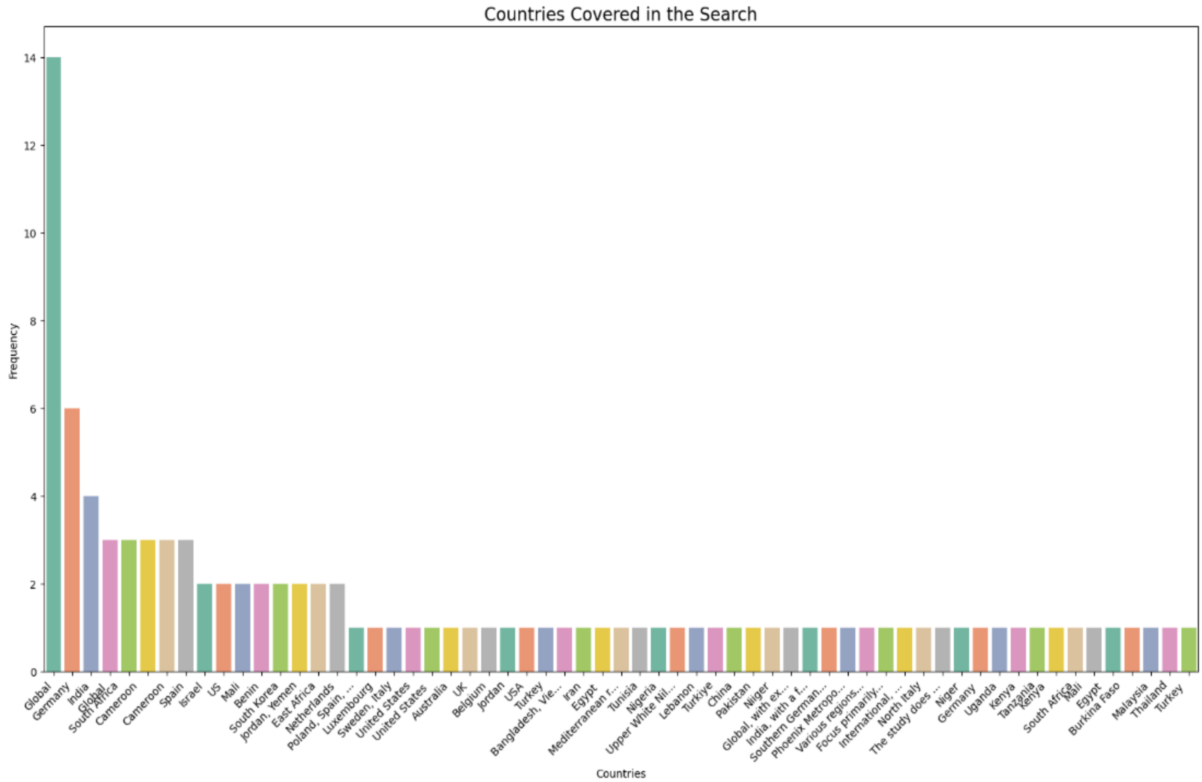

Figure 5: **Countries Covered in the Search**

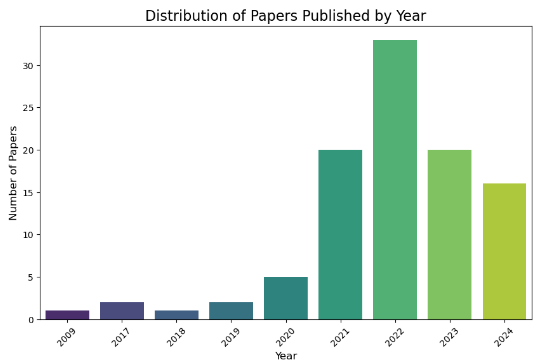

Figure 6: **Publication Trends in APV Research**

3. Recurring Keywords and Research Focus Areas The analysis of recurring keywords in APV literature reveals the dominant focus areas within the field, offering insights into the prevailing themes and gaps. Figure 7 presents the top 20 most frequently occurring terms in the literature, reflecting the multifaceted nature of the APV research. The term "energy" is the most frequently mentioned, highlighting the centrality of energy generation within the APV paradigm. This is closely followed by "agrivoltaics" and "systems," emphasizing the interdisciplinary and systemic approach to integrating solar energy with agricultural production. Words such as "efficiency," "renewable," and "sustainable" underscore the emphasis on optimizing land use for dual purposes while addressing climate and sustainability goals.

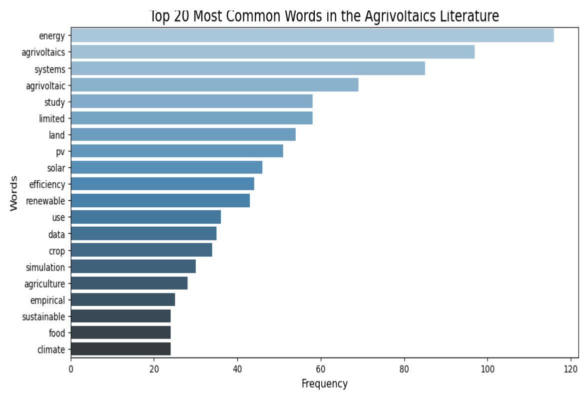

Figure 7: **Top 20 Most Common Words in the APV Literature**

Interestingly, terms such as crop," "simulation," and "empirical" reflect the growing interest in quantifying agronomic and economic outcomes through modelling and field-based studies [12], [36], [50], [98], [99], [138], [139]. However, the relatively lower frequency of terms like "climate" and "food" suggests that while sustainability is a recurring theme, there is room for deeper exploration of APV's potential in mitigating food security challenges in climate-vulnerable regions like SSA.

APV research encompasses diverse themes, as illustrated in Figure 8. This figure highlights the proportional distribution of papers across five primary areas: Energy &

Systems, Agriculture, Efficiency & Sustainability, Data & Research, and Environmental Factors.

Most studies, accounting for 66.2%, concentrated on Energy & Systems, emphasizing optimizing PV technologies and their integration with agricultural practices. This focus reflects the foundational aim of APV: to generate renewable energy while maximizing land use efficiency [138].

Agriculture followed at 19.6%, exploring the impacts of shading, soil moisture retention, and crop yield under PV installations. These studies aimed to understand the synergies between energy generation and agricultural productivity.

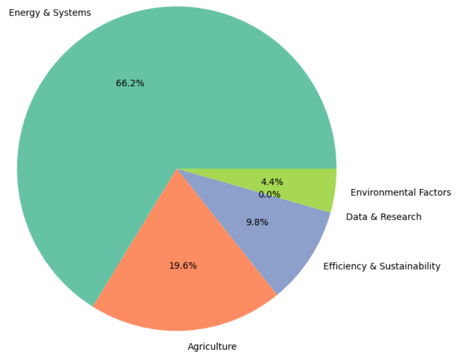

Figure 8: Research Focus Areas in APV by Percentage distribution.

Research addressing Efficiency & Sustainability (9.8%) seeks to balance resource use, reduce environmental impacts, and optimize the overall system performance. Data and research (4.4%) and Environmental Factors (0.0%) appeared as less represented areas, potentially pointing to opportunities for further exploration, such as detailed environmental assessments and better data analytics for system improvement [2], [50], [98].

Figure 8 provides a visual representation of how research efforts are distributed, shedding light on current priorities and gaps in APV research. This helps to identify areas for future investigation to achieve a more holistic understanding of the implications of the system.

The visualizations provide a clear snapshot of the field's research priorities, aligning with the overarching themes of the energy-food nexus, land-use efficiency, and sustainability in APV. This highlights the need to expand research efforts toward underrepresented topics, particularly concerning socioeconomic implications and localized studies in SSA.

E. LIMITATIONS

While this review provides a detailed exploration of APV systems, several limitations affect their comprehensiveness and applicability, particularly in the context of underrepresented regions such as SSA. The exclusion of unpublished studies and grey literature, such as government reports, NGO publications, and industry white papers, may have omitted critical practical insights and undocumented innovations. These sources often capture on-the-ground realities, offering valuable perspectives on localized challenges and solutions for adopting APV systems in diverse socioeconomic and environmental contexts [50], [98], [99].

While offering rich qualitative analysis, the narrative synthesis employed in this review lacks the statistical rigor of meta-analytical techniques. This limitation constrains the ability to generate precise metrics and comparisons for key APV impacts such as land-use efficiency, energy generation, and crop productivity. Integrating quantitative methods in future research could provide more robust generalizations and enhance the validity of the findings across varying contexts.

Furthermore, reliance on English-language publications introduces linguistic bias, potentially excluding critical research from francophones, lusophones, and other non-English-speaking regions in SSA. These regions may provide valuable insights into the deployment and performance of APV systems, which are integral to a holistic understanding of their applicability.

Despite these limitations, this review adopts a thematic approach that effectively synthesizes existing academic knowledge and offers actionable insights and policy recommendations. This highlights critical gaps in research and practice, underscoring the importance of addressing challenges specific to SSA. Future research should aim to overcome these limitations by incorporating grey literature, employing quantitative analyses, and exploring multilingual sources. Such efforts would ensure a more inclusive and comprehensive understanding of the potential and limitations of APV systems, particularly in regions that benefit the most from their adoption.

IV. DISCUSSION AND ANALYSIS

A. CROP-SPECIFIC APV CONSIDERATIONS

APV systems offer immense adaptability to different crop types, making them a promising solution for land use optimization and agricultural productivity in SSA[93]. By reducing heat stress and conserving soil moisture under shaded conditions, APV systems can support staple crops, such as cassava, maize, and millet, which dominate the region's agriculture [140], [141]. For example, cassava grown in West Africa has shown resilience to partial shading, with reduced heat stress contributing to improved tuber quality and soil moisture retention. Similarly, maise and millet, which are common in arid and semi-arid regions, benefit from moderate temperatures and reduced water loss under solar panel arrays, enhancing their yields during critical growth stages [18], [142], [143].

APV configurations, such as adjustable panel heights and rotational systems, have been proposed to cater to the SSA's high-demand crops. Adjustable panel heights are particularly advantageous for crops with high canopies, such as bananas and vineyards, because they facilitate pest control, improve airflow, and accommodate harvesting machinery [94], [110], [130], [144]. Rotational APV systems that align with seasonal crop rotations or intercropping practices can

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maximize land-use efficiency and adapt to diverse farming systems across SSA agro-climatic zones (see Figure 9) [75], [86].

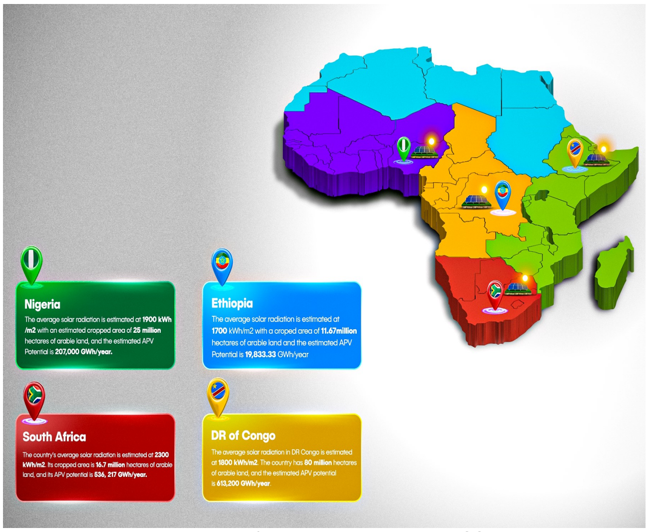

Figure 9. **Regional Potential for APV Deployment in SSA**

Advances in PV technology, including bifacial panels and semi-transparent modules, are pivotal for enhancing agricultural productivity in APV systems [12], [145]. Bifacial panels can capture sunlight reflected from the ground, thereby increasing energy efficiency without significantly altering the light transmitted to crops [7], [86], [88]. Semi-transparent modules optimize the transmission of Photosynthetically Active Radiation (PAR), which is critical for crop growth [6], [117], [146]. For instance, experimental studies have shown that lettuce grown under semi-transparent modules exhibits a 20% increase in leaf surface area compared to conventional open-field cultivation [18], [45]. These innovations are particularly relevant in SSA's sun-rich regions, where balancing light availability for crops and energy generation is vital. Table 6 highlights examples of shade-tolerant crops for APV in SSA and explains why a better understanding of these crop dynamics is pivotal before the deployment of APV.

The LER is a critical metric for assessing the efficiency and sustainability of APV systems, especially in SSA, where land availability is often a limiting factor [94], [129]. LER quantifies land-use efficiency by comparing the total yield of dual-purpose production (electricity and crop yield) with the standalone crop yield [94]. A high LER value (>1) indicates that the APV systems are more productive than traditional agricultural methods [94].

Studies [10], [18] have reported LER values ranging from 1.5 to 1.8 for crops such as potatoes, winter wheat, celeriac, and clover grass, demonstrating the enhanced productivity of APV systems. In SSA, where abundant sunlight and diverse agricultural conditions prevail, tailored APV designs can achieve similar or higher LERs. However, these designs must consider factors such as PV module type, crop variety, mounting structure, and inter-row spacing to optimize the performance.

TABLE VI
EXAMPLES OF SHADE TOLERANT CROPS FOR APV IN SSA [18], [110], [143], [144], [147], [148], [149], [150], [151]

Crop Name	Suitable Soil	Height (cm)	Special Features	Countries Grown
Spinach	Well-drained, fertile soil (pH 6-7)	30-60	Tolerates low temperatures, thrives with partial shade	South Africa, Kenya, Zambia
Lettuce	Organic soil, sandy/loamy (pH 6-6.8)	15-25	Grows well in cooler temperatures and partial shade	Rwanda, DR Congo, South Africa
Cabbage	Moist, fertile soil (pH 6-7)	30-60	Thrives in cooler climates; requires sufficient watering	Kenya, Nigeria, etc
Rice	Clay-loam soil (pH 4.5-8.0)	80-100	Adaptable to waterlogged or upland fields	Uganda, Tanzania, Senegal
Maise	Fertile, loamy soil (pH 5.5-6.5)	100-200	Grows in a wide range of climates	Kenya, Uganda, Nigeria
Tomato	Well-drained, loamy soil (pH 6-6.8)	40-120	Requires warm temperatures; tolerates partial shade	Kenya, South Africa
Cabbage Lettuce	Fertile, loamy soil (pH 6-7)	50-60	Thrives in cooler temperatures	Rwanda, DRC
Sweet Potato	Loamy soil (pH 5-6.5)	30-60	Adapts to poor soils and tolerates partial shade	Nigeria, Ghana, Kenya
Sunflower	Well-drained loamy soil (pH 6.5-7.5)	100-200	Grown for edible oil and animal feed	Tanzania, Kenya

One challenge in maximizing the LER in SSA is balancing the trade-off between PV panel density and crop yield. Overhead APV systems, for example, may require 20–40% more land than ground-mounted PV systems, potentially reducing the available crop space. Nevertheless, the increased electricity generation may offset this drawback and improve overall land productivity [56], [92].

In SSA mixed farming systems, crop selection is pivotal for determining the LER. Staple crops, such as maise, sorghum, millet, yam, and cassava, exhibit varying responses to shading from PV modules [42], [48]. Designing systems to accommodate agricultural machinery without damaging the APV infrastructure, such as by increasing the height of PV panels, can further optimize the LER [6], [117]. Strategic planning and region-specific designs are essential for APV systems to effectively balance agricultural, and energy demands while boosting farmers' income.

The efficiency of APV systems can be quantitatively assessed using the Land Equivalent Ratio (LER) formula in [8]. A case in point, a hypothetical APV system in Nigeria generating 10 GWh/year from a 5-hectare installation, combined with a crop yield of 50 tonnes /year, would result in:

$$LER = \frac{10}{5} + \frac{50}{5} = 12$$

The LER 1.2 (metric conversion for hectares and tonnes (LER) demonstrated a significant improvement in land-use efficiency compared to standalone agricultural or solar installations, reinforcing the potential of APV systems in SSA [11], [94].

SSA's diverse agro-climatic zones of SSA demand region-specific APV designs. For example, cassava, a staple in West Africa, thrives under reduced sunlight, making it suitable for partial shading by APV systems. In contrast, coffee in East Africa benefits from APV configurations that protect against direct sunlight and reduce heat-induced stress on crops [70], [81]. Additionally, viticulture in Southern Africa, particularly for wine production, can leverage APV systems to regulate microclimates and prevent sunburn and early grape ripening, thereby preserving crop quality under high-temperature conditions [18], [48].

To optimize APV systems for SSA, controlled plot evaluations are essential for assessing the impact of shading and microclimates on region-specific crops. Such an assessment should integrate advancements in PV technology and insights from mathematical modelling to refine configurations tailored to SSA's unique agricultural and environmental needs [70], [81], [88]. Data collection and research will ensure that APV systems align with local farming practices and a region's renewable energy goals [45], [81].

This crop-focused approach underscores the transformative potential of APV systems to harmonize energy generation and agricultural productivity, providing a sustainable pathway to address SSA's intertwined food and energy challenges.

B. ENERGY GENERATION POTENTIAL

APV systems in SSA present a transformative approach to address the dual challenges of energy and food security. By leveraging the region's abundant solar resources, as shown in Figures 4 and 9, APV systems can generate significant amounts of renewable energy while supporting sustainable agricultural practices [13], [16], [152]. With solar energy yields ranging from 1,500 to 2,200 kWh per kWp annually, depending on the configuration and panel efficiency, the potential for energy generation across SSA is immense [11], [67].

The energy output of an APV system can be modelled using the Equation (6) [153]:

$$G_t = G_b\,(R_b) + G_d\,(R_d) + G_r\,(G_r) \qquad (6)$$

where G_b, G_d, and G_r denote the beam, diffuse, and reflected solar irradiance, respectively, while R_b, R_d, and R_r account for view factors that are dependent on panel orientation. By applying this equation, designers can predict the energy output of panels and assess the availability of light for crops, which is crucial for ensuring agricultural productivity.

This demonstrates the immense energy generation capacity of APV systems, particularly in high-irradiance regions, such as Southern Africa [67]. APV systems significantly improve water use efficiency by reducing evaporation rates under the shade of solar panels [42], [68]. Research indicates that shaded areas can achieve 20–40% water savings, which is particularly crucial for arid regions in SSA [83], [154]. Furthermore, integrating rainwater harvesting systems with APV structures can augment water availability and support precision irrigation for crops such as maize, cassava, and sorghum. By powering these irrigation systems with on-site solar energy, APV systems enhance the resilience of agricultural operations in drought-prone areas, such as East Africa [55], [70].

APV adoption in SSA can also contribute to significant greenhouse gas (GHG) reduction by decreasing reliance on fossil fuels for agricultural operations [14], [46], [55]. Carbon savings were estimated using the following formula [14]:

$$CO_{2\ Savings} = Energy\ Yield\ x\ Emmision\ Factor \quad (7)$$

This emphasises the environmental benefits of transitioning to renewable energy through APV systems [152], [155].

Another key metric for determining the energy generation potential in the SSA is the optimal tilt angle (θ_t). The optimal tilt angle (θ_t) for the solar panels in the SSA can be evaluated using Equation (1). For example, in SSA, regions close to the equator may require minimal seasonal adjustment. Incorporating optimal tilt angles maximizes energy generation and ensures that adequate light reaches the crops below, particularly for shade-tolerant species. Optimizing the panel tilt is critical not only for maximizing the incident irradiance but also for mitigating the adverse shading effects that complicate MPPT. However, one critical challenge that often arises in APV systems is the impact of partial shading on PV panels. Partial shading, which is common in APV installations owing to crop growth and varying sun angles, causes non-uniform irradiance conditions, complicating MPPT. In such regions, standard MPPT algorithms may fail to consistently identify the actual maximum power point, thereby reducing the energy yield. Recent studies [15], [17] have demonstrated that advanced dynamic MPPT algorithms are essential in these scenarios, as they can adapt in real time to rapidly changing shading patterns. These algorithms not only improve the overall energy generation from PV arrays but also ensure that the performance of the system remains stable under varying agroclimatic conditions.

Adjusting the tilt angle ensures maximum energy capture throughout the year, particularly in high-irradiance regions like Southern and East Africa [1], [9], [10], [80]; Table 7 showcases the potential for APV systems across SSA.

TABLE VII
REGIONAL ENERGY DISTRIBUTION

Region	Cropped Area (Mha)	Solar Irradiation (kWh/m²/year)	Energy Potential (GWh/year)
East Africa	45	1,800	81,000
West Africa	75	1,600	120,000
Central Africa	35	1,700	59,500
Southern Africa	12.5	2,200	27,500

These figures underscore SSA's immense potential of SSA for renewable energy generation using APV systems, paving the way for sustainable development [55], [70].

To fully harness the potential of APV systems, SSA must prioritize localized pilot projects, refine APV designs to align with regional agro-climatic conditions, and develop policies that incentivize adoption. Integrating advanced technologies such as bifacial panels and organic PVs will further enhance energy and crop productivity and drive sustainable regional growth [156], [157].

C. LAND-USE EFFICIENCY AND APV DEPLOYMENT IN SSA

APV systems significantly enhance land use efficiency by facilitating dual-purpose utilization of arable land for food and energy production [6], [102]. Studies in regions such as Europe and Japan have reported LUE improvements of 60–80% compared to traditional agriculture or standalone solar installations [113], [158]. These findings suggest immense potential for SSA, where competing demand for land often limits productivity. By optimizing design factors, such as spacing and crop compatibility, APV systems could potentially boost the total output per unit of land by up to 70% [6], [102]. However, further empirical validation under SSA-specific conditions is needed.

Studies that [18], [129] offer a detailed classification of APV systems could serve as a blueprint for SSA to maximize agricultural output and renewable energy generation simultaneously. This classification was based on the spatial arrangement of crops with PV modules. For example, some designs use inter-row spaces and elevated PV modules to cultivate crops that thrive in partial shade (Figures 10A and 10B). Such configurations are particularly beneficial for SSA where excessive solar radiation can hinder certain agricultural activities.

Moreover, using semi-transparent PV modules (Figure 10C), as discussed in [129], allows partial solar radiation to pass through, benefiting crops and soil, while simultaneously generating electricity. This approach aligns with the SSA's high solar potential, offering a sustainable way to balance energy and agricultural needs. Further innovations include hybrid greenhouse setups with conventional PV modules that provide controlled shading (Figure 10D) or semi-transparent modules that enhance light distribution for optimized crop growth (Figure 10E). These methods are particularly advantageous for controlled agricultural environments in SSA, where maximizing productivity is critical.

Integrating hydroponics with APV systems (Figure 10F), as proposed in [129], holds promise for urban or soil-scarce areas in SSA. Utilizing water from PV module cleaning for hydroponic farming exemplifies resource efficiency, while addressing water conservation challenges in the region. The adaptability of APV configurations shows their potential to meet diverse agricultural and energy needs across the SSA.

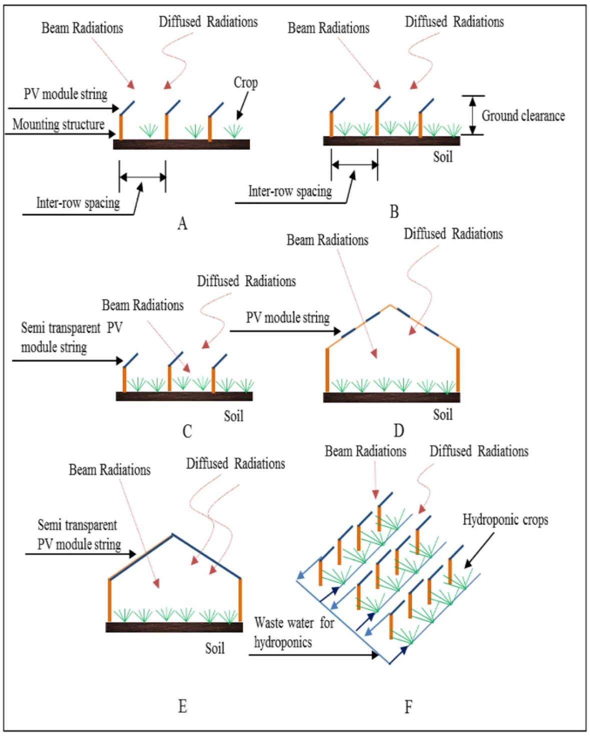

Figure 10. Different kinds of APV systems can be identified. Adapted from [18].

An essential design parameter for APV systems, particularly relevant to SSA, is the shading ratio (RShade), which is mathematically expressed as[126]:

$$R_{shade} = \frac{Maximum\ area\ shaded\ by\ PV\ modules}{Total\ land\ area\ of\ APV\ plant} \quad (8)$$

This parameter is critical for balancing energy generation and agricultural productivity, especially in resource-constrained regions such as SSA. According to[129], [159], bifacial PV modules with a shading ratio of approximately 21.3% have been identified as the most profitable configuration for different regions and can be adapted for SSA-like conditions. However, the impact of shading is not uniform and varies depending on several factors, including the seasonal solar altitude, PV module orientation, tilt angle, and inter-row spacing [89], [126]. Table 8 was used to elucidate the impact of shading ratio (Rshade) on crop and energy yields, and some examples of crop responses to shading are highlighted in Table 9. Crops grown under moderate shading, defined as a 15–40% reduction in sunlight, can achieve yields ranging from 81% to 99% of their open-field potential, provided that light availability during critical growth stages is sufficient [126], [127]. For instance, a 20% reduction in solar radiation may lead to a proportional decline in the yield of staple crops such as rice [126], [160]. Conversely, shading can sometimes induce physiological adaptations such as increased leaf size, which helps mitigate the adverse effects of reduced light availability by improving water-use efficiency [110], [160], [161].

TABLE VIII
IMPACT OF SHADING RATIO (RSHADE) ON CROP AND ENERGY YIELDS [11], [18], [125]

Shading Ratio (%)	Sunlight Availability (%)	Crop Yield (% of Open-Field)	Energy Yield (kWh/m²/year)
10	90	95–99	1800
20	80	85–95	1700
30	70	70–85	1600
40	60	60–75	1500

TABLE IX
EXAMPLE CROP RESPONSES TO SHADING IN SELECTED CROPS [125], [126], [129], [160]

Crop Type	Optimal Shading Ratio (%)	Yield (% of Open-Field)	Details
Maise	15–25	85–95	Moderate impact; shade-tolerant during maturity stages
Sorghum	20–30	80–90	Reduced water stress enhances overall productivity
Rice	10–20	70–85	Sensitive to shading; early growth periods critical
Cassava	20–30	90–95	Physiological adaptations observed under shaded conditions

The current understanding of shading effects in APV systems, particularly in SSA, is limited and often extrapolated from agroforestry studies. A customized APV design tailored to the SSA's specific agro-climatic conditions could help mitigate potential yield losses. SSA faces intertwined food and energy security challenges compounded by a growing population, climate change, and limited arable land. The early deployment of APV systems in SSA demonstrated their potential to address these challenges by integrating food and energy production on the same land. Empirical studies and simulations have [89], [129] [18] revealed that when APV systems are customized by reducing module density, crops can access between 60% and 85% of the sunlight they typically receive under open-field conditions. In SSA, where smallholder farming is prevalent, smaller APV facilities may experience additional benefits from border effects, which allow sunlight to penetrate from the sides, particularly during the early morning and late afternoon hours.

For instance, in a study conducted in a comparable climate with a panel row distance of 3.2 m, reducing the PV module density enabled up to 73% of incoming radiation to reach the plant level [18]. This configuration suggests that crops in SSA under such APV systems could achieve yields comparable to 81–99% of those observed under full sunlight. However, the availability of sufficient light during early growth periods is crucial for yield optimization. Dense shading caused by closely packed PV panels may elicit physiological responses from crops, such as the production of larger leaves, which can partially compensate for reduced sunlight [126], [160].

Figure 11 illustrates the Impact of the Shading Ratio on Crop and Energy Yields. This demonstrates the relationship between shading ratio (%), crop yield (% of open-field yield), and energy yield (kWh/m²/year) in an APV system. This was based on data gathered from previous studies [125], [129]. This visualization highlights how shading ratio changes affect agricultural productivity and energy generation. The blue line with square markers represents the energy yield, which decreased linearly as the shading ratio increased. This trend suggests that higher shading reduces the energy output owing to diminished light exposure on the PV panels. The observed decline emphasizes the sensitivity of energy yield to shading adjustments within the APV framework. The green line with circular markers shows the crop yield, which decreased with increasing shading ratio. However, the decline in crop yield is less steep than that in energy yield, indicating that crops can perform reasonably well under moderate shading conditions. The dashed red line indicates the optimal yield threshold of 70%. This threshold is a critical benchmark for balancing the energy generation and agricultural productivity in APV systems. This underscores the importance of determining the optimal shading ratio to achieve a sustainable equilibrium between these competing objectives [125], [156], [157]. This finding highlights two key insights. First, there is a clear trade-off between energy and crop yields: increasing the shading ratio benefits energy generation and negatively affects crop yield. Therefore, optimizing the shading ratio is essential for balancing these needs. Second, the adaptability of crops under shading is evident, as moderate shading (e.g., 20–30%) allows for significant agricultural productivity [125], [129]. This supports the feasibility of APV systems in regions such as SSA, where resource optimization is critical.

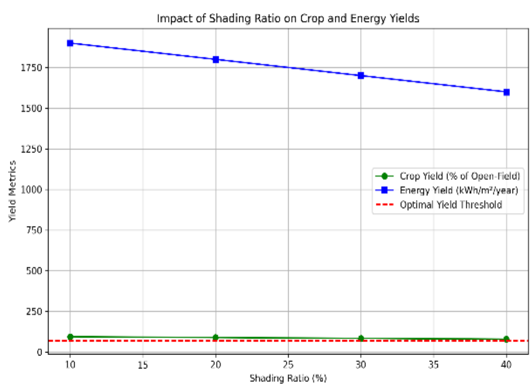

Figure 11: Relationship Between RShade, Crop Yield, and Energy Yield

Figure 12 illustrates the relationship between the panel spacing (in meters) and the yield of three different crops

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(maize, sorghum, and cassava) in the extrapolated SSA. The diagram shows that cassava consistently achieves the highest yield compared to maize and sorghum, with its yield increasing significantly as panel spacing widens, starting from approximately 4 tons/ha at 1 m to over 7 tons/ha at 5 m. Maise, on the other hand, demonstrated steady growth in yield with increasing panel spacing, starting at approximately 1 ton/ha at 1 m and reaching nearly 2 tons/ha at 5 m. Sorghum exhibits the lowest yield among the three crops but shows a gradual increase similar to maise, starting at about 1 ton/ha at 1 meter and slightly exceeding 1.5 tons/ha at 5 meters.

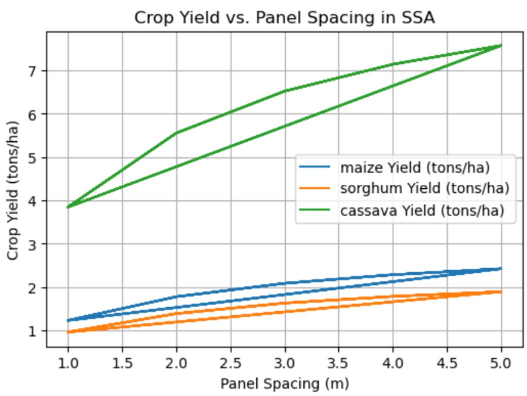

Figure 12. Impact of Panel Spacing on Crop Yields (Maize, Sorghum, and Cassava) adaptable to SSA

These trends indicate that increased panel spacing is positively correlated with crop yield for all three crops, with cassava benefiting the most. A wider panel spacing likely allows for better sunlight penetration and reduced shading, which enhances crop growth. These findings emphasize the importance of optimizing panel spacing in APV systems to balance energy generation and crop production in SSA areas.

Figure 13 illustrates the geographical distribution of SSA APV projects, highlighting the countries involved in sustainable energy systems, climate adaptation, and water management initiatives. The map represents countries and their marked project locations, with orange dots labelled by their respective acronyms. For instance, projects such as YESPV-NIGBEN span multiple countries, such as Nigeria and Benin, while others such as LoSENS and RETO-DOSSO are localized in Senegal and Niger, respectively. The visual representation shows the focus areas and the spread of these projects across the continent.

The emergence of APV in SSA is a gradually unfolding process, with notable projects marking the initial steps towards integrating agriculture with solar energy. One of the first APV systems in Africa was established by AUTARCON in 2018 in Rombo Usseri, Tanzania (WKF Foundation/AUTARCON 2018) [130]. This pioneering project aimed to power a water disinfection facility while supporting agricultural activities beneath the solar arrays [130]. Although it was an early example in SSA, APV development in the region lagged behind the more extensive advancements seen in Europe, China, and North America. However, recent initiatives, such as APV projects in Benin, South Africa, Mali, and Gambia, indicate a growing interest in this technology in SSA [11], [18], [40], [67]. These projects focused on installing APV systems in educational institutions and community farms, thereby promoting a deeper understanding and adoption of this technology[70], [81].

Similarly, the introduction of East Africa's first combined solar and agricultural system in 2022 marked a significant milestone [70]. This development showcased the region's inaugural APV system and offered insights into its design, performance, and replication potential in Kenya and other East African countries [81]. Led by Professor Sue Hartley from the School of Biosciences, a substantial initiative sponsored by the UK Research and Innovation's Global Challenges Research Fund (GCRF) Collective Programme unites a consortium of academic and research institutions [81].

Figure 13. Geographical Distribution of SSA APV Projects(Generated using pandas Geoplot for Python)

This initiative focuses on West African nations, which are particularly susceptible to climate change, and confront substantial land, energy, and food security challenges [11], [81]. These conditions make them ideal candidates for piloting APV systems adapted to local contexts. The planned APV installations are designed to be both practical and sustainable, featuring 200 kWp systems equipped with bifacial solar modules elevated at 2.5 meters and incorporating rainwater harvesting capabilities to support irrigation, cold storage units, and processing equipment [81]. Project experiments with various crops, including traditional vegetables, tubers, and high value produce such as strawberries and broccoli [81]. The controlled microclimate created by APV systems is crucial for enabling crop growth [18], [81], [134], [135]. Successful field demonstrations of these systems could pave the way for their broader acceptance, establishing their financial viability, and social benefits [81].

V. CRITICAL ANALYSIS

A thorough critical analysis of APV systems reveals significant potential and challenges for their adoption in SSA. The findings from this review highlight key contradictions, gaps, and opportunities for enhancing the applicability of APV systems in SSA's unique socioeconomic and environmental context.

A. CONTRADICTIONS IN GLOBAL APV STUDIES

Global research on APV systems has demonstrated their potential to address dual energy and food security objectives. Studies in Europe and Asia have frequently reported increased land-use efficiency by 60–80%, enhanced crop yields for shade-tolerant crops, and significant renewable energy generation. However, these findings are context-dependent, and not all studies align with the outcomes. For instance, while some studies highlight a 30% increase in crop yield under APV systems, others, such as greenhouse APV setups, report yield reductions of up to 64% for specific crops. These contradictions underscore the variability in APV performance based on factors, such as panel design, crop type, and local climatic conditions.

Applying these findings to SSA introduces further complexity. Many staple crops in SSA, such as maise and sorghum, thrive under full sunlight, posing a challenge to conventional APV designs that create partial shading[128]. Moreover, smallholder farming, a dominant agricultural practice in SSA, often lacks the scale and capital investment required for large APV installations, raising questions about the practicality of transferring global APV models directly to the region.

B. APPLICABILITY OF GLOBAL APV FINDINGS TO SSA

SSA's unique socioeconomic and environmental conditions require adaptation to global APV design. Land tenure issues, for example, represent a significant barrier to APV adoption in SSA, as unclear ownership or communal land-use practices complicate the long-term investment required for APV infrastructure. Additionally, the region's reliance on rain-fed agriculture and its vulnerability to climate change necessitate APV systems that optimize energy generation and enhance water use efficiency and crop resilience [67], [144]. In terms of policy, SSA lacks a comprehensive framework to support dual-use systems. By contrast, countries such as Germany and Japan have established technical standards and subsidy programs to incentivize APV adoption [18], [94]. Without similar support mechanisms, the financial burden of APV installation remains prohibitive for most smallholder farmers in SSA. This gap calls for targeted policy interventions including subsidies, tax incentives, and credit schemes tailored to the needs of the region.

C. CHALLENGES UNIQUE TO SSA

The high upfront installation cost is a critical barrier to APV adoption in SSA. While global APV projects often benefit from government subsidies and private sector investments, SSA lacks the financial infrastructure to support widespread adoption. Furthermore, the technical complexity of APV systems, including the maintenance of tracking panels and energy storage, may exceed the capacity of local labour markets and infrastructure, particularly in rural areas. Cultural and social perceptions play a significant role. Many farmers in SSA view land primarily as a resource for food production, with limited understanding of its potential for dual-use applications. This cultural bias and restricted access to technical training and education hinders the acceptance and integration of APV systems.

D. RESEARCH GAPS AND OPPORTUNITIES

This review identified significant gaps in the understanding and implementation of APV systems within SSA. Empirical research addressing the performance of APV systems in a region's unique environmental conditions, such as high temperatures, fluctuating rainfall patterns, and diverse soil types, is scarce. Additionally, limited evidence exists on the economic viability of these systems in smallholder farming contexts, particularly in cost-benefit analyses and long-term profitability. Addressing these gaps provides several opportunities for future research. Localized pilot studies could assess crop-specific performance within APV systems while developing cost-effective SSA-tailored APV designs, such as modular or lightweight panels, which may reduce installation and maintenance costs. Additionally, integrating APV systems with existing off-grid renewable energy solutions could be pivotal for advancing rural electrification and sustainable energy access in the region.

E. ACTIONABLE RECOMMENDATIONS FOR POLICY AND PRACTICE

Based on this analysis, several recommendations have emerged to advance the adoption of APV systems in SSA. Policymakers should prioritize the development of regulatory frameworks that support dual-use systems, including guidelines on land-use planning, subsidies for APV installations, and tax incentives for renewable energy investments. International collaborations and partnerships with private sector actors can facilitate technology transfer and capacity-building.

From a practical standpoint, APV projects in SSA should focus on low-cost, high-impact solutions that align with the socioeconomic realities of the region. For example, pairing APV installations with community farming cooperatives could distribute costs and benefits to multiple stakeholders, making the technology more accessible. Furthermore, educational campaigns and training programs are essential to increase awareness and build local expertise in APV systems.

VI. CONCLUSION

The energy and food security challenges in SSA present a unique opportunity for successful implementation of APV systems. These systems offer a dual solution by enabling the simultaneous production of renewable energy and crops on the same land, thereby optimizing land use while addressing a region's pressing sustainability needs. APV have considerable potential to mitigate energy deficits, enhance crop production, and improve water-use efficiency under the high-irradiance conditions characteristic of many SSA environments. To fully capitalize on this potential, concrete fiscal instruments and supportive land-use policies must be established within SSA's governance frameworks. One promising fiscal mechanism is the implementation of feed-in tariffs (FITs) specifically designed for agrivoltaics. FITs guarantee renewable energy producers an above-market price for electricity generated secured through long-term contracts (typically 15–20 years). This arrangement provides a stable and predictable revenue stream that is critical for attracting investment and securing financing for APV projects. For example, in Kenya, where the National Energy Regulatory Commission (NERC) has already approved FITs for renewable energy sources, similar schemes could be expanded to support APV deployment. By ensuring a guaranteed return on investment for electricity generated from APV systems, FITs not only incentivize both smallholder and large-scale projects, but also contribute to grid stabilization and energy diversification across SSA.

In parallel, land use policies should be aligned with renewable energy and agricultural development goals. Policymakers in SSA must adopt cross-sectoral strategies that designate specific zones for APV projects, while ensuring that these zones are integrated into broader agricultural and rural development plans. For instance, land zoning regulations can be revised to permit dual-use agriculture–energy operations, thereby reducing bureaucratic barriers. Additionally, measures such as tax incentives, reduced land rental fees, and subsidies for infrastructure development (e.g., grid extension and smart metering) can further encourage the adoption of APV systems. The experiences of projects such as Kenya's Malindi Solar Plant, which has not only contributed 40 MW of renewable energy to the national grid but has also spurred local economic development, illustrate the significant socioeconomic benefits of such policy support. These include job creation, improved rural energy access, and enhanced resilience to climate variability, all of which are critical to the long-term success and scalability of APV initiatives in SSA.

Furthermore, as agrivoltaics evolve in SSA, emerging trends suggest a promising future driven by the integration of digital twin technologies and IoT-enabled precision agriculture. Recent studies [16], [17], [37], [137] indicate that dynamic control systems that combine real-time monitoring with advanced predictive modelling are paving the way for more resilient and efficient APV installations. Pilot projects in countries such as Ghana and Kenya have already shown that digital platforms can continuously monitor parameters such as panel performance, crop growth, and water usage. These data are then employed to fine-tune operational settings, including maximum power point tracking (MPPT) under complex shading conditions. For instance, the successful operation of Kenya's Malindi Solar Plant, which integrates robust grid-integration strategies with localized monitoring, provides a clear blueprint for scaling the APV in the region.

In addition to technological advancements, socioeconomic aspects are critical to the future scalability of agrivoltaics. The deployment of fiscal instruments, such as feed-in tariffs, along with tailored land-use regulations can create an enabling environment for investment, particularly for smallholder farmers. By ensuring a stable and predictable return on investment, these instruments not only facilitate capital flow, but also drive community buy-in and improve overall rural electrification. Moreover, the incorporation of localized case studies—detailing, for example, the adaptive practices employed in Ghana's solar hydro projects and Kenya's digital monitoring systems—further validates the dual benefits of APV systems for energy access and food security in SSA. Looking ahead, these integrated strategies—combining cutting-edge digital technologies with supportive fiscal and land use policies—are expected to accelerate the adoption of APV systems across the region. Such an approach will not only enhance technical performance by optimizing both solar energy yield and crop productivity, but also promote sustainable rural development, ultimately contributing to the achievement of Sustainable Development Goals (SDG 2 and 7) in Sub-Saharan Africa.

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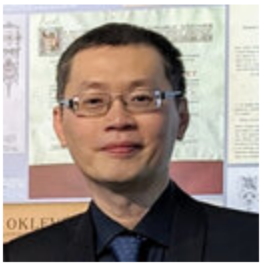

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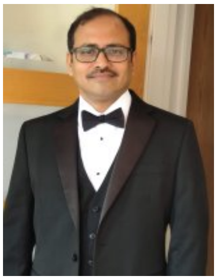

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