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LEVERAGING AGRIVOLTAICS TO INCREASE FOOD, ENERGY, AND WATER ACCESS IN THE GLOBAL SOUTH: A CASE STUDY SUB-SAHARAN AFRICA

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Abstract

Today, about 760 million people, mostly in sub-Saharan Africa (SSA) and Asia, are without access to electricity; over 2.5 billion people are without access to clean cooking facilities and this is connected to around 2.5 million premature deaths yearly; and modern sustainable energy supply is to account for only 18% by 2030. Over half of the global undernourished lives in Asia (418 million) and over one-third are found in Africa (282 million); SSA Latin America and the Caribbean were noted for the highest food insecurity (66.2%). Sub-Saharan Africa faces complex and interconnected challenges of food, energy, and water (FEW), which have significant implications for the region's socio-economic development and the well-being of the people. The study aims to assess the socioeconomic advantages and potential drawbacks of agrivoltaics through the following study objectives: to x-ray and discuss agrivoltaics brief history, principle, and merits of agrivoltaics; to examine the impacts of shades created by PV panels on crop performance. Others are examining the impacts of panels and crops on microclimate conditions; and evaluation and identification of steps required for developing and deploying agrivoltaics in SSA in SSA. This study recognises agrivoltaics as a single-solution approach with multiple effects that need to be developed and deployed. This study identifies universities and other research institutions, governments, non-government organisations (NGOs), private sector entities, and international organizations as stakeholders that need to collaborate and invest in research on agrivoltaics. The research proposes embracing and customising agrivoltaics approaches in SSA, taking cues from the development trajectories observed in Europe and America.

1.0 INTRODUCTION

The nexus of food, energy, and water (FEW) holds significant socioeconomic importance in the Global South (GS) due to its impact on various aspects of livelihoods, economic development, and sustainability. These fundamental socioeconomic defining components are essential for human existence and development, and without them, human existence goes into extinction. Their supplies must be adequate in terms of quantity and quality; otherwise, it triggers human health and socioeconomic development issues. Food, energy, and water are interconnected and pose significant challenges in the GS and sub-Saharan Africa (SSA), especially. The region experiences complex and interrelated issues in each of these sectors, creating a dynamic relationship.

In this study, SSA is the main focus because globally, the region accommodates the highest population living below the extreme poverty line and without

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access to electricity; it has the lowest levels of water access, and the highest prevalence of hunger and food insecurity in the world [1-3]. Addressing these challenges requires understanding, and a holistic and integrated approach that considers the interdependencies of food, energy, and water systems, promotes sustainable practices, and ensures inclusive governance and policy frameworks. Sections 1.1, 1.2, and 1.3 provide an overview of deficiencies in food, energy, and water, respectively, covering their current status, causes, and their impact on the socioeconomic well-being of the population.

1.1 Food Insecurity in the Global South

Food insecurity is a common trend in all the GS countries, especially in SSA and Asia, manifesting as famine or acute hunger, undernourishment, and consequential poor health outcomes. The number of undernourished people with serious health and well-being consequences across Eastern and Southern Africa has increased from 21% in 2019 to over 25% in 2020 [4]. According to the United Nations (UN) report [5], hunger affects 9% and 9.1% of the population of Latin America and the Caribbean and Asia, respectively. Over half of the global undernourished live in Asia (418 million) and over one-third are found in Africa (282 million). Latin America and the Caribbean, as well as SSA, have been recognised for experiencing the most rapid increase in prevalence (rising from 24.9% in 2014 to 40.9% in 2020) and the highest level of food insecurity (66.2%), respectively. Numerous factors contribute to this issue including poverty, inadequate power supply, climate change, conflict, population growth, and limited access to resources and infrastructure. The poverty rates across the regions of the world are presented in Figure 1. For instance, high poverty rates are prevalent in many countries in SSA. Poverty limits people's ability to afford and access nutritious food, perpetuating a cycle of food insecurity.

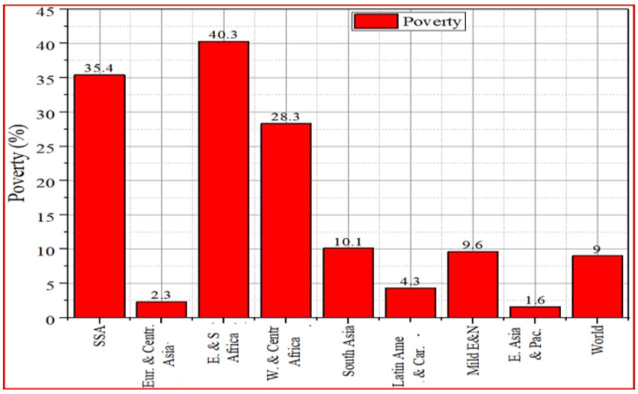

Figure 1: Poverty rates across the regions of the world [6]

Lack of irrigation systems and reliance on seasonal rainfall make agricultural production vulnerable to climate variability and water scarcity. Food insecurity contributes to malnutrition and related health issues. Inadequate access to diverse and nutritious food leads to undernutrition, stunting, and micronutrient deficiencies, particularly affecting children and women. The region is vulnerable to the impacts of climate change, including droughts, floods, and erratic rainfall patterns. These climate-related events can lead to reduced agricultural productivity, crop failures, and livestock losses, negatively affecting food production and availability.

Several countries in SSA are experiencing prolonged periods of conflict and political instability. These situations disrupt agricultural activities, displace populations, and hinder economic development, exacerbating food insecurity. The region has one of the highest population growth rates globally. Rapid population growth puts pressure on agricultural systems and limits access to land, water, and other resources required for food production. It becomes challenging to meet the food demands of a growing population. Inadequate infrastructure, including roads, storage facilities, and irrigation systems, hampers agricultural productivity and impedes the movement of food from surplus to deficit regions. Limited access to inputs such as seeds, fertilizers, and modern farming techniques further restricts agricultural potential.

1.2 Inadequate Energy Supply

Today, about 760 million people globally with sub-Saharan Africa (SSA) accounting for 80%, are without access to electricity [7]; over 2.5 billion people are without access to clean cooking facilities and this is connected to around 2.5 million deaths yearly; modern sustainable energy supply is expected to account for only 18% by 2030 [7, 8]. As it stands, the future of electricity supply in the region does not look great, unless urgent steps are taken in terms of policy, investment, technology, and priority. Otherwise, about 670 million people in SSA will still be without access to electricity in 2030 [8]. The power inadequacy in the region is posing a lot of challenges and accounts for many of the extreme social vices, bedevilling the GS today. Power supply insufficiency creates unemployment that leads to a scenario that aligns with the saying "An idle mind is the devil's workshop." Some of these vices are youth militancy, hunger, banditry, prostitution, pickpocketing, armed robbery, kidnapping, street begging, and over-profiteering. Unemployment, which is a product of energy poverty in the GS, makes businesses on natural resources, such as firewood supply and lumbering massive. The firewood business in SSA is billions of USD [9], resulting in the rise of deforestation, harmful gases, and other environmental challenges in the region. Other shortcomings of the firewood business are distortion of the ecosystem and land degradation, indoor air pollution from firewood cooking leading to diseases and deaths, and underage children and women labour involved in sourcing firewood [10]. The negative impacts of energy poverty on household indoor air and natural resources in SSA are depicted in Figure 2.

Figure 2: Impacts of energy poverty (a) household indoor air pollution; (b) business pressure on natural resources in SSA [10]

Besides the drawbacks of energy poverty, the utilisation of fossil fuels to meet humanity's need for sufficient power supply has brought about substantial repercussions. Fossil fuel-based pollution is a significant issue in SSA, although the region's overall contribution to global greenhouse gas (GHG) emissions is small compared to other parts of the world. The primary sources of fossil fuel-based pollution in the region include energy generation, industrial activities, transportation, and inefficient use of fuels for cooking and heating. Sub-Saharan Africa relies heavily on fossil fuels, particularly coal and oil, for electricity generation. Many countries in the region have limited access to reliable and affordable energy sources, leading to a dependence on fossil fuels. Inadequate infrastructure, outdated power plants, and limited investment in RE contribute to the continued use of fossil fuels. Industries such as manufacturing, mining, and construction in SSA often rely on fossil fuels for power generation and transportation.

The transportation sector in the region heavily depends on fossil fuels, particularly gasoline and diesel. Inefficient and outdated vehicles, inadequate public transportation systems, and the use of low-quality fuels contribute to air pollution. Vehicle emissions, including carbon dioxide, nitrogen oxides, and particulate matter, contribute to poor air quality in urban areas. A large portion of the population in SSA still relies on traditional biomass fuels, such as wood, charcoal, and agricultural waste, for cooking and heating. The burning of these fuels in open fires or inefficient stoves releases smoke and pollutants into the air, leading to indoor and outdoor air pollution, as well as health issues for households. Fossil fuel-based pollution contributes to climate change, leading to more frequent extreme weather events, droughts, and floods, which can disrupt agricultural activities and exacerbate food insecurity. Air pollution from fossil fuels also poses significant health risks, including respiratory diseases, cardiovascular problems, and premature deaths. The environment and human health have been compromised in the pursuit of providing the required energy to sustain human existence and power socio-economic development.

This has led to many severe serious adverse effects that the world is presently facing, such as climate change, depletion of fossil fuels, deforestation, greenhouse emissions, and extreme weather conditions. The extreme weather conditions attributed to climate change include more frequent wildfires, an increase in wind intensity, drought longer periods in some regions, and rainfall from tropical cyclones. Frequent devastating droughts and deadly floods are now yearly recurrent extreme weather conditions. In 2022, deadly floods that took several lives swept through SSA, affecting 5.9 million people in 20 countries in West and Central Africa. This has had a significant effect on human life (killing 1,132 people, injuring 4,005, and displacing 1.8 million), livestock, 458,000 houses, and farmlands. Some of the countries severely impacted by torrential rains and floods are the Republic of Congo, Nigeria, Chad, Niger, the Central African Republic, Liberia, the Democratic Republic of Congo, and Cameroon [11, 12].

1.3 Limited Access to Safe Water

Sub-Saharan Africa and other GS countries are facing significant water supply, access to clean water and irrigation challenges. A significant portion of the population in SSA lacks access to safe and clean water sources. Many people rely on contaminated water from rivers, lakes, or shallow wells, leading to the spread of waterborne diseases such as cholera, dysentery, and typhoid. Other clean water supply hindrances are inadequate water infrastructure, such as piped water systems, storage facilities, and treatment plants. Limited investment in water infrastructure, particularly in rural areas, makes it difficult to provide reliable and safe water services to the population.

The region is highly vulnerable to climate change, which affects water availability and quality. Changing rainfall patterns, prolonged droughts, and increased water evaporation rates affect water resources, making it more challenging to ensure a consistent water supply. Rapid population growth and urbanization put additional strain on water resources and infrastructure. Increased demand for water, coupled with inadequate water management systems, leads to water stress and difficulties in meeting the growing needs of urban populations. Inefficient water management practices, including over-extraction of groundwater and unsustainable agricultural practices, contribute to water scarcity. Lack of awareness about sustainable water use and poor water governance further exacerbate the challenges.

1.4 Food, Energy, and Water Interconnectivity

Adequate and reliable access to FEW is crucial for societal well-being, economic development, and public health. Inadequate access to any of these resources can lead to energy poverty, food insecurity, and water scarcity, disproportionately affecting vulnerable populations. Ensuring equitable access and addressing security concerns in these sectors is vital for sustainable development. Growing populations, urbanisation, climate change, and environmental degradation put pressure on the availability and accessibility of these resources. This study recognises that the three essential fundamental resources, FEW, are interconnected and share common factors responsible for their challenges and similarities. The scarcity of one has ripple effects on the availability and affordability of others. They are interwoven with scarce resources, and influenced by environmental effects.

They are to be supplied and accessed adequately. For instance, the production of food requires energy for farming, irrigation, transportation, and processing. Water is essential for agricultural irrigation and food processing, while energy is required to extract, treat, and distribute water and power the irrigation system. Food, energy, and water are finite resources that face challenges of scarcity and availability. The production, distribution, and consumption of FEW have significant environmental impacts. Recognising the interconnected nature of FEW is crucial for addressing GS challenges, such as inadequate access to clean energy, climate change, food insecurity, and water scarcity [13]. Unsustainable practices in agriculture, such as excessive use of water and chemical fertilizers, lead to water depletion and pollution, respectively. It is essential to adopt sustainable practices and reduce the environmental footprint of these sectors.

Considering the aforenoted challenges, commensurate efforts are required to address - FEW inadequacies, fossil fuel-based pollution, and food insecurity in the region. In this regard, several technical discourses have been propounded leading to emerging technologies cuts across of FEW sectors, as presented in Table 1. In addition to technical factors, effective governance, policies, and international cooperation are essential for managing and balancing the demand, supply, and equitable distribution of FEW resources. Technological innovations play a crucial role in improving the efficiency, accessibility, and sustainability of FEW systems [14].

Table 1: Emerging technologies in FEW sectors

Sector	Emerging technologies
Food	Indoor vertical farming, laser scarecrows, farm automation, soil and water sensors, weather tracking, final thoughts, and minichromosomal technology [15]
Energy	Sustainable energy transition, hybrid RE systems (HRES), energy justice, energy trilemma, agrivoltaics, blockchain in energy trading, carbon capture and storage, hydrogen technologies, smart grids, energy storage, RE integration
Water	Smart water management, desalination with RE, water harvesting, and blue-green infrastructure and smart water management.

Despite the advancements in RE technologies, precision agriculture, efficient irrigation techniques, water treatment, and conservation, SSA is grossly experiencing FEW inadequacies, as discussed in subsections 1.1-1.3. Integrated approaches recognise the interdependencies of FEW and seek coordinated solutions to ensure sustainable management of FEW resources. Such integrated methods include resource efficiency and circular economy, agroecology and sustainable agriculture, RE integration in agriculture, climate-resilient agriculture, and green technology. The green technology incorporates RE sources, such as solar and wind power into water management systems, and solar and plant or animal into a system (agrivoltaic). These RE sources power irrigation systems, pumps, filtration processes, and wastewater treatment plants, thereby diminishing dependence on fossil fuels. Agrivoltaic system involves cultivating crops or rearing of animals beneath solar panels, a practice supported by scientific studies demonstrating the enhanced growth of certain crops under this arrangement. Utilising land for both agricultural and solar energy purposes has the potential to contribute to feeding the expanding global population while simultaneously generating sustainable energy [16]. Presently, agrivoltaics is emerging as an alternative and sustainable energy source that maximises multifunctional land utilisation by concurrently facilitating electricity generation and agricultural activities [17].

Therefore, this study recognises agrivoltaic systems as a single-solution approach with multiple effects that need to be examined, hypothetically. The study focuses on the investigation of the perceived positive multiple effects of agrivoltaics application in the GS, using SSA as a case study. The study aims to provide valuable insights into the feasibility and benefits of combining agriculture and solar energy generation, fostering a sustainable and more resilient approach to land use and energy production. To achieve this aim, the following objectives will be carried out:

i. To x-ray and discuss agrivoltaics brief history, principle, and merits of agrivoltaics.
ii. Examining the impacts of shades created by PV panels on crop performance in terms of crop growth, yield, and nutritional quality.
iii. Examining the impacts of panels and crops on microclimate conditions, such as temperature, humidity, and wind and how these influence PV panel cooling, crop growth and yield, and local biodiversity.
iv. Evaluation and identify the steps required for adoption and adaptation in SSA
v. Examining the benefits of utilising agrivoltaics to address socio-economic challenges in SSA

The paper systematically addresses its objectives in six sections, commencing with Section 1 as the introduction. Section 2 presents the methodology layout in a sequential format. Section 3 provides a historical background and contextual understanding, primarily focusing on agrivoltaics principles, their classification, and merits. Sections 4 and 5 outline and discuss the necessary steps for adoption, adaptation, and leveraging agrivoltaics to address socio-economic challenges in SSA. The study concludes in the final section.

2.0 METHODOLOGY

This study is deeply rooted in the exploration of contemporary issues, advancements in technology, diverse perspectives, and a thorough examination of articles about agrivoltaics. The research encompasses a comprehensive overview of agrivoltaics, an analysis of food, energy, and water (FEW) challenges specifically within SSA, and a focused exploration of how agrivoltaics can be strategically utilized to address FEW issues in the region. To conduct this study, a methodological approach was employed that involved the collection of secondary data from reputable platforms such as ScienceDirect, Springer, and verified official websites. These sources house a wealth of published feasibilities, reports, and investigations on agrivoltaics from global organizations specializing in renewable energy (RE), energy policies, and academic research. Recognized sources of reports include esteemed institutions such as the African Development Bank Group (AfDB), the European Union, the United Nations, the World Bank, and the International Energy Agency.

The methodology of this study was organized into a systematic arrangement, starting with an introduction and followed by a detailed exploration of the brief history and principles of agrivoltaics. The subsequent sections addressed the necessary steps for adopting and adapting agrivoltaics in SSA, as well as the strategic leveraging of agrivoltaics to address socio-economic challenges in the region. The study concludes with a summarizing section, presenting a coherent and structured research framework as illustrated in Figure 3.

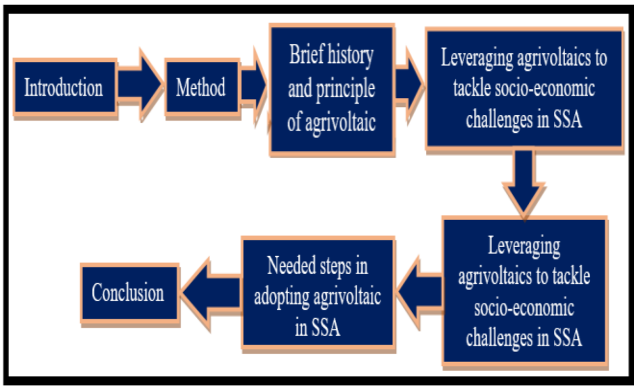

Figure 3: The layout of the method

3.0 AGRIVOLTAICS BRIEF HISTORY AND PRINCIPLE

The inception of agrivoltaics technology dates back to 1981 when two Germans, Armin Zastrow and Adolf Goetzberger pioneered its development optimising land utilization [18, 19]. The concept was to leverage arable land for both solar energy generation and plant cultivation, thereby enhancing overall production. This symbiotic relationship involved plant species absorbing photons from the light. Recognizing that the high photon rate did not necessarily increase photosynthesis, Nagashima proposed the integration of farming and photovoltaic (PV) systems to prevent excess light from going to waste. Consequently, the prototype for this integrated approach was established in Japan in 2004 [20].

Novel approaches involving ground-mounted vertical PV systems alongside agricultural areas have emerged since 2015 [18]. This form of agrivoltaics, known as interspace or vertical agrivoltaics, has underscored the need for defining and classifying agrivoltaics. In 2018, classification, differentiating between arable farming, PV GHG, and buildings emerged. However, their classification did not encompass highly elevated and ground-mounted agrivoltaics. Another study introduced classification, identifying crop production and livestock as the two primary applications of agrivoltaic systems [21], presented in Figure 4. While these authors also included highly elevated and ground-mounted systems, a more recent study in 2020 suggests associating typical tilt and tracking technologies of PV modules with agricultural applications in both contexts [22].

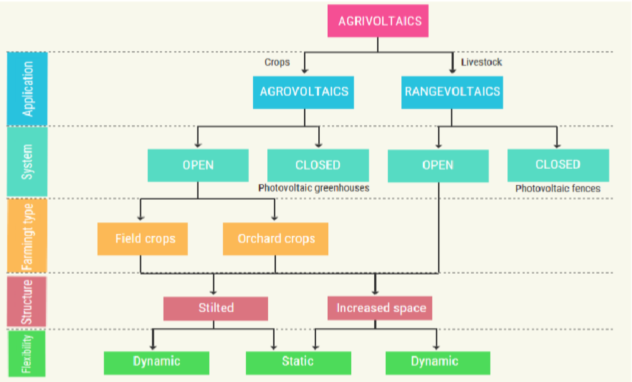

Figure 4: Classification of agrivoltaic systems [21]

Figure 5: Agrivoltaic systems [26] (a) PV system and crop; (b) PV system and animal

Agrivoltaics, also known as agrophotovoltaics (agrovoltaics) or solar sharing, introduces an innovative approach that integrates agricultural practices with solar energy generation. This method involves integrating solar panels into agricultural areas, allowing for simultaneous crop cultivation and electricity production. In SSA, Kenya has been actively exploring the potential of agrivoltaics to address its energy and food security challenges in recent years. It is an innovative and sustainable approach that combines agriculture with PV energy production [23], as shown in Figure 5. The main objective of agrivoltaic studies is to explore and optimise the coexistence of agricultural activities and solar energy generation in the same land area [24]. This principle known as agrivoltaics or agriphotovoltaics, is based on the integrated use of land for both agricultural and PV energy production purposes. The solar panels are elevated above the ground, allowing sunlight to pass through and reach the crops growing underneath [25]. Presently, there exist two categories of agrivoltaic – the integration of agricultural practices to existing PV facilities on available land; and deliberately planned and implemented systems aimed at simultaneously generating crops and PV electricity.

The principle of agrivoltaics seeks to demonstrate that combining agriculture and solar energy generation is not only feasible but also advantageous from both environmental and economic perspectives. By promoting sustainable land use practices and RE production, agrivoltaics represents a promising approach to address the trio of challenges of FEW securities in the GS amid the changing climate. The primary goal is to create a symbiotic relationship between agriculture and solar energy generation, where the two activities complement each other and enhance overall land productivity and sustainability. The key merits of agrivoltaics are as follows [27-29]:

3.1 Land Availability

Land availability has been recognised as one of the several challenges associated with the widespread adoption of solar PV systems [30]. There is a growing suitable land competition between solar farms and other various purposes, such as agriculture, urban development, and conservation. Identifying and securing large, contiguous parcels of land for solar farms creates a challenge, especially in densely populated, places where land are expensive, and in urbanised areas. The cost of acquiring and developing land for large-scale PV projects could be significant, making it less economically viable in some regions. In areas with high land prices, solar developers might face financial challenges in making their projects financially attractive. Land use regulations and zoning restrictions could hinder the development of large-scale solar projects in certain areas. Local laws might limit or prohibit solar installations in specific regions, which creates additional obstacles for developers. Large solar installations could influence the local environment and ecology. In some cases, there were concerns about the disturbance of natural habitats, potential land degradation, and the loss of agricultural land [29, 31, 32]. Identifying and negotiating with multiple landowners, especially in areas with fragmented land ownership, could complicate the development process and delay project timelines.

3.2 Water use Efficiency and Microclimate Management

Agrivoltaics considers the microclimate conditions created by the presence of solar panels [33]. The partial shading can affect temperature, humidity, and wind patterns, which may affect crop growth and water use. The cover from the panels can potentially reduce water evaporation from the soil, leading to improved efficiency of water use for crops. Managing these microclimatic changes and water is essential for optimising crop performance and beneficial in water-scarce regions.

3.3 Enhancing PV System Performance and Maintenance through Cooling

Agrivoltaic systems aim to optimise the efficiency of PV panels by selecting appropriate panel technology, tilt angles, and maintenance practices to maximise energy generation. Solar panels are affected by temperature, and excessive heat can reduce their power output and potentially decrease their lifespan. Cooling of PV panels aids in better performance and maintenance of PV systems, and plants can influence this cooling in agrivoltaic systems. The agrivoltaic system, which combines agriculture with solar energy production, offers some natural cooling advantages compared to traditional solar farms. In the symbiotic relation (agrivoltaic system) between plant and PV system, cooling of PV panels is a significant benefit, and this comes from crops grown beneath the PV panels. A study investigated the cooling effect of crops on PV panels and revealed that as the structure's height increases, the temperature beneath the panels reduces [34]. Several factors contribute to the cooling of solar panels in agrivoltaic setups, and these include evapotranspiration, wind circulation, ground cooling, lower soiling, water use for irrigation, and higher tilt angle [27, 35-38].

Crops release moisture through a process called transpiration. This evaporative cooling effect can help reduce the ambient temperature around the solar panels, further contributing to the cooling effect. The presence of crops in an agrivoltaic system alters the wind patterns and promotes better airflow between the solar panels, which aids in dissipating heat. The soil under the solar panels tends to be cooler compared to open ground in conventional solar farms. This soil cooling effect helps lower the temperature of the solar panels mounted above it. In some agrivoltaic designs, the PV panels may be mounted at a slightly higher tilt angle than traditional solar installations. This configuration enhances convective cooling as more air circulates underneath the panels. Agrivoltaic system experiences lower soiling (accumulation of dirt and dust) on the solar panels due to reduced exposure to wind-blown particles, contributing to better panel efficiency. In some cases, water used for crop irrigation may also be used to cool the solar panels directly, especially in dry and hot climates. The agrivoltaic ecosystems and parameters for estimating the net all-wave radiation are presented in Figure 6.

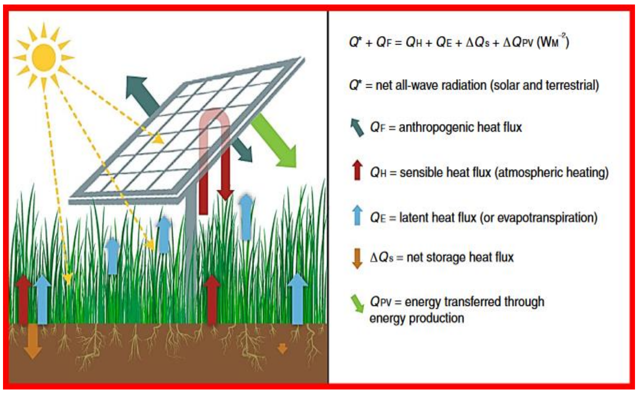

Figure 6: Agrivoltaic ecosystems [39] – a hybrid of RE and food production in tackling changing climate and FEW insufficiency

3.4 Other Benefits of Agrivoltaic

Agrivoltaic contributes to climate change mitigation by producing RE while promoting sustainable land use practices. The combination of agriculture and solar energy production can enhance the resilience of food and energy systems [40]. Integrating solar panels with agriculture creates opportunities to enhance biodiversity and soil health. Providing partial shade supports a broader range of plant and animal species, while the cultivation practices can help improve soil quality. Further, it offers socio-economic benefits by generating clean energy alongside agricultural revenues and this creates local jobs that improve the living standard of rural communities.

3.5 Optimising PV System Performance and Crop Growth and Yield Levels

Despite the numerous research work on agrivoltaic, a lot of theoretical, computational modelling, and empirical investigative, optimisation, and prediction studies are still required to be carried out. This is because PV potential is location dependent and plants have different favourable ambient conditions, which may necessitate distinctive PV panel orientation for different plants to create and allow agrivoltaic system optimisation ambient conditions. The placement and orientation of solar panels are carefully planned to ensure adequate sunlight reaches the crops and to create a cooling effect on the PV panels. The spacing between panel rows and the height of panel mounting structures are designed to minimise shading on the crops while maximising solar energy generation. Recently published agrivoltaic systems articles are presented in Table 2.

Table 2: Some recent works on agrivoltaic

Study	Target	Method	Finding
[34]	Examined agrivoltaic design features (evapotranspiration, panel mounting height, and ground albedo) that affect the solar farm microclimate and PV panel's surface temperature	Empirical and computational modelling	According to the study, agrivoltaic PV panels mounted at 4 m with soybeans underneath show 10 °C PV panel temperature reductions compared to a PV panel mounted at 0.5 m over bare soil
[41]	Investigated water evaporation reduction in three scenarios by placing evaporation dishes and pans for 45 days (i) under the Even-lighting Agrivoltaic System (EAS); (ii) under the Concentrated-lighting Agrivoltaic System (CAS); (iii) on the plane soil	Empirical	The result shows that cumulative soil surface evaporation of plan soil, EAS, and CAS was 80.53 mm, 54.14 mm, and 63.38 mm, respectively.
[42]	A study to determine the improvement of land productivity and revenue advantages of agrivoltaic systems to farmers was conducted using 11 m2 of the land area with the variable of 0.675 kWp PV capacity and 1.5 kg turmeric farming underneath.	Empirical	The study reported: • Land equivalent ratio, benefit-cost ratio, price-performance ratio, and payback period of 1.73, 1.71, 0.79, and 9.49 years, respectively • Reduction of the ambient temperature of between 1–1.5 °C.
[43]	A study suggests an environmentally friendly development model for cities abundant in solar energy but delicate ecological environments, by integrating distributed control systems (DCS) and pasture-based photovoltaic (PPV) power stations.	Theoretical	According to the findings: • The model demonstrates its ability to boost the local economy while efficiently curbing carbon emissions. Within the study area's planned DC scale, the model achieves a reduction of over 3 million tons of GHG emissions annually. • it successfully converts more than 1140 hectares of Gobi land into grassland, leading to a rise in carbon stock by 150,262 tCO2e and substantial savings of 39 million yuan in desert management costs
[28]	This study enhances the agrivoltaic design methodology by introducing a novel approach that combines a digital replica and genomic optimization framework. The framework utilizes a procedurally generated agrivoltaic system, which simulates light rays at an hourly timestep for a specified crop, location, and growing season. This enables the modelling of light absorption by both the photovoltaic panels and the crops beneath. The hourly radiation data is further aggregated into daily values, which are then used as inputs for a crop model to simulate the performance of both the agrivoltaic system and a reference crop daily	Theoretical	The work presented a framework that shows promise in connecting light modelling with crop modelling to effectively simulate agrivoltaic performance
[44]	This study quantified the increase in land productivity derived from the integration of an experimental vertical farm (VF) for baby leaf lettuce inside a pre-existing commercial CA.	Empirical	The study reported that the mixed system increased the yield by 13 times compared to the CA and the average LER was 1.31, but only 12 % of the energy consumption was covered by the CA energy.
[45]	This research delves into the complex relationship among radiation transmission, maize crop growth, and irrigation requirements in field settings. It accomplishes this by analysing the dynamics of crop development, differentiating between fixed and dynamic panels.	Empirical	The findings underscore that the maize crop is influenced by individual as well as combined stressors, such as shade and water deficit, leading to notable declines in leaf area index, overall dry matter, and grain yield. In terms of water usage, the study demonstrates the capability of AV (presumably a specific technique or technology) to curtail irrigation needs significantly, potentially reducing input requirements by 19–47% when compared to plots without shading. This reduction is attributed to diminished soil water depletion and reference evapotranspiration.

The success of agrivoltaics relies on thoughtful crop selection and some crops that are suitable and compatible with partial shade have been identified for agrivoltaic systems [39, 46]. Shade-tolerant crops are most suitable for agrivoltaics, making lettuce an excellent choice for dual-use planting. These crops tolerate and benefit from reduced sunlight while maintaining acceptable growth and yield levels. A recent study on agrivoltaics conducted by Chad Higgins, revealed that combining PV projects with agricultural practices has demonstrated the greatest potential thus far [47]. The study found that integrating solar panels with leafy greens like lettuce and spinach, as well as root crops such as potatoes, radishes, beets, and carrots, yielded promising results. Other crop species that adapt well to understory growth, such as chiltepin peppers and certain types of tomatoes; can also be successful in agrivoltaic systems. In a study conducted at Biosphere, chiltepin production tripled under the partial shade provided by agrivoltaics. On the contrary, cereal grains, which prefer full sun, are unlikely to perform as effectively when integrated with agrivoltaics. While chiltepin pepper production experienced a significant increase, jalapeño production declined by 11% [26]. These findings demonstrate that agrivoltaics cannot be effectively paired with every crop.

3.6 Agrivoltaics in SSA

Solar PV is not a new way of providing power across SSA but agrivoltaics, which is the growing of crops underneath panels, as shown in Figure 7, is new. Limited information is available regarding agrivoltaics in SSA and its involvement. Currently, the empirical evidence highlighting agrivoltaics potential advantages is inadequate and the awareness of such alternatives to the traditional solar parks is lacking in SSA. While research in the Global North (GN) has demonstrated the benefits of agrivoltaic systems, only a handful of literature has been published on the challenges and potential of agrivoltaic systems in SSA. They noted that PV and agriculture integration technology has not been exploited in the GS [48]. The absence of cross-sectoral policy support poses an uncertainty and challenge for farmers and agribusinesses seeking electrification infrastructure with broader benefits. To garner political, business, and community support for agrivoltaic systems in the region, empirical research that generates locally relevant evidence and demonstrates the benefits under specific environmental conditions and target crop varieties is essential.

Figure 7: Illustration of agrivoltaics pilot system showcasing the integration of solar power generation, crop cultivation, and rainwater harvesting within a unified land area [49]

In SSA, the starting of the agrivoltaic system is traceable to Kenya with an initial yearlong research collaboration between the Kajiado-based Latia Agripreneurship Institute, University of Sheffield, and World Agroforestry [50]. There are indications of planned collaborations between African and European research centres, exemplified by projects like Watermed4.0 in Algeria. This ongoing research initiative involves eight institutions, with the German research organization Fraunhofer ISE being one of the partners [51]. Brendon Bingwa, the project manager of Agrivoltaics Africa at Fraunhofer, reported promising initial results from the project's research phase. Early data from the first harvest of potatoes indicated approximately a 16% increase in both yield and crop size. The trial, which started in Kenya, is showing promising results, ready to be scaled up. Other countries in SSA where agrivoltaic pilot systems are being tried are Uganda and Tanzania and the details of three pilot agrivoltaic systems are presented in Table 3. According to the report, cabbages grown under the 180 solar panels (345-watt) were a third bigger, and healthier, than those grown in control plots with the same amount of fertiliser and water [49]. Additionally, crops, such as maize, aubergine, and lettuce were reported to have shown similar improvements. The solar panels are positioned as high as 3 m or more, above the ground, offering sufficient space for a farmer to work beneath them. In larger systems, they can be elevated even higher to accommodate access to agricultural machinery [49].

Table 3: Locations of agrivoltaic pilot systems in SSA [48]

Country and region	Installed capacity of PV in the agrivoltaics system	Agro-ecological zone
Kenya (Kajiado County)	56 kWp	Semi-arid
Uganda (Lamwo District)	3x60 kWp	Humid
Tanzania (Morogoro)	35 kWp	Semi-arid

4.0 LEVERAGE AGRIVOLTAICS TO TACKLE SOCIO-ECONOMIC CHALLENGES IN SSA

Despite the substantial potential of PV resources in SSA, the region has not fully embraced solar PV technology. Parallel to challenges in the energy sector, issues in the supply of FEW across SSA demand innovative solutions [51]. Effectively, addressing the nexus of these elements calls for strategies that maximise outputs across agricultural, energy, water, and economic value chains. This is what agrivoltaics brings to the table, hence, it should be adopted in SSA, judging by the numerous agrivoltaics benefits and concepts that have been formulated and deployed with encouraging results [17, 52]. Agrivoltaics signifies a pioneering strategy in which agricultural production and PV systems are harmoniously integrated into a single land plot, aiming to optimise crop output, land utilisation efficiency, and power generation concurrently.

A well-designed agrivoltaics system can concomitantly tackle FEW security challenges in SSA while also improving farmer livelihoods. This study postulates that an agrivoltaic system that is rooted in artificial intelligence-managed sensory technology (AI-managed sensory technology) will adequately improve the supply of FEW in the region, as represented in Figure 8. This sustainable FEW system promotes crop yield increase, RE access increase, and regulated and optimal water use. Nevertheless, several further studies need to be carried out to establish favourable meteorological conditions and enhanced crop yield parameters. This is because improvements in crop yield rely on various factors, including the level of available photosynthetically active radiation and the shade tolerance of crop varieties [48].

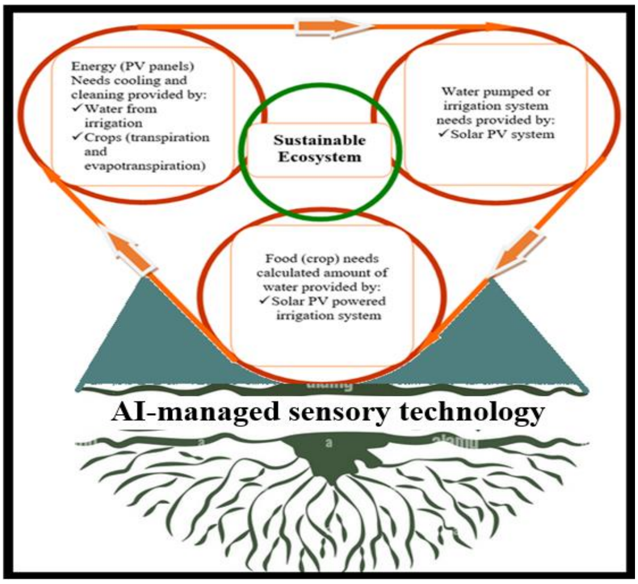

Figure 8: Interdependence of FEW rooted in AI-managed sensory technology

4.1 The Trio Issues – Food, Energy, and Water (FEW)

Agrivoltaics presents a unique opportunity to address some of the perennial socio-economic challenges faced by SSA. Fundamentally, the exploitation of agrivoltaics has the potential to tackle FEW if well harnessed, as portrayed by research results [39, 53]. Subsequently, this will positively affect other challenges, such as climate change, poverty, land use, and inadequate personnel capacity facing the region for decades. Agrivoltaic systems provide food and clean electricity; the generated electricity is utilised to power water pumps, clean PV panels and irrigation systems. Agrivoltaics helps to increase energy access and expand the RE infrastructure in both urban and rural areas. The generated energy provides clean electricity for industrial, domestic, and agricultural activities. This improved energy access and infrastructure can spur economic development and improve the living standards of people in SSA.

4.2 Creating a Favourable Microclimate for Crop Yield

Climate change is posing increasing threats to agriculture in the region, leading to food insecurity. Agrivoltaics can mitigate the impact of climate change by reducing extreme temperatures and evaporation, creating a more favourable microclimate for crops. Because the solar panels act as a canopy that protects crops from direct sunlight and excessive rainfall. Consequently, this guarantees that crops receive sufficient water that supports maximising yields, thereby improving food security in the region. In regions where water scarcity is a challenge, agrivoltaics can help conserve water by reducing evaporation and transpiration rates from crops.

4.3 Human Capacity Development, Job Creation, and Income Diversification for Farmers

Skilled personnel significantly influence RE development and have far-reaching effects on the progress of RE projects and the transition to a sustainable energy future. Renewable energy personnel skill inadequacy in SSA has been reported and this accounts for the huge untapped RE potential in the region [54, 55]. In addition, unattended inadequate skilled personnel can lead to reduced efficiency, limited investment, lack of innovation, slow project implementation, missed economic opportunities, and hindered energy transition.

4.4 Technology Transfer, Rural Development, and Poverty Alleviation

Implementing agrivoltaics projects often involves collaboration between the RE and agricultural sectors. This fosters technology transfer and knowledge sharing, as experts in both fields work together to optimize the design and operation of agrivoltaic systems. Such collaborations can lead to advancements in RE and sustainable agriculture practices. This in turn can lift communities out of poverty and promote economic growth at the grassroots level by generating income from electricity selling, providing reliable energy, creating jobs, and fostering entrepreneurship.

4.5 Reduced Carbon Emissions and Sustainable Land use

In many parts of sub-Saharan Africa, competition for land resources between agriculture and solar energy development can be a concern. Agrivoltaics optimizes land use by combining both activities on the same piece of land. This minimizes the need for additional land conversion and reduces the impact on natural habitats and ecosystems. As agrivoltaics rely on RE, the adoption supports global efforts to combat climate change as the systems contribute to GHG emissions reduction. 470-

5.0 THE NEED FOR AGRIVOLTAICS AND THE REQUIRED STEPS IN ADOPTING SSA

The GN (Europe and North America) through various instrumentalities of research and development have led to advancements in agrivoltaics technology, making systems more efficient and economically viable [56, 57]. They have demonstrated that agrivoltaic systems can enhance crop yields the creation of optimal ambient yield conditions and favourable microclimate crops [58-61]. Japan has equally made some outstanding contributions to the growth of agrivoltaics. According to a study [62], agrivoltaics, initiated in Japan in 2004, has produced an estimated total power ranging from 500,000 to 600,000 megawatt-hours (MWh). This accounts for about 0.8% of Japan's overall PV-generated power in 2019 and reflects a 76% increase in RE supply in Japan from 2012 to 2019. Globally, countries such as Japan, China, Italy, and Germany are adopting the agrivoltaics system, especially in land-constrained areas. With over 1,000 systems operational, Japan is actively pursuing additional contracts for further site development [20].

5.1 Benefits of Agrivoltaics

The advantages and highlights of agrivoltaics include heightened agricultural productivity, dual land utilisation, diversified income streams, energy generation, and enhanced water management [39, 63, 64]. While both agriculture and solar PV generation demand considerable space, they can exist in harmony, offering various ways, in which farming and solar panels can mutually benefit [65, 66].

5.1.1 Crop-related advantages

Agrivoltaics proves particularly advantageous in hot and arid regions, where PV panels not only provide shade but also contribute to retaining groundwater. Similarly, positive outcomes were observed in a trial in Kenya [49]. It is important to acknowledge that not all crops thrive in partial shade; wheat, for instance, is incompatible with agrivoltaics due to its sunlight requirements. In cases where the soil beneath solar panels is unsuitable for crops, farmers can opt for dual use by allowing sheep or other small livestock to graze in the shaded area.

5.1.2 Diversification of income for farmers

Integrating PV generation with traditional agricultural practices, such as crops or livestock, provides farmers with multiple income streams, ensuring greater financial stability compared to relying solely on one source of income. Passive income begins accruing once the solar energy generation system is operational.

5.1.3 Enhanced working conditions for farm workers

Farmers working in hot, sunny conditions are susceptible to health risks like heatstroke and skin cancer. The shade provided by solar panels creates a conducive working environment, offering protection from the harsh sunlight.

5.1.4 Water conservation

The separate operation of solar energy generation and agriculture poses challenges related to water consumption. Agrivoltaics addresses this by mitigating freshwater evaporation. The moderate shade from the panels prevents soil water evaporation and reduces transpiration in plants, particularly beneficial in areas prone to drought. Installed at a height of seven to ten feet above the ground in agrivoltaic setups, solar panels provide shade during peak sunlight hours. This indirect sunlight is advantageous for shade-loving and heat-sensitive crops, contributing to water conservation, especially in regions with low water availability or abundant sunlight.

5.1.5 Crop protection

Given the rising occurrences of extreme weather events like hail, storms, droughts, heavy rainfall, and heatwaves, the rows of solar panels in Agrivoltaic systems offer robust protection for crops. This proves particularly valuable for crops sensitive to direct sunlight.

5.1.6 Positive impact on the environment

Agrivoltaics exerts a favourable influence on the environment by enabling electricity generation and fostering enhanced growth in rural regions. Beyond that, this growing practice contributes to community enrichment through associated business activities such as access, construction, and repair. Simultaneously, it plays a pivotal role in the conservation and enhancement of the ecosystem.

5.1.7 Global decarbonisation goals and job create-on

Agrivoltaic systems possess the potential not only to contribute to achieving global decarbonisation goals for the electricity grid but also to do so in a sustainable manner, concurrently addressing various environmental, economic, and social objectives. The solar PV sector is anticipated to generate 22.2 million jobs by 2050 [67]. Given that agricultural areas are optimal locations for solar energy development, the implementation of agrivoltaic systems may positively impact rural economies by creating job opportunities, contributing tax revenues for local programmes, and facilitating income diversification for farmers and landowners [65].

5.2 The Required Steps

Given the substantial benefits of the agrivoltaic systems, this paper advocates for SSA to harness it as a pivotal solution to address the persistent challenges related to FEW in the region. This requires the adoption and adaptation of agrivoltaics development strategies of the GN, effectively, through meticulous planning and well-structured collaborations among various stakeholders. This paper advocates for these collaborations to encompass governments, non-governmental organisations (NGOs), universities, specialised research institutions, private sector entities, and international organisations. Additionally, the recommended steps involve substantial investments in research, development, and the implementation of an integrated system deeply rooted in AI-managed sensory technology. By promoting collaboration between academia, the private sector, research institutions, and local communities, the aim is to cultivate innovation, drive research and development efforts, and facilitate knowledge exchange, ultimately expediting the widespread adoption of agrivoltaics in the region. Agrivoltaics is a product of research and development and this is what informed the study of the choice of stakeholders required to drive and entrench it in SSA.

5.2.1 Policies and frameworks for agrivoltaics adoption in SSA

To support the development and implementation of agrivoltaic systems, various policies and frameworks can be established at different levels of governance. The policies should support education and training, agricultural and energy policies, incentive programs, research and development funding, and zoning and land use Regulations. Others to be supported are research and data sharing, demonstration projects, collaborative partnerships, environmental regulations, and long-term planning.

5.2.2 Human capacity development

Human capacity development is a cornerstone of societal advancement, encompassing economic, social, cultural, and environmental dimensions. It empowers individuals to drive the adoption and implementation of agrivoltaics and contribute socio-economically to their communities. In this study, the required human capacity development is categorised into investigative studies and training initiatives.

5.2.3 Training initiatives

Educational programs and training initiatives that will aid the farmers, agricultural extension agents, and energy professionals to understand the technical, economic, and environmental aspects of agrivoltaics, should be designed.

5.2.4 Expected investigative studies

The adoption of agrivoltaics in any region should include academic-based research and development of agrivoltaics technologies on PV system optimal configuration, crop selection, optimal layouts, and irrigation techniques that maximise co-benefits. The recommended study objectives to entrench and adopt agrivoltaic systems in SSA are:

i. To assess the economic benefits and possible potential drawbacks of integrating agriculture and PV energy production. This involves analysing factors, such as crop revenues, energy generation income, cost savings, and return on investment.
ii. To identify suitable potential crops in agrivoltaic systems for optimal land use and energy production in SSA.
iii. Photovoltaic potential and feasibility assessment of various locations across SSA for agrivoltaics database formation.
iv. To study the social and community aspects of agrivoltaics, such as the acceptance of these systems by farmers and local communities, potential job creation, and social benefits.
v. To examine the needed policy and regulatory frameworks to support the propagation of agrivoltaics in SSA.
vi. To identify barriers to the implementation of agrivoltaics in SSA.
vii. To examine the potential of agrivoltaics in promoting climate change resilience
viii. To investigate the feasibility of small, medium, and large-scale agrivoltaic systems models in SSA and the potential of replicating successful models in different GS regions to support widespread adoption.

Generally, a combination of policy frameworks that supports financial incentives, supportive regulations, research support, collaborative efforts, and personnel development can create favourable conditions for a successful implementation of agrivoltaic systems.

6.0 CONCLUSION

Sub-Saharan Africa faces complex and interconnected challenges of FEW, which have significant implications for the region's socio-economic development and the well-being of the people. Other challenging issues in the region, such as climate change, unemployment, limited access to resources and infrastructure, and poverty are linked to FEW inadequacies. These challenges require a comprehensive and multi-faceted approach, which promotes inclusive economic growth, and enhances resilience to environmental and economic shocks. This study presents agrivoltaics technology as a multi-faceted approach and a unique opportunity to address some of the identified perennial socio-economic challenges facing SSA. This technology is emerging, and it aims at leveraging a symbiotic relationship between agriculture and PV systems to enhance overall land productivity and sustainability with FEW as key byproducts. An adequate supply of FEW has positive ripple effects on other challenges. Other merits of deploying agrivoltaics are creating a favourable microclimate for crop yield, human capacity development and job creation, income diversification for farmers, technology transfer, rural development, poverty alleviation, reduced carbon emissions and sustainable land use.

This study identified some stakeholders that need to collaborate and invest in research including universities and other research institutions, governments, non-government organisations (NGOs), private sector entities, and international organizations. Policymakers are expected to create supportive regulatory frameworks and incentivise the adoption of agrivoltaics to maximise its positive socio-economic impacts in the region. The GN has seen numerous pilot studies on agrivoltaics while little exists in SSA and this communicates the level of participation in agrivoltaics by the two divides. Agrivoltaics are still in the early stages of adoption in SSA and there is a notable potential for fostering sustainable development and enhancing livelihoods. The region's environmental conditions, electricity access, farming systems, and political scenarios offer both opportunities and challenges for the implementation of agrivoltaic technology [48, 51, 68]. The considerable potential benefits of agrivoltaics in SSA are evident and to realise these benefits, ongoing research and dedicated implementation initiatives are crucial.

The study recommends the following research objectives to entrench agrivoltaic systems in SSA:

- To assess the economic benefits and possible potential drawbacks of integrating agriculture and PV energy production. This involves analysing factors, such as crop revenues, energy generation income, cost savings, and return on investment.
- To identify suitable potential crops in agrivoltaic systems for optimal land use and energy production in SSA.
- To study the social and community aspects of agrivoltaics, such as the acceptance of these systems by farmers and local communities, potential job creation, and social benefits.

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