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# Climate Stress and Food-Energy-Water Challenges in Nigeria and Ghana: A DPSIR Systems Approach to Sustainable Agriculture

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Integrated strategies to mitigate crop heat stress and enhance agricultural productivity are crucial for sustaining rural livelihoods in the semi-arid regions of Nigeria and Ghana. Climate change has intensified challenges such as rising temperatures, erratic rainfall, and prolonged dry spells, all of which significantly threaten smallholder farmers who rely on rain-fed agriculture. This study employed systems analysis using the DPSIR framework and drew on secondary qualitative data from scholarly journals, government publications, and credible online repositories. Targeted search terms and Boolean operators were applied across major academic databases, including the Education Resources Information Centre (ERIC) via EBSCO, Web of Science, JSTOR, Scopus, ResearchGate, and ScienceDirect, to explore climate and environmental stress, agriculture, and adaptation strategies in Nigeria and Ghana.

The study evaluated the technical, economic, and social potential of three climate-smart agricultural interventions: agrivoltaics, drip irrigation, and agroforestry. These solutions were analysed using the Food-Energy-Water (FEW) nexus framework and economic concepts such as externalities and market failure. The findings from this study reveal that while each solution has distinct trade-offs, collectively they offer a resilient, scalable approach to mitigate heat stress, increase productivity, reduce emissions, and promote equity. Agrivoltaics yields high returns but requires significant investment. Drip irrigation is cost-effective and rapidly deployable, and agroforestry ensures long-term ecological and social benefits. This study underscores the need for policy support, financial incentives, and inclusive governance to facilitate adoption, especially among marginalized communities in West Africa, particularly in the northern regions of Nigeria and Ghana. These integrated strategies offer a path toward sustainable and socially optimal agricultural systems in Nigeria and Ghana under climate change.

**Keywords:** Climate-smart agriculture; Food-Energy-Water nexus; semi-arid regions; DPSIR framework; systems analysis; heat stress

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## Introduction

Across Africa, the impacts of climate change are increasingly alarming. One of the most severe consequences is the worsening food insecurity in many low-income countries, especially where conflict and climate change are driving hunger for over 100 million people across East, West, and Central Africa (World Bank, 2025). This challenge is particularly evident in the agricultural sector, which remains the backbone of rural livelihoods in semi-arid West Africa, where the majority of the population relies on rain-fed farming for sustenance and economic survival (Zougmoré *et al.,* 2016). However, the agricultural sector faces increasing threats from unpredictable rainfall, rising temperatures, and prolonged dry spells, which severely affect crop productivity and food security (Sultan & Gaetani, 2016; Twumasi-Ankrah *et al.,* 2025). Natural disasters like flooding also pose serious risks to vulnerable communities (Agha *et al.,* 2025), leading to widespread fragility in the region's food systems and exacerbating poverty and inequality in countries such as Nigeria and Ghana.

In Nigeria, agriculture is particularly vulnerable in the northern regions, where crop failure from extreme heat and water scarcity undermines food security (Ogar *et al.,* 2025). Similarly, in Ghana, agriculture plays a vital role in both employment and economic output yet remains highly exposed to climatic variability due to the predominance of rain-fed systems and the underdevelopment of irrigation infrastructure (Forkuor *et al.,* 2013; Jalloh *et al.,* 2013; Worqlul *et al.,* 2019). Ghana experiences unpredictable rainfall, rising temperatures, and delayed rainy seasons, all of which reduce crop suitability and threaten food security (Armah *et al.,* 2011; Chemura *et al.,* 2020). Although Ghana has abundant water resources, relatively little of its farmland is irrigated (Mensah & Ibrahim, 2017), and climate projections indicate a further decline in suitable land for irrigation by the 2070s (Worqlul *et al.,* 2019). Moreover, poor management of irrigation systems and limited adoption of sustainable practices further constrain agricultural productivity and environmental resilience.

Given these challenges, climate-smart agriculture (CSA) has emerged as a promising solution. CSA integrates strategies such as drought-tolerant crop varieties, efficient irrigation, sustainable land management and soil-water conservation to increase productivity while enhancing resilience (Tabe-Ojong *et al.,* 2023; Amankwaa-Yeboah *et al.,* 2024). Innovations such as the Stress Tolerant Maize for Africa (STMA) and Drought Tolerant Maize for Africa (DTMA) programs have shown significant yield gains even under stress conditions (Badu-Apraku *et al.,* 2023). Furthermore, water-smart technologies and remote sensing tools are enabling more effective management of scarce water resources (Oiganji *et al.,* 2025). However, adaptation is not just a technical challenge; it is also a social one. Rural communities' ability to adopt climate-smart agriculture (CSA) practices is often shaped by social structures, including access to resources and decision-making power (Lawson *et al.,* 2020). This underscores the need for integrated strategies that address both technological and social dimensions of resilience.

This study investigates integrated strategies to reduce crop heat stress and enhance agricultural productivity in semi-arid regions of Nigeria and Ghana. By reviewing evidence on climate-smart agriculture (CSA) practices, irrigation potential, climate adaptation technologies, and social resilience factors, it aims to inform sustainable policy and investment decisions that can secure food systems in the face of escalating climate threats.

## Study areas

Nigeria and Ghana are the study areas. Both countries are located in West Africa, along the Gulf of Guinea, and are bordered to the south by the Atlantic Ocean.

Nigeria, especially the northern region (Adamawa, Bauchi, Benue, Borno, Gombe, Jigawa, Kaduna, Kano, Katsina, Kebbi, Kogi, Kwara, Nasarawa, Niger, Plateau, Sokoto, Taraba, Yobe, Zamfara, Federal Capital Territory), has a vast semi-arid zone characterized by high temperatures and erratic rainfall (Ogar *et al.,* 2025). Agriculture in these areas is predominantly rain-fed, focusing on staple crops such as millet, maize, and sorghum. However, rising temperatures and unpredictable rainfall have led to decreased soil moisture, increased evapotranspiration, and heightened vulnerability to pests and diseases, all contributing to reduced crop yields (Ogar *et al.,* 2025).

Northern Ghana (Upper East, Upper West, Northern, Savannah, North East) is also a semi-arid savannah zone that is similarly affected by climate variability, characterized by increasing temperatures, delayed onset of rains, and prolonged dry spells. These changes disrupt traditional farming calendars and reduce the reliability of rain-fed agriculture (Chemura *et al.,* 2020). The region's climate is marked by a short rainy season and a prolonged dry season, making agriculture heavily dependent on erratic rainfall patterns (Lawson *et al.,* 2020). Smallholder farmers in regions like Bawku East face direct exposure to extreme heat, which adversely affects both crop production and human health (Frimpong *et al.,* 2020). Studies have shown that existing coping mechanisms are often insufficient, highlighting the need for more effective adaptation strategies (Frimpong *et al.,* 2017).

In both Nigeria and Ghana, the semi-arid regions are at the forefront of climate change impacts, necessitating integrated strategies that combine sustainable land management, technological innovation, and supportive policies to mitigate heat stress and bolster agricultural productivity. The case study areas are shown in Figure 1.

**Figure 1: Map of the study areas**

## Literature Review

### Identifying food-energy-water (FEW) connections and trade-offs

In addressing the challenges of crop heat stress and agricultural productivity in semi-arid Nigeria and Ghana, it is important to understand the connection between the Food-Energy-Water (FEW) system. The FEW nexus emphasizes that sustainable agricultural solutions must consider synergies and trade-offs among these three sectors to ensure resilience, productivity, and equity (Abdi & Gaunand, 2020; Purwanto *et al.,* 2021).

*FEW connections*

Figure 2 highlights the connections between food, energy, and water, emphasizing how each resource depends on and influences the others within the agricultural system.

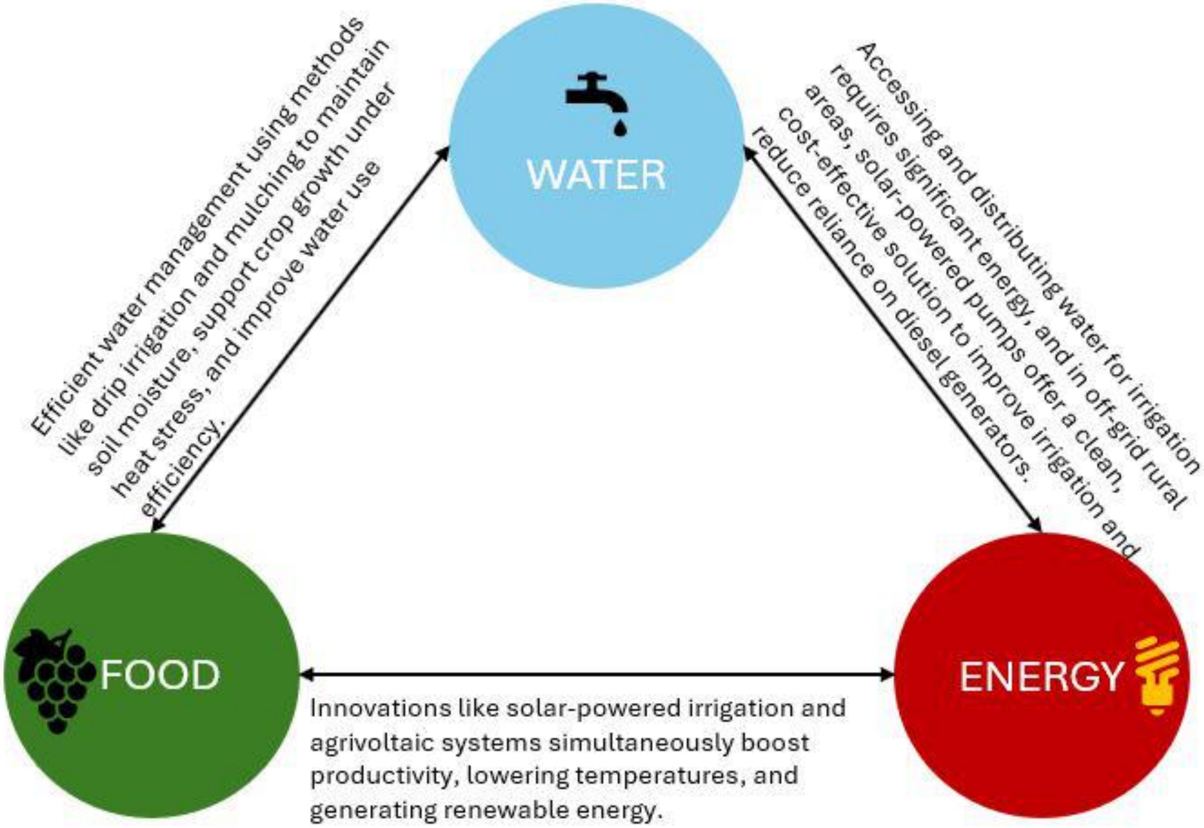

**Figure 1: FEW connections for the study**

**Food – Water:** Agriculture in semi-arid regions is fundamentally dependent on water availability, particularly under climate-change-induced heat stress. Maintaining adequate soil moisture through irrigation supports plant physiological functions such as transpiration and nutrient uptake, which is crucial under elevated temperatures (Allen *et al*., 1998; Savva & Frenken, 2002). Integrated strategies like drip irrigation and mulching help conserve water while sustaining or enhancing yields (Prosdocimi *et al.,* 2016). For instance, drip irrigation delivers water to the root zone and reduces non-productive evaporation (Woltering *et al.,* 2011), while mulching reduces soil erosion and improves water retention (Demo *et al.,* 2024); agroforestry also reduces erosion and improves soils by integrating trees and crops, which enhance soil structure, increase organic matter, and help retain moisture and nutrients (Mbow *et al.,* 2014).

**Food - Energy:** Modern agricultural interventions to counteract crop heat stress increasingly depend on energy access, including solar-powered irrigation, mechanized equipment, and cold storage to reduce post-harvest loss (Amjad *et al.,* 2023). Agrivoltaic systems, which integrate solar panels with crop production, can create cooler microclimates that mitigate heat stress and maintain or improve yields while producing clean energy (Barron-Gafford *et al.,* 2019; Neesham-McTiernan *et al.,* 2025)

**Water - Energy:** The energy-water nexus highlights that extraction, treatment, and distribution of water, especially for irrigation, are energy-intensive processes (U.S. Department of Energy, 2014). In many off-grid rural areas of West Africa, limited and costly energy access constrains reliable irrigation (Falchetta *et al.,* 2023), whereas solar-powered pumps can reduce life-cycle costs and emissions relative to diesel but require governance to avoid groundwater over-abstraction (Xie *et al.,* 2021)

**Integrated FEW Systems:** Sustainable, climate-smart agricultural systems harmonize food production goals with efficient water use and renewable energy adoption (World Bank, 2024). Bundled interventions such as rainwater harvesting combined with solar irrigation and drought-tolerant varieties align with climate-smart agriculture approaches that can improve resilience and productivity when tailored to local contexts (IPCC, 2022)

*Trade-offs in FEW integration*

While integrated FEW strategies offer promising synergies, they also involve trade-offs that must be carefully managed. Table 1 summarizes key trade-offs associated with implementing FEW solutions in these semi-arid agricultural systems.

**Table 1: FEW Trade-offs in Integrated Strategies to Reduce Crop Heat Stress in Nigeria and Ghana**

| Trade off | Description | Implications |
|---|---|---|
| **Water use vs. Energy demand** | Irrigation alleviates crop heat stress but increases energy consumption for water pumping and distribution (U.S. Department of Energy, 2014; IEA, 2016). | Without renewable energy solutions, energy demand can become unsustainable, increasing GHG emissions and operating costs (U.S. Department of Energy, 2014). |
| **Technology access vs. Equity** | Advanced FEW technologies (e.g., solar irrigation, precision agriculture) enhance productivity but are often expensive, limiting access for smallholder farmers (FAO, 2023). | May widen social and economic inequalities unless accompanied by targeted support, policies, subsidies, or cooperatives for small-scale farmers (Rutta, 2022). |
| **Land for solar vs. Crops** | Agrivoltaics installations share land for both energy and food production but may reduce planting areas and alter farming practices (Barron-Gafford *et al.,* 2019). | Balancing energy generation with optimal crop density is critical to avoid losses in food production (Neesham-McTiernan *et al.,* 2025). |
| **Energy subsidies vs. Climate goals** | Some regions subsidize fossil fuels to support agricultural energy needs, but this conflicts with climate resilience strategies (World Bank, 2024). | Emphasizes the urgent need for a clean energy transition in agriculture, favoring solar, wind, or bioenergy alternatives (World Bank, 2024). |
| **Short-term yield vs. Long-term soil health** | Some heat-mitigation inputs (e.g., plastic film mulches) can boost near-term yields and water-use efficiency (Huang *et al.,* 2024). | Residual plastics and microplastics can degrade soil structure and microbiota over time, arguing for conservation-oriented practices (Sajjad *et al.,* 2022). |

In designing integrated strategies to reduce crop heat stress and improve agricultural productivity in Nigeria and Ghana, acknowledging FEW system connections and trade-offs is essential. Approaches that prioritize renewable energy, efficient water management, and equitable access to technology are critical to sustainable and resilient food systems in the region (FAO, 2023).

## The problem framed in economic terms

Climate change-induced productivity challenges in semi-arid Nigeria and Ghana's agricultural systems can be economically framed as issues of externalities, market failure, and the need for social optimization. In particular, when social costs and benefits diverge from private ones, markets alone will not choose the socially efficient level of adaptation or mitigation (Hutchinson, 2017).

*Externalities*

The challenge of crop heat stress and declining agricultural productivity in semi-arid Nigeria and Ghana can be understood through key economic concepts, particularly externalities and market failure. Crop heat stress, exacerbated by climate change, reduces yields and threatens food security for smallholder farmers who largely depend on rainfed agriculture (IPCC, 2022). This issue reflects a negative externality: the economic activities that contribute most to global greenhouse gas emissions, such as industrial production and fossil fuel consumption, impose unintended costs on farmers in vulnerable regions, who are not responsible for these emissions but suffer from the resulting climate impacts. At the same time, positive externalities arise from integrated strategies such as renewable energy-based irrigation (e.g., solar pumps), drought-resistant crop varieties, and agrivoltaic systems (Barron-Gafford *et al.,* 2019). These strategies not only benefit the individual farmer but also produce broader societal gains: improved food security, poverty reduction, and enhanced rural resilience. However, because markets typically fail to value these wider benefits fully, private investment in such strategies remains insufficient.

Thus, the current agricultural economy in semi-arid Nigeria and Ghana exhibits market failure. Resources are not allocated efficiently because the true social costs and benefits of agricultural practices and climate change impacts are not fully reflected in market prices. To correct these inefficiencies and achieve better outcomes, public interventions, such as subsidies, incentives for sustainable practices, and investments in climate-smart agriculture, are necessary.

*Economics as socially optimal*

In the present situation, economics in the agricultural systems of Nigeria and Ghana cannot be described as socially optimal. Social optimality in economics occurs when the allocation of resources results in the greatest overall welfare for society, meaning that private costs and benefits align perfectly with social costs and benefits (Hutchinson, 2017). However, the agricultural sector in these regions is characterized by significant market failures, primarily due to externalities associated with climate change, environmental degradation, and energy poverty. Without mechanisms to internalize externalities, such as subsidies for sustainable practices, investment in renewable energy infrastructure, and support for technological innovation, individual decision-making will not lead to socially optimal outcomes (Pigou, 1932). Therefore, targeted interventions are necessary to correct these market failures and move the agricultural economy toward a more socially optimal and resilient state.

## Describing the problem from the perspective of social discourse

From a social discourse perspective, the challenge of reducing crop heat stress and improving agricultural productivity in semi-arid Nigeria and Ghana extends beyond technical adaptation to issues of equity, representation, and power. Smallholder farmers, particularly women, who are most affected by climate change, often lack access to the resources and institutional support needed to implement climate-resilient practices (FAO, 2023). Their voices are frequently marginalized in policy dialogues and development programmes, resulting in a disconnect between top-down strategies and the lived realities of rural communities (UN Women, 2019). Moreover, prevailing narratives around climate resilience often prioritize scientific and technocratic solutions, while undervaluing indigenous knowledge systems and traditional coping mechanisms that have sustained communities for generations. These dynamics shape not only the adoption of integrated strategies but also the trust and legitimacy of institutions promoting them (Kristjanson *et al*., 2014). Thus, addressing crop heat stress requires a more inclusive and participatory approach, one that recognizes the socio-political dimensions of climate adaptation and centres the experiences, knowledge, and agency of vulnerable farming populations (IPCC, 2022).

## Greenhouse gas emissions

Globally, Agriculture, Forestry and Other Land Use (AFOLU) accounts for 23% of total net anthropogenic GHG emissions (2007–2016), which is approximately 12 ± 2.9 $GtCO_2$-eq per year (IPCC, 2019). Energy production, especially from fossil fuels, contributes over 70% of global $CO_2$ emissions (IEA, 2023). The FEW nexuses, especially energy used in farming (e.g., diesel for irrigation), land-use inefficiencies, and deforestation, represent a critical cluster of emissions sources that these interventions aim to address.

## Research Methodology

Systems analysis, which is the DPSIR framework, and secondary qualitative data were used in this study. Database sources included scholarly journal articles, government publications, books, and credible online repositories. Academic databases such as the Education Resources Information Centre (ERIC) via EBSCO, Web of Science, JSTOR, Scopus, ResearchGate, and ScienceDirect were used in this study. Search terms were strategically selected to reflect the core themes of the study, including but not limited to: climate and environmental stress in Nigeria, climate and environmental stress in Ghana, food-energy-water nexus, and agriculture, with additional emphasis on terms such as "heat stress in crops," "climate-smart agriculture," "resilient farming systems," "adaptation strategies," "semi-arid regions," and "agricultural productivity." Boolean operators were employed to combine search terms and enhance the precision of results.

## Systems analysis: DPSIR framework

The system analysed in this study includes crop production and other agricultural activities, integrating natural environmental factors (e.g., temperature, rainfall, soil moisture, and evapotranspiration), agricultural practices (such as crop selection, irrigation methods, and soil management), and socio-economic elements (including smallholder farmer livelihoods, energy access, and water availability). These components interact dynamically with climate conditions, infrastructure, and resource management, jointly shaping the resilience and productivity of farming systems. To support systems thinking and provide a structured, system-level assessment of the problem (as illustrated in Figure 3), this study applies to the Drivers-Pressure-State-Impact-Response (DPSIR) framework developed by the European Environment Agency (Kristensen, 2004).

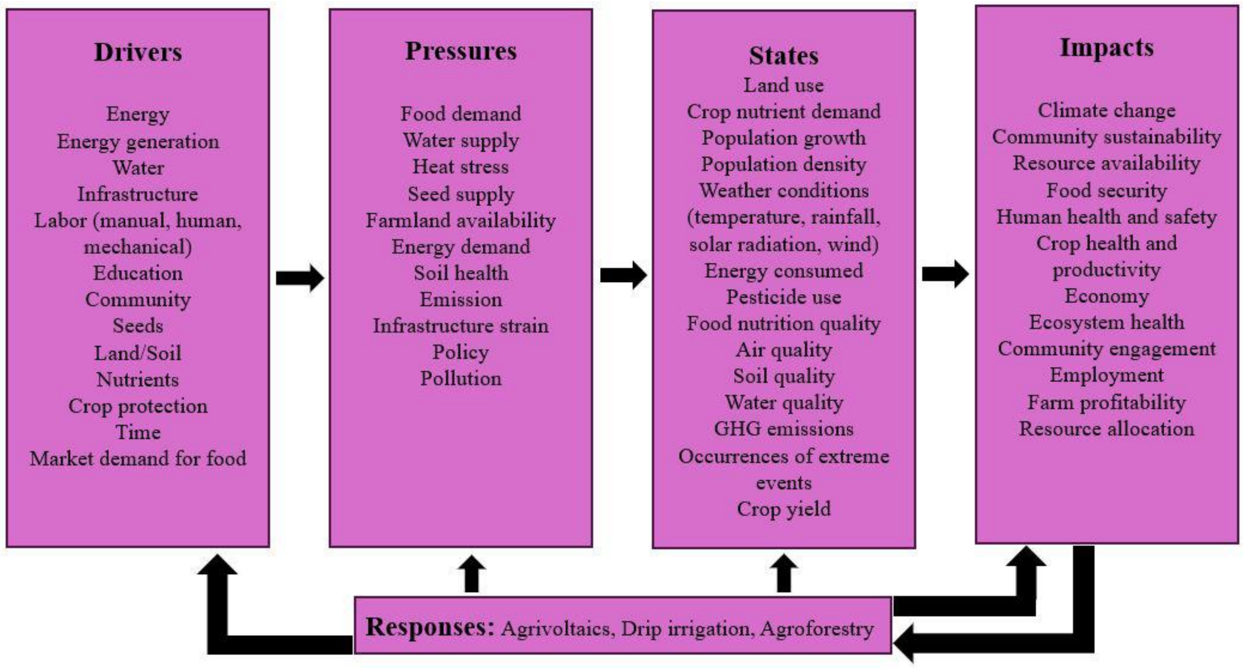

**Figure 2: DPSIR framework for this study**

## Findings

### Proposed solutions for this study

Three technical solutions were developed for this study to address the issue of crop heat stress and improve agricultural productivity in both Nigeria and Ghana. The solutions include Agrivoltaics, Drip irrigation, and Agroforestry (trees and crop systems).

*Agrivoltaics*

Agrivoltaics combines food and energy production by installing solar panels above crops, creating shade for these crops that reduces heat stress and evaporation (Trommsdorff *et al.,* 2022). Agrivoltaics can boost crop yields while generating clean energy to power irrigation, cold storage, and processing. These are the kind of benefits farmers in the northern parts of Nigeria and Ghana need. The panels improve water retention and allow efficient land use by serving dual purposes. Agrivoltaics enhances climate resilience, provides new income streams, creates green jobs, and supports the inclusion of youth and women in sustainable agriculture. While agrivoltaics may not be the only solution, it stands out for its ability to address multiple FEW challenges simultaneously, as shown in Table 2**.** Its true impact will be realized when implemented alongside supportive policies**,** public education**,** and complementary interventions such as solar-powered infrastructure and water-efficient technologies. Together, these tools can help smallholder farmers in these regions not only survive but thrive amid the pressures of a changing climate.

**Table 1: Quantitative Performance Indicators of Agrivoltaic Systems**

| Category | Quantitative Data |
|---|---|
| **Crop yield** | Under PV shade, fruit production rose 3× (chiltepin pepper) and 2× (cherry tomato), while jalapeño used 65% less transpirational water for similar yield (Barron-Gafford *et al*., 2019) |
| **Water efficiency** | On Oregon pasture, late-season biomass was +90% and water-use efficiency +328% under panels (Hassanpour Adeh *et al*., 2018) |
| **Evaporation reduction** | Agrivoltaic canopies cut cumulative soil evaporation by 21–33% and pan evaporation by 14–19% (Omer *et al*., 2022). |
| **Solar energy output** | Utility-scale PV typically delivers ~975–1,105 MWh $ha^{-1}$ $yr^{-1}$ (US medians for 2019 plants; tracking vs fixed-tilt) (Bolinger & Bolinger, 2022) |
| **Carbon/Emissions** | Using the 2022 U.S. grid average ~0.37–0.39 kg $CO_2$/kWh (EPA, 2024), and PV life-cycle emissions ~40 g $CO_2e$/kWh (NREL, 2025), net avoided emissions are ~0.33–0.35 kg $CO_2e$/kWh. With PV energy density ≈ 975–1,105 MWh $ha^{-1}$ $yr^{-1}$ (LBL), which is roughly ~320–390 t $CO_2e$ $ha^{-1}$ $yr^{-1}$ avoided, depending on grid mix. |
| **Land use efficiency** | Representative agrivoltaic layouts achieve LER ≈ 1.35–1.73 (i.e., 35–73% higher combined land productivity than single-use) (Dupraz *et al*., 2011) |
| **Costs** | Recent global projects show utility-scale PV LCOE ≈ USD 0.044/kWh (2023), reflecting continuing cost declines (IRENA, 2024) |

*Drip irrigation*

Drip irrigation is a type of water-saving technology. This irrigation delivers water directly to plant roots, minimizing waste and improving efficiency, as shown in Table 3. It is particularly effective in conserving water in dry regions. However, the system requires energy, typically for water pumping, which can be a barrier in some areas. The initial installation cost is also high, making adoption difficult for smallholder farmers in Nigeria and Ghana without external support from the government. Its effectiveness is limited where energy access is unreliable.

**Table 3: Quantitative Performance Indicators of Irrigation Systems**

| Category | Quantitative Data |
|---|---|
| **Crop yield** | Across crops and regions, drip fertigation increases yields by ~12% on average relative to conventional methods, while also improving water-use efficiency (Delbaz *et al.,* 2023). |
| **Water efficiency** | Compared with surface/sprinkler methods, drip systems raise water-use efficiency by ~26% on average and align with FAO guidance to evaluate irrigation performance via water productivity (kg $m^{-3}$) rather than simple "efficiency" percentages (Delbaz *et al.,* 2023). |
| **Energy impact** | Since more than 90% of an irrigation system's energy use comes from pump power, switching from diesel or electric pumps to solar-powered irrigation systems (SPIS) eliminates on-farm fuel consumption for pumping and reduces operating energy demand from purchased fuels (Dong & Kelley, 2023). |
| **Carbon/Emissions** | For diesel pumping, emissions are ~10.19 kg $CO_2$ per gallon of diesel (US-EIA, 2024); by contrast, PV electricity used for pumping has ~10–36 g $CO_2e$ $kWh^{-1}$ cradle-to-grid life-cycle emissions (Smith *et al*., 2024), so replacing diesel pumps with solar-powered irrigation systems (SPIS) eliminates direct combustion $CO_2$ and yields large net avoided emissions per unit of pumping energy. |
| **Land-use efficiency** | Efficient irrigation enables expansion/stabilization of irrigated areas and productivity for smallholders; in Sub-Saharan Africa, farmer-led/small-scale approaches are emphasized as more cost-effective and scalable (Burney *et al.,* 2013). |
| **Cost** | Reported costs span widely by technology and scale: large, centrally planned schemes ~US$10,000/ha (SSA average experience) (Shah *et al.,* 2020), while solar pumping solutions often prove cost-effective on farm economics and can achieve short paybacks depending on fuel/electricity prices and system size (IRENA, 2021). |

### *Agroforestry (trees and crop systems)*

Agroforestry is a type of shade farming that integrates trees with crops that offer a climate-resilient solution to crop heat stress and declining productivity in semi-arid West Africa by creating cooler microclimates, improving soil moisture retention, and enhancing nutrient cycling, as highlighted in Table 4. Tree canopies reduce direct solar radiation and evapotranspiration, helping crops like maize and tomatoes stay within optimal temperature ranges. These systems also restore soil health, prevent erosion, and diversify farm outputs through fruit, timber, and other tree products, thereby strengthening food security and farmer income (Danjuma *et al.,* 2018). In Nigeria and Ghana, where traditional land-use practices already include tree-crop integration, agroforestry presents a scalable, sustainable strategy for improving agricultural resilience amid climate change.

**Table 4: Quantitative Performance Indicators of Agroforestry Systems**

| Category | Quantitative Data |
|---|---|
| Crop yield | The study of Kuyah *et al.* (2019) reveals that agroforestry systems in sub-Saharan Africa significantly increased crop yields compared to traditional farming practices, with their finding supported by analysis of 1,106 observations from 126 peer-reviewed studies. |
| Water efficiency | Trees enhance soil moisture retention and reduce evapotranspiration. Shade trees in agroforestry help buffer crops during dry seasons (Siriri *et al,* 2013). |
| Energy output | Agroforestry is not primarily an energy-generating system; its energy benefits are typically indirect, e.g., conserving energy by reducing inputs like irrigation and fertilizers (Xu *et al*., 2019). Direct energy outputs occur only in designs explicitly aimed at biomass/fuelwood (Hinchee *et al*., 2009). |
| Carbon/Emissions | The study of Albrecht & Kandji (2003) shows that tropical agroforestry systems can sequester 12-228 Mg C $ha^{-1}$ (median 95 Mg C $ha^{-1}$), with global implementation on 585-1215 million hectares of suitable land potentially storing 1.1-2.2 Pg C over 50 years. |
| Land use efficiency | Multi-strata land use integrates perennial trees and annual crops, often increasing long-term productivity and ecosystem services (Danjuma *et al.,* 2018). |
| Cost | Agroforestry generates more than three times the net present value of monocropping systems while being less sensitive to price fluctuations, yield variations, and economic changes, making it significantly more profitable and financially stable than single-crop farming (Shode & Amanuel, 2016). |

## Impacts of the solutions on greenhouse gases

Greenhouse gas (GHG) emissions from agriculture and energy use in semi-arid West Africa are significant contributors to the global climate crisis. The region's dependence on diesel-powered irrigation, deforestation for farmland, and intensive fertilizer use results in high levels of carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$) emissions. The solutions proposed in this study, agrivoltaics, drip irrigation, and agroforestry, offer varying degrees of mitigation potential by reducing fossil fuel reliance, enhancing carbon sequestration, and improving resource efficiency. In terms of greenhouse gas emissions, the strategies collectively contribute to climate mitigation.

### *Agrivoltaics and emissions mitigation*

Agrivoltaics combines solar energy generation with crop production, enabling farmers to produce electricity while simultaneously growing food on the same land. In northern Ghana and northern Nigeria, agrivoltaics systems can avoid 250–350 metric tons of $CO_2e$ per hectare per year by displacing fossil fuel-based electricity such as diesel (Majumdar & Pasqualetti, 2018; IEA, 2023). While the manufacturing of solar panels entails embodied emissions of approximately 20–60 g $CO_2e$ per kWh, these emissions are amortized over 25–30 years, resulting in net emissions that are substantially lower than those from fossil fuels (Fraunhofer ISE, 2023). Agrivoltaics also confers biophysical benefits, as reduced crop heat stress under solar panels supports carbon sequestration through increased plant biomass and improved soil conditions (Barron-Gafford *et al*., 2019). By targeting one of the largest global emissions sectors, electricity generation, agrivoltaics provides a mitigation pathway aligned with United Nations Sustainable Development Goals 7 (Affordable Clean Energy) and 13 (Climate Action).

### *Drip irrigation and emissions reduction*

Drip irrigation itself does not generate energy, but when paired with solar pumps, it reduces reliance on diesel fuel, a common source of off-grid electricity in West Africa. Solar-powered drip systems can lower diesel use by 40-70%, leading to substantial emissions savings (IFAD, 2015; Alemayehu *et al*., 2019). Also, by improving water efficiency and boosting crop productivity, drip systems support greater biomass production, which indirectly enhances $CO_2$ absorption by plants (CGIAR, 2020).

*Agroforestry and carbon sequestration*

Agroforestry is highly effective at sequestering atmospheric $CO_2$ in both biomass and soils, making it one of the most sustainable land-use strategies for climate mitigation. Sequestration rates in agroforestry systems vary depending on species and management, with systems in northern Ghana and Nigeria capturing between 3 and 10 $tCO_2e$/ha/year (Zomer *et al.,* 2009; Bayala *et al.,* 2016). In addition to carbon sequestration, agroforestry enhances smallholder farmers' resilience to climate risks, providing a dual benefit for climate action (Lasco *et al.,* 2014).

**DPSIR framework to identify the impacts of solutions**

To assess the effect of the response on each variable in the DPSI, the following was used.

(+) – increase in variable
(-) – decrease in variable
(0) – no effect on variable
(+/-) – unknown or could be either positive or negative

Figures 4, 5, and 6 present the DPSIR frameworks, each illustrating the specific impacts of one of the proposed solutions.

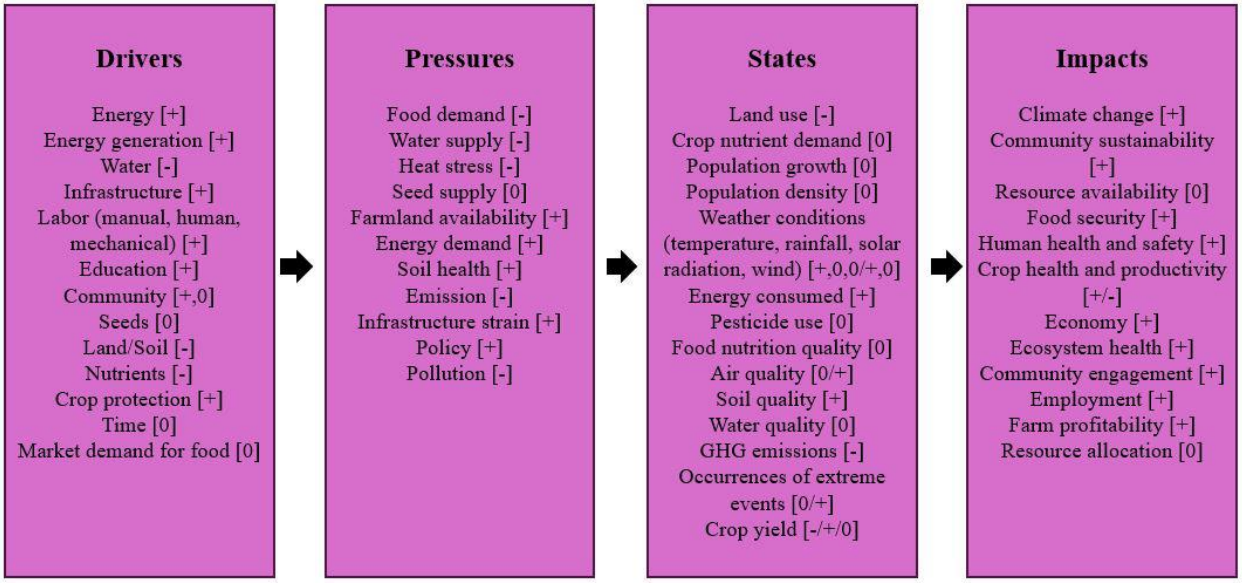

**Figure 3: The DPSIR framework identifies the impacts of agrivoltaics solutions**

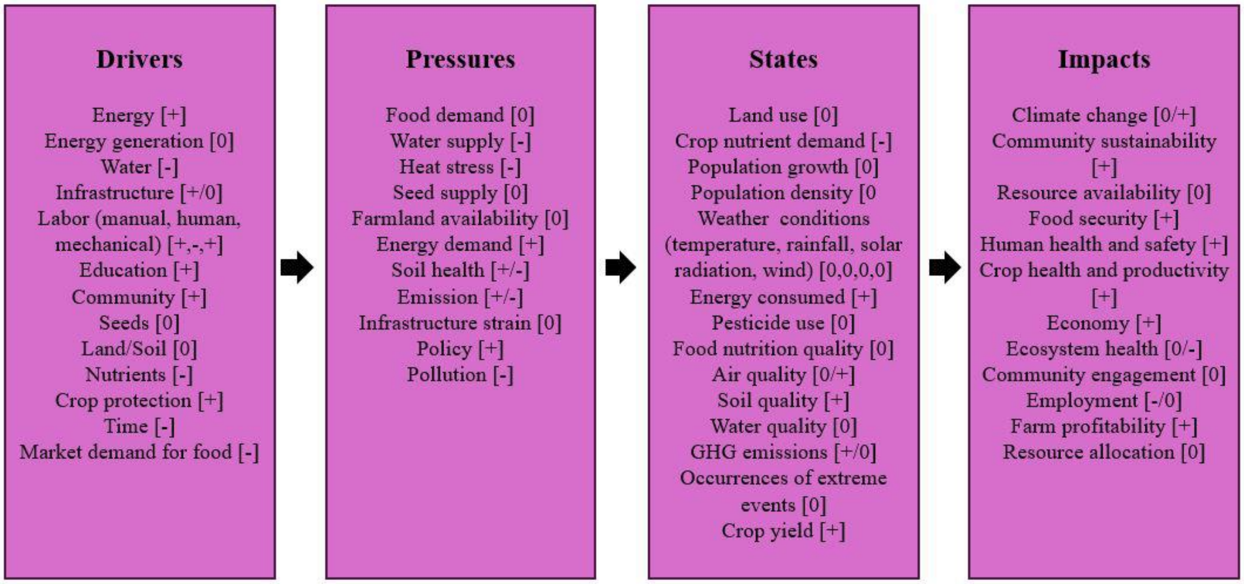

**Figure 4: The DPSIR framework identifies the impacts of drip irrigation solutions**

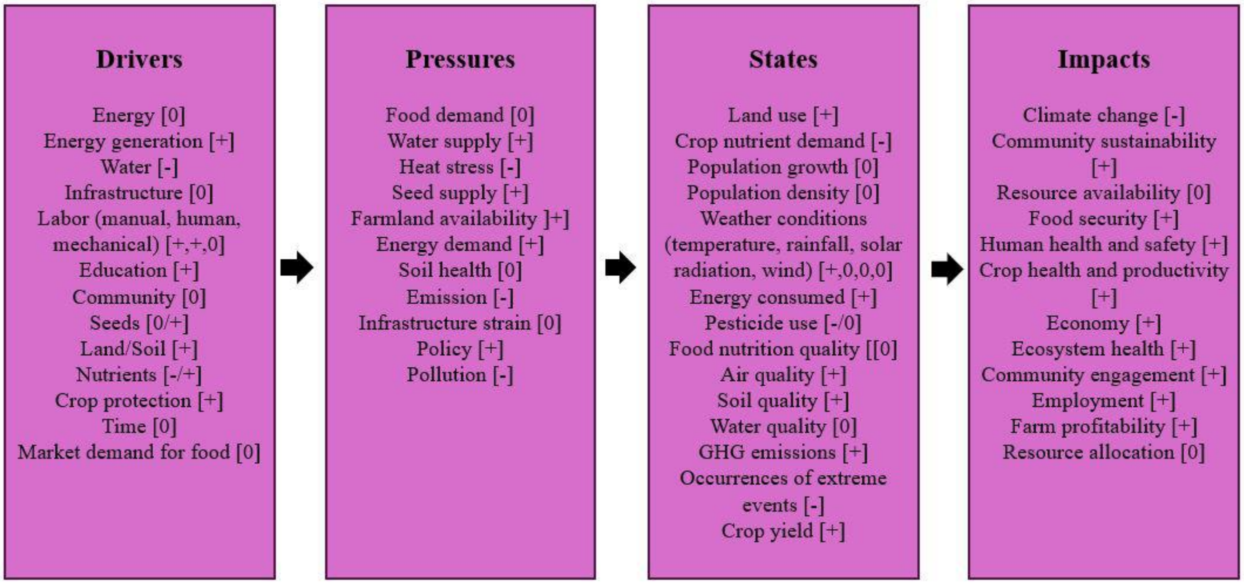

**Figure 5: The DPSIR framework identifies the impacts of agroforestry solutions**

### Socioeconomic impacts of proposed solutions

Our proposed solutions, which are agrivoltaics, drip irrigation, and agroforestry, offer integrated economic, social, and environmental benefits that align with the goals of enhancing agricultural productivity and resilience in Nigeria and Ghana.

Economically, each solution contributes to improved livelihoods through increased productivity and resource efficiency. Agrivoltaics, despite its high initial cost, provides dual benefits by generating both food and renewable energy, leading to new income streams, improved land use efficiency, and long-term returns from energy sales. Drip irrigation is more affordable and scalable, particularly with subsidies, and delivers immediate increases in crop yield and water-use efficiency, making it ideal for smallholder farmers. Agroforestry, with the lowest upfront cost, restores degraded lands and reduces the need for synthetic inputs, offering a strong benefit-cost ratio over time through diversified farm outputs.

Socially, these solutions enhance food security, empower marginalized groups, particularly women and youth, and build community resilience. Agrivoltaics supports clean energy access and creates green jobs, while drip irrigation reduces labor demands and promotes year-round farming. Agroforestry aligns with traditional land-use practices and strengthens rural livelihoods through ecosystem restoration and household diversification.

## Technical analysis of FEW considerations across solutions

A comparative technical analysis was conducted to evaluate how each of the three proposed solutions performs in terms of food productivity, water efficiency, and energy contributions. These FEW dimensions are central to the challenges faced in semi-arid West Africa.

### *Comparative analysis of FEW integration strategies - food productivity*

Agrivoltaics and drip irrigation both show strong potential for enhancing food productivity under climate stress, as shown in Table 5. Agrivoltaics provides moderate to high yield stability through shading, which protects crops from heat and moisture loss. Drip irrigation, however, offers the highest boost in yield by delivering water directly to plant roots, avoiding drought stress. Agroforestry supports food production in the long term, especially through intercrops and fruit-bearing trees, though it requires more time to mature. Overall, agrivoltaics and drip irrigation offer more immediate yield benefits, while agroforestry contributes gradual gains and additional food sources.

**Table 5: Food productivity comparison across solutions**

| Metric | Agrivoltaics | Drip Irrigation | Agroforestry |
|---|---|---|---|
| **Yield response (under heat stress)** | Moderate-high (crop-dependent) | High (especially in water-stressed regions) | Moderate (varies with tree maturity) |
| **Yield consistency** | Improved via microclimate control | Consistent if the water source is reliable | Improves over time with ecosystem recovery |
| **Additional food sources** | Not applicable | Not applicable | Fruits, nuts, and intercrops |
| **Risk of crop loss** | Reduced (shade protection) | Reduced (avoids drought shock) | Slightly reduced (windbreak, moisture retention) |
| **Income from food** | Potentially high | High (improved quality & quantity) | Moderate (depends on tree crop value) |

### *Comparative analysis of FEW integration strategies - water efficiency*

As shown in Table 6, drip irrigation clearly leads to water-use efficiency, reducing irrigation demand greatly as compared to traditional methods. Agrivoltaics also improves water conservation by shading the soil and reducing evaporation. Agroforestry offers natural moisture retention through tree cover and organic matter, making it effective in soil health and water holding capacity. While all three solutions reduce water loss, drip irrigation is the most efficient for areas where water scarcity is acute and access to irrigation infrastructure exists.

**Table 6: Water efficiency comparison across solutions**

| Metric | Agrivoltaics | Drip Irrigation | Agroforestry |
|---|---|---|---|
| **Water use efficiency** | Moderate-high (reduced evaporation) | Very high (targeted delivery) | Moderate (reduced evapotranspiration) |
| **Soil moisture retention** | High under panels | High at the root zone | High under the canopy and leaf litter |
| **Water loss via evaporation** | Reduced by panel shading | Very low (minimal surface loss) | Reduced due to tree cover |
| **Risk of overuse** | Low | Moderate-high (if not regulated) | Very low |

### *Comparative analysis of FEW integration strategies - energy efficiency*

Table 7 highlights the role of each solution in either reducing energy consumption or generating clean energy within agricultural systems. Agrivoltaics stands out as the only solution that generates clean energy, offering significant benefits for rural electrification and farm operations. Its ability to offset fossil fuel use and supply power for irrigation or processing adds a unique advantage. Drip irrigation, while not energy-producing, becomes more sustainable when paired with solar pumps, reducing diesel dependence. Agroforestry has a minimal direct energy impact but indirectly supports emissions reduction through carbon sequestration. In terms of energy access and emissions mitigation, agrivoltaics offers the most comprehensive benefits.

**Table 7: Energy impacts comparison across solutions**

| Metric | Agrivoltaics | Drip Irrigation | Agroforestry |
|---|---|---|---|
| **Energy generation** | High (solar PV power generation) | None directly, but compatible with solar pumps | None |
| **Energy use efficiency** | High (clean, on-site energy) | Moderate (low-pressure systems save energy) | Not applicable |
| **Dependency on fossil fuels** | Reduced significantly | Reduced if paired with renewables | No direct energy input |
| **Energy access for farmers** | Improved (can power irrigation/processing) | Possible with solar pumps | No direct benefit |
| **Emissions reduction potential** | High (offsets electricity and improves efficiency) | Moderate (via diesel reduction) | Indirect (carbon storage, no energy link) |

## Conclusion

In semi-arid regions of Nigeria and Ghana, climate change-induced crop heat stress, erratic rainfall, and limited infrastructure have critically undermined agricultural productivity, posing severe threats to food security, local farming practices, and rural livelihoods. This study synthesizes an integrated systems analysis of the problem through the FEW (Food-Energy-Water) nexus and socio-economic lenses, revealing that traditional coping strategies are no longer sufficient. Our analysis shows that the agricultural systems in these regions suffer from significant market failures and externalities, where smallholder farmers bear the brunt of climate impacts without the resources to adapt, necessitating public and policy interventions. In response, we propose three climate-smart, interdependent solutions: agrivoltaics, drip irrigation, and agroforestry. Agrivoltaics offers dual benefits of energy generation and crop shading but requires high initial investment; drip irrigation efficiently conserves water and boosts yields, making it ideal for smallholders when paired with solar pumps; and agroforestry restores degraded lands, sequesters carbon, and aligns with traditional practices. Together, these strategies address the economic, social, and environmental dimensions of resilience, boosting productivity, reducing greenhouse gas emissions, and empowering vulnerable communities, while paving the way for a more equitable, sustainable, and climate-resilient agricultural future in Nigeria and Ghana.

Among the three strategies analyzed, agrivoltaics emerges as the most promising solution for long-term food-energy-water resilience in semi-arid West Africa. Its ability to simultaneously reduce crop heat stress, conserve water, and generate clean energy makes it uniquely impactful. However, its high upfront cost remains a major barrier for smallholder farmers. With the support of government subsidies, low-interest loans, or cooperative financing models, agrivoltaics could become more accessible. Moreover, the sale of surplus electricity offers farmers a potential income stream, helping offset installation costs over time. When viewed through this lens, agrivoltaics is not only a climate-smart strategy but also an economically strategic one if integrated through inclusive policy and support systems.

## Data Limitation and Future Research

There is minimal quantitative data on agrivoltaics or shade systems specifically in Northern Ghana/ Northern Nigeria. Most agrivoltaics yield/water results come from temperate trials or modelling. More field trials testing local crops (maize, millet, sorghum, vegetables) under PV arrays are needed to measure real yield changes and microclimate effects. Similarly, data on drip irrigation performance in smallholder plots (with local soil and crop varieties) are sparse.

Co-design could fill data gaps: work with farmers, extension agents, and energy planners to pilot one or more technologies. On-farm trials (e.g., farmer-managed drip plots, community solar + crop sites, new agroforestry groves) would yield practical data on yields, water use, and costs. Interviews and focus groups can reveal barriers (e.g., technical know-how, land tenure) and local parameter values (e.g., yields under new practices, prices, labour costs).

Data and case-study results are drawn from peer-reviewed agrivoltaics and irrigation research and project reports, as well as technical analyses of PV land use. These cover a range of climates, where Nigeria or Ghana specific data are lacking, comparable evidence from other semi-arid regions has been cited. Each solution's performance will depend on a detailed local evaluation.

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