

A Critical Review of Irrigation-as-a-Service (IAS) Models in Ghana: Current Practices, Opportunities, and Challenges

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Front cover photograph: Irrigated cocoa farm in Central Region of Ghana. Credit: Kekeli Gbodji/IWMI

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SUMMARY

Ghana's irrigation sector is at a pivotal juncture, transitioning from traditional, donor-driven models toward decentralized, farmer-led, and market-based systems. With increasing climate variability, rising water demand, and growing feasibility of solar-powered irrigation systems (SPIS), the country has an opportunity to redefine its approach to agricultural water management. SPIS presents a sustainable pathway to enhance productivity, climate resilience, and income diversification, particularly for cocoa and vegetable farmers. However, adoption remains limited by high upfront costs, weak extension support, fragmented supply chains, and inadequate institutional and policy coordination. To overcome these challenges, three differentiated scaling pathways are proposed, aligned with the diverse resource capacities of Ghanaian farmers. Resource-rich farmers, typically owning medium to large plots and with access to credit, are best suited for ownership models, allowing them to invest directly in SPIS and potentially offer irrigation services to neighboring smallholders. Resource-limited farmers, cultivating smaller plots with irregular cash flows, would benefit from cooperative or shared ownership models, such as Pay-As-You-Go (PAYG) or seasonal leasing schemes that distribute costs and risks among groups. Resource-poor farmers, often land-insecure or marginalized, require fully serviced irrigation-as-a-service (IAS) models, where third-party providers own and operate systems, offering irrigation through contract-based or on-demand services. Scaling these pathways will require coordinated public-private partnerships, innovative financing mechanisms, capacity development, and policy alignment. Integrating SPIS into national programs such as *Planting for Food and Jobs* and *Climate-Smart Cocoa* will help mainstream adoption, while digital tools and blended finance can enhance affordability and efficiency. By tailoring business and service delivery models to farmer realities, Ghana can unlock the transformative potential of solar-powered irrigation advancing climate-smart agriculture, improving water and energy efficiency, and fostering inclusive, sustainable rural livelihoods.

1. INTRODUCTION

Climate change is increasingly disrupting agricultural systems in Ghana, particularly those dependent on rainfed water sources. Both food security and economic stability are at risk, especially in sectors like cocoa production that are highly climate sensitive. With erratic rainfall patterns, prolonged dry spells, and rising temperatures, traditional farming systems are becoming unsustainable without adaptation. Irrigation offers a powerful solution, but current irrigation coverage remains low, fragmented, and often inaccessible to smallholder farmers. Meanwhile, the country faces a dual imperative: improve agricultural productivity and adapt to climate risks, all while reducing greenhouse gas emissions. This is where climate-smart irrigation, especially solar-powered systems, becomes central to policy and development discourse. Such systems not only provide water security but also promote energy independence and resilience in off-grid rural areas (Akpoti et al. 2023; Gbodji et al. 2023).

Irrigation development in Ghana dates to the 1960s, with early projects led by the government through the Ghana Irrigation Development Authority (GIDA). These initial large-scale schemes focused on staple food production and were primarily located in northern Ghana, where rainfall is most erratic. Despite considerable investment over several decades, the sector has experienced limited expansion due to aging infrastructure, weak maintenance systems, and underutilization of existing facilities (Glitse et al. 2018). Estimates suggest that Ghana has about 1.9 million hectares of land with irrigation potential, yet less than 2% (approximately 30,000 hectares) is currently irrigated (Glitse et al. 2018). Most of the irrigated land is found under smallholder or informal irrigation schemes, rather than state-managed systems. Informal irrigation is especially common along riverbanks, around dams, and in low-lying areas where water is more accessible without high capital investment. Historically, one of the biggest bottlenecks in irrigation expansion has been high energy costs. Diesel-powered and electric pumps are expensive to operate, making irrigation economically unviable for many smallholder farmers (Amankwah 2015). This challenge is compounded by encroachment on irrigation lands, weak enforcement of land-use policies, and limited technical support from extension services (Glitse et al. 2018). In recent years, however, there has been a shift toward farmer-led irrigation development (FLID) and solar-powered irrigation technologies. These innovations enable smallholders to bypass traditional bottlenecks and expand access to irrigation in a decentralized and adaptive manner (Gbodji et al. 2023; Wanyama et al. 2023).

In Ghana, irrigation is predominantly used for the cultivation of high-value and water-demanding crops, particularly in areas with seasonal or erratic rainfall. The most common irrigated crops include vegetables, maize, rice, and sorghum, all of which significantly contribute to household food security, income generation, and year-round farming activities. Vegetables such as tomatoes, onions, lettuce, cabbage, and peppers are the primary crops in small-scale irrigation farming, particularly in urban and peri-urban areas like Accra, Kumasi, and Tamale. These crops are highly profitable, respond well to regular watering, and have short growth cycles that allow for multiple harvests per year (Adusei 2021). Urban farmers often rely on informal irrigation systems, including shallow wells and wastewater reuse, due to limited access to formal water infrastructure (Amankwah and Egyir 2013). Rice cultivation has expanded in irrigated valleys and inland floodplains. Both public and private irrigation schemes, especially in regions such as the Volta, Northern, and Upper East, support rice production. Supplemental irrigation enhances yields and reduces the risk of crop failure during periods of delayed or insufficient rainfall (Ahiamadia et al. 2024).

Cocoa production remains a foundation of Ghana's agricultural economy, contributing approximately 3% to national GDP and accounting for about 30% of the country's export earnings. Over 800,000 smallholder households rely on cocoa as a primary source of income. However, the sector is under serious threat from climate variability, with increasingly unpredictable rainfall patterns, prolonged dry spells, rising temperatures, and increased incidence of droughts that are affecting both yields and the long-term viability of cocoa farming in traditional growing zones. Recent studies document a significant decline in annual rainfall in cocoa-growing areas, with some regions experiencing over 15% less precipitation and as many as 25 fewer wet days per year over the past decade (Akpoti et al. 2025). This trend is especially pronounced in the transition and forest-savannah zones, where cocoa production has already begun to decline. Cocoa is particularly sensitive to water stress during critical stages such as flowering and pod development. Even moderate droughts during these phases can significantly reduce yields.

Furthermore, temperature increases of just 1.5 to 2°C are projected to push much of the current cocoa belt outside its optimal range. In response, some farmers are migrating cocoa production toward higher elevations or more forested, humid zones, but this raises concerns about deforestation and ecological degradation. In years with low rainfall or extended dry seasons, yield losses have ranged between 20–40%, depending on the location and farm management practices (Akpoti et al. 2025). These yield shocks have cascading effects on farmer income, access to education, and household food security. As climate extremes increase in frequency, so does the risk of crop failure and economic instability for rural household's dependent on cocoa. Beyond yield declines, climate change is also influencing pest and disease dynamics. Higher temperatures and increased variability in humidity are contributing to the spread of fungal infections (e.g., black pod disease) and pests, such as mirids, further undermining crop health and harvest quality (Asitoakor et al. 2022).

In response to these challenges, various climate adaptation initiatives have been launched, including tree shading, agroforestry systems, drought-tolerant cocoa varieties, and improved agronomic practices. While these practices provide short- to medium-term benefits, they do not fully address the water insecurity faced by cocoa farmers during increasingly frequent dry spells. There is growing recognition that irrigation must be part of the adaptation toolkit, particularly for maintaining yield stability during unpredictable weather conditions. Despite the increasing risks posed by climate change to cocoa farming in Ghana, the sector remains overwhelmingly rainfed, with minimal adoption of irrigation technologies. Unlike vegetable or rice cultivation, where irrigation has long been recognized as a productivity-enhancing tool, cocoa has traditionally been viewed as a low-input, low-water-demand perennial crop. This perception, combined with structural, technical, and financial barriers, has led to a significant underutilisation of irrigation in cocoa systems, even as rainfall patterns become more erratic and unreliable.

Climate-smart irrigation (CSI) involves technologies and practices that enhance water-use efficiency, strengthen resilience to climate variability, and reduce greenhouse gas emissions. In Ghana, the shift toward CSI is driven by urgent environmental, economic, and energy-related challenges. Increasingly frequent droughts, erratic rainfall, and declining surface water resources are pushing both farmers and policymakers to adopt solar-powered irrigation systems (SPIS) and other off-grid solutions tailored to smallholder contexts. Solar-powered irrigation is emerging as a practical and sustainable alternative to diesel or electric pumping. These systems enable farmers to irrigate their crops using free, abundant solar energy, thereby avoiding recurring fuel costs and unreliable electricity access. Studies show that SPIS is not only cost-effective in the long term but also reduces carbon emissions and provides flexibility for off-grid communities (Glitse et al. 2018; Gbodji et al. 2023). A study by Akpoti et al.

(2023) found that over 80% of cocoa-growing regions in Ghana have moderate to high groundwater potential, making solar-powered borehole irrigation a viable option for cocoa and other crops. Community-level solar grids can reduce equipment costs by over 80% compared to individual solar home systems by leveraging demand diversity in rural settings (Afonaa-Mensah et al. 2015).

A central challenge in scaling solar-powered irrigation systems (SPIS) is that ownership-based models, while promising, are not sufficient to ensure equitable, sustainable, and widespread adoption. Much of the work at IWMI has emphasized farmer ownership and financing structures as a way to expand access. However, evidence from Ethiopia, Bangladesh, and India shows that multiple pathways are needed. For example, IWMI has piloted “market linkage pathways” in Ethiopia, where SPIS are bundled with services and market access to make adoption more viable (Gebreyes et al. 2023). At the same time, comparative studies of ownership, community management, and fee-for-service models highlight that each comes with trade-offs. In Bangladesh, the fee-for-service and public-private partnership approach has been identified as the most financially sustainable pathway, especially given the high upfront costs of SPIS, while ownership models risk excluding poorer farmers (Mitra et al. 2023). Similarly, in India, small-scale solar pumping systems revealed that sustainability depends on context-specific institutional arrangements, system sizing, and post-installation support (Spielberg et al. 2016).

Beyond financing and management models, SPIS adoption also delivers co-benefits in climate resilience and food security. In Bangladesh, systems reduced vulnerability to drought, improved farmer resilience, and generated indirect benefits such as social group formation and employment opportunities (Rahman et al. 2021). As solar-powered irrigation gains momentum in Ghana, questions around who can access, afford, and sustainably operate these systems have become increasingly urgent. The current expansion of solar irrigation is largely driven by market forces and donor-supported pilots, but these often cater to resource-rich farmers with land, capital, and technical capacity. Without intentional design of inclusive ownership pathways, solar irrigation technologies risk reinforcing existing inequalities and leaving behind the vast majority of smallholder farmers, particularly women, tenant farmers, and the land-poor. Currently, the most common model in Ghana is individual ownership, where farmers independently invest in solar-powered irrigation pumps and related infrastructure. This model offers autonomy and flexibility, allowing farmers to scale up systems as needed. However, a 2023 study of cocoa-producing communities found that only wealthier households were likely to adopt solar irrigation primarily due to their access to income, education, land title, and credit (Gbodji et al. 2023). The study also highlighted structural exclusion based on gender and land ownership. For instance, tenant farmers and women with limited decision-making power often lack the collateral or legal rights needed to access financing or participate in ownership schemes.

Scaling solar-powered irrigation systems (SPIS) faces both structural barriers and promising opportunities. High upfront capital costs, limited financing options, insecure land tenure, and gender inequities restrict farmer ownership, while weak institutional coordination and fragmented service delivery further constrain uptake. At the same time, SPIS offers transformative opportunities: it reduces dependence on expensive diesel, improves water security, and creates co-benefits for climate resilience, income diversification, and rural employment (Mitra et al. 2023; (Rahman et al. 2021). Evidence from IWMI’s work in Ethiopia demonstrates that bundling SPIS with market access and services can accelerate adoption (Gebreyes et al. 2023), while comparative studies across South Asia highlight fee-for-service and cooperative models as viable alternatives to individual ownership (Spielberg et al. 2016).

This review argues that solar-powered, farmer-led irrigation must be repositioned as a central pillar of climate-smart cocoa production, not merely as a supplemental strategy, but as a transformative mechanism bridging adaptation policy and the lived realities of rural producers. By synthesizing understandings from climate adaptation, irrigation science, cocoa-sector governance, and rural development, it identifies potential pathways including inclusive financing mechanisms, gender-responsive policies, and cross-sector coordination between cocoa actors, irrigation planners, and energy policymakers. In doing so, it contributes a critical synthesis that addresses long-standing fragmentation in research and practice, and positions SPIS as a scalable, equitable, and climate-resilient innovation for Ghana's cocoa sector.

2 ANALYTICAL FRAMEWORK

Figure 1 presents analytical elements to analyze the enabling environment for scaling irrigation-as-a-service (IAS) and solar-powered irrigation systems (SPIS) in Sub-Saharan Africa, with specific reference to Ghana.

Physical and resource environment: The framework highlights the importance of assessing groundwater potential, solar irradiance, land characteristics, and supporting infrastructure as foundational determinants of IAS viability. In Ghana, significant shallow groundwater reserves and strong solar radiation levels provide favorable conditions, but fragmented landholdings, weak hydrogeological mapping, and poor rural infrastructure constrain deployment. These factors underscore the need for spatially explicit resource assessments to guide investments and ensure technical feasibility across diverse agroecological zones.

Service environment (enabling conditions): The institutional context, including policy, regulatory frameworks, and social inclusion, plays a decisive role in shaping the IAS landscape. In Ghana and wider SSA, fragmented governance between water, energy, and agricultural agencies often leads to duplication and inefficiency. Weak policy integration undermines the mainstreaming of SPIS into irrigation planning. Gender and tenure inequalities further exacerbate exclusion, particularly for women and tenant farmers. At the same time, climate-smart cocoa initiatives and adaptation finance provide an opening for embedding SPIS into broader resilience strategies, highlighting the importance of cross-sectoral policy coordination and inclusive program design.

IAS business model design: Different farmer segments require tailored business models to ensure equitable participation. Resource-rich farmers are best suited to ownership models, while resource-limited farmers benefit from cooperative ownership or pay-as-you-go arrangements. For resource-poor farmers, full-service IAS models, where providers deliver irrigation on demand, are most viable. Bundling irrigation services with training, inputs, and financial tools has proven effective in Ethiopia and Ghana, reducing risks and making services accessible. The business model design thus connects barriers like high upfront costs and weak technical knowledge with opportunities for innovation in bundled, flexible service offerings.

IAS market and supply chain: The supply chain encompasses global imports, national distribution, local retailing, and critical after-sales services. In Ghana, supply networks are concentrated in urban centers, leaving rural cocoa-producing areas underserved. The scarcity of trained technicians, fragmented distribution channels, and lack of spare parts undermine reliability. Yet, youth-led cooperatives, private entrepreneurs, and mobile service providers are emerging as intermediaries, signaling potential for market diversification. Lessons from Ethiopia and Kenya show that bundling training and certification into supply networks improves confidence and uptake, a strategy directly applicable to Ghana.

Farmer demand and investment behaviour: Farmer adoption depends on affordability, awareness, and trust in IAS models. While evidence shows strong willingness to pay for irrigation services once technologies are introduced, baseline awareness remains low, particularly among women and marginalized farmers. Irregular cash flows limit adoption under high-cost ownership models, making cooperative, seasonal, or PAYG approaches more attractive. Digital platforms and mobile money services increasingly support flexible payments, service coordination, and accountability, reducing transaction barriers. *Systemic barriers and opportunities:* Across these domains lie systemic barriers, such as high upfront costs, poor institutional coordination, limited technician networks, and exclusion of vulnerable groups. At the same time, opportunities exist in spatial planning tools, digital innovations, youth-led service provision, and alignment with climate-smart agriculture programs. By explicitly linking barriers to opportunities, the framework identifies leverage points for reform and innovation. *IAS pathway for scaling solar-powered irrigation:* Ultimately, *the IAS pathway in Ghana represents a spectrum of ownership*, cooperative, PAYG, and full-service models, underpinned by multi-stakeholder partnerships. By aligning physical resources, enabling institutions, market systems, and farmer demand, IAS can bridge systemic gaps and catalyze equitable, climate-smart irrigation expansion in cocoa and vegetable systems across Ghana and the wider SSA region.

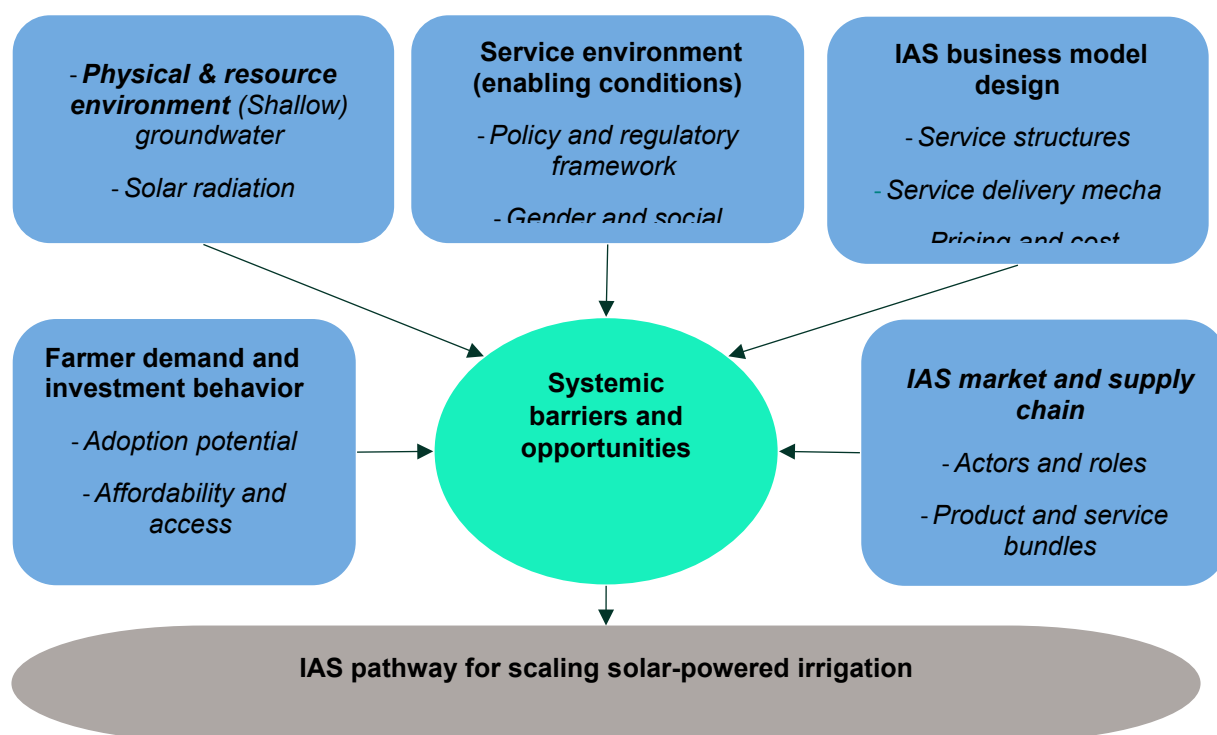


Figure 1. Analytical Framework

Source: Adopted from IWMI-Nigeria Report, 2025

3 METHODOLOGY

3.1 Review Process

This review employed a structured literature synthesis approach to explore the landscape of solar-powered irrigation development in Ghana, with specific attention to smallholder agriculture, cocoa systems, and farmer-led innovation. A systematic search of academic and grey literature was conducted using the Consensus academic research platform. The search strategy combined relevant keywords such as “solar irrigation,” “Ghana,” “climate-smart agriculture,” “farmer-led irrigation,” “cocoa farming,” and “off-grid renewable energy.” Inclusion criteria focused on studies published between 2002 and 2024, with an emphasis on those that provided empirical data, policy analysis, or conceptual frameworks related to irrigation adoption, solar technology, and smallholder resilience in Ghana or comparable Sub-Saharan African contexts. Sources included peer-reviewed journal articles, working papers from CGIAR institutions, policy briefs from organizations like IWMI, GIZ, and FAO, as well as national strategy documents (e.g., the Ghana Irrigation Development Policy and the Renewable Energy Master Plan). To ensure thematic consistency, all documents were assessed using a coding framework aligned with the six core domains identified in this review: (1) the physical and resource environment, (2) Service environment, (3) IAS business model design, (4) farmer demand and behaviour, (5) IAS market and supply chain dynamics, and (6) Systemic Barriers and Opportunities. Articles were selected iteratively, with reference snowballing used to expand the source base when key citations appeared in multiple documents. Where overlapping findings emerged, synthesis techniques were used to consolidate insights and reduce duplication.

3.2 Data Analysis

The data collected through the review process was analyzed using a thematic content analysis approach, designed to identify, categorize, and interpret recurring patterns across diverse sources. After selecting relevant literature, each study was coded according to the six predefined domains central to this review as found in Table 1 below: (1) the physical/resource environment, (2) Service environment (enabling conditions and policies), (3) IAS business model structures, (4) farmer demand and behavior, (5) IAS market and supply chain, and (6) systemic barriers and enabling opportunities. Coding was done manually by extracting key findings and accumulating them into a shared matrix, enabling cross-comparison of results across crop types (e.g., vegetables, maize, cocoa), technologies (e.g., solar pumps, drip systems), and actor types (e.g., individual farmers, cooperatives, public-private partnerships). Where possible, quantitative data such as cost-benefit estimates, yield increases, or adoption rates were compared across studies to triangulate outcomes. Studies presenting similar conclusions were clustered to emphasize consensus, while outliers were flagged for contextual explanation. Attention was also paid to gender, tenure status, and geographic equity, given their central role in determining access to irrigation. Additionally, particular weight was given to papers that used rigorous methods such as randomized trials, econometric modeling, or geospatial groundwater analysis (Gbodji et al. 2023; Akpoti et al. 2023).

Table 1: Coding Framework for Thematic Analysis of IAS in Ghana

Main Theme	Subthemes	Example Codes / Indicators
a) Physical & Resource Environment	Water Availability	Groundwater recharge rates, aquifer distribution, and seasonal stream flow
	Energy & Infrastructure	Solar irradiance (kWh/m ² /day), off-grid energy access, rural road quality, logistics for SPIS transport
	Land and Farm Characteristics	Cocoa farm sizes (hectares), land slope, tenure security, plot fragmentation
b) Service Environment (Enabling Conditions)	Policy & Regulatory Framework	Third-party irrigation licenses, solar irrigation subsidies, water abstraction permits, and IAS policy inclusion
	Institutional Support	Extension services for SPIS, inclusion of IAS in MoFA programs, and gender-equitable training initiatives
c) IAS Business Model Design	Service Structures	Cooperative ownership, farmer-owned vs. provider-operated, embedded private entrepreneur models
	Service Delivery Mechanisms	On-demand vs. contract services, mobile units, fixed installations, drip vs. hose systems
	Pricing & Cost Recovery	Per-hour pricing, seasonal fees, credit-based payments, and subsidy access for service providers
d) IAS Market and Supply Chain	Actors and Roles	Solar pump suppliers, borehole drillers, local repair technicians, and aggregator platforms
	Product & Service Bundles	SPIS packages (solar panel + pump + hose + operator), bundled with training or agronomy advice
	Market Trends	Demand growth in vegetable-producing zones, off-grid cluster development, and cocoa irrigation emergence
e) Farmer Demand & Investment Behavior	Adoption Potential	Willingness to pay (WTP), demand elasticity by crop type, and trust in service providers
	Affordability & Access	Household income levels, access to mobile money or agri-credit, and gender gaps in finance
	Service Preferences	Preferred service frequency, interest in mobile vs. fixed systems, and equipment familiarity
f). Systemic Barriers and Opportunities	Barriers	Limited farmer awareness, absence of local technicians, weak inter-agency coordination, and lack of groundwater data
	Opportunities	Use of mobile apps for service scheduling, youth-led irrigation businesses, and donor climate funding

Source: Author's Construct (2025)

4. RESULTS

4.1 Result of Review on the Following Categories for both Sub-Saharan Africa and Ghana

4.1.1 Physical & Resource Environment

Irrigation system viability in Ghana's cocoa landscapes is shaped by three interlinked factors: water availability, energy access, and land characteristics. Among these, water availability remains the most critical foundation. While national narratives often emphasize scarcity, emerging evidence highlights substantial untapped potential. For example, recent hydrological analysis in Ghana's Upper Offin basin shows that subsurface flows and deep percolation could sustain groundwater-fed irrigation on up to 10% of land during the dry season, doubling if deep percolation is harnessed. This supplemental irrigation could close

nearly half of the cocoa yield gap and significantly improve resilience, though land-use change threatens to destabilize the water balance (Tilahun et al. 2025). Broader suitability assessments reinforce this potential: nearly 80% of Ghana’s cocoa belt has moderate-to-high suitability for groundwater-fed irrigation (Akpoti et al. 2023), echoing earlier findings that shallow wells already sustain dry-season farming in the Upper East Region (Namara et al. 2011). These insights suggest that Ghana’s irrigation challenges are less about physical scarcity than about underutilization and poor spatial planning. Figure 2 shows the potential groundwater for Climate-Smart Cocoa Irrigation in Ghana.

In the energy and infrastructure sectors, Ghana holds favourable conditions for solar-powered irrigation. Solar irradiance consistently exceeds 5.0 kWh/m²/day across much of the cocoa zone, closely aligning with dry-season evapotranspiration needs (Figure 3) (Danso and Dietzen 2025). Research by the International Water Management Institute (IWMI) has mapped the technical suitability of solar irrigation across Ghana, finding wide potential but emphasizing that viability depends on business models that are accessible to smallholders. Their work highlights the promise of both ownership and service-based models but underscores the importance of targeted investment and risk-sharing mechanisms (Gebrezgabher et al. 2021). Yet, despite this technical promise, systemic barriers remain. Fragmented supply chains, high import tariffs on pumps, limited availability of spare parts, and the absence of reliable maintenance services continue to restrict the scale-up of solar-powered irrigation systems (SPIS). These challenges mirror a broader sub-Saharan African pattern where weak last-mile delivery and high upfront costs constrain adoption, even in climatically suitable regions (Agyapong & Anto, 2023; Durga et al. 2024).

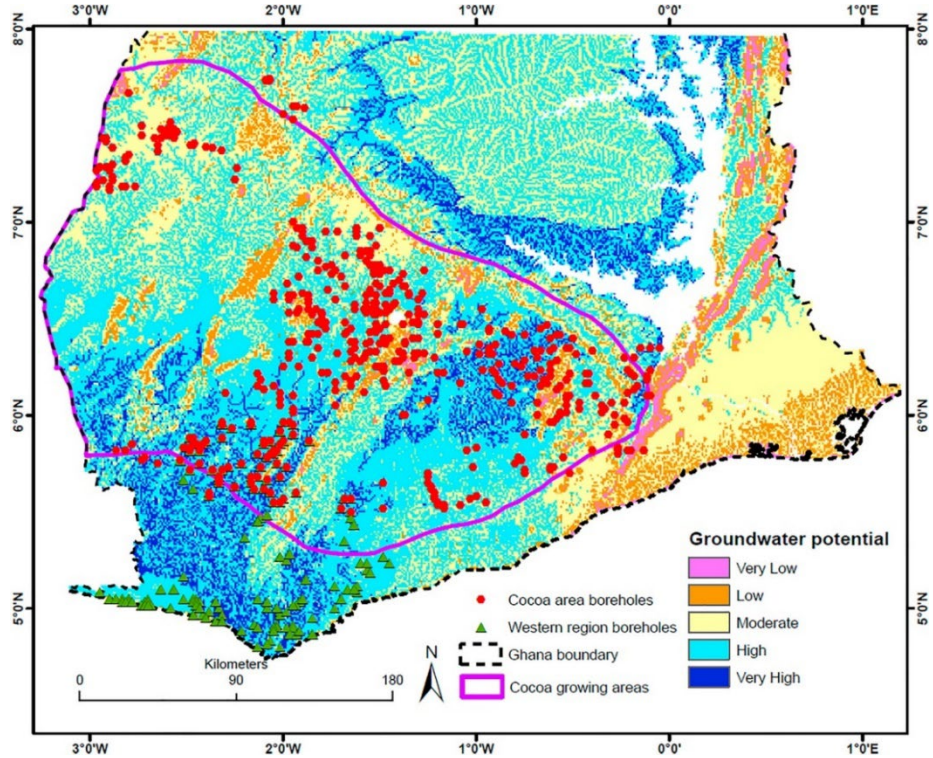


Figure 2: Integrating GIS & Remote Sensing for Land Use/Land Cover Mapping & Groundwater Potential Assessment for Climate-Smart Cocoa Irrigation in Ghana

Source: Adopted from Akpoti et al. (2023).

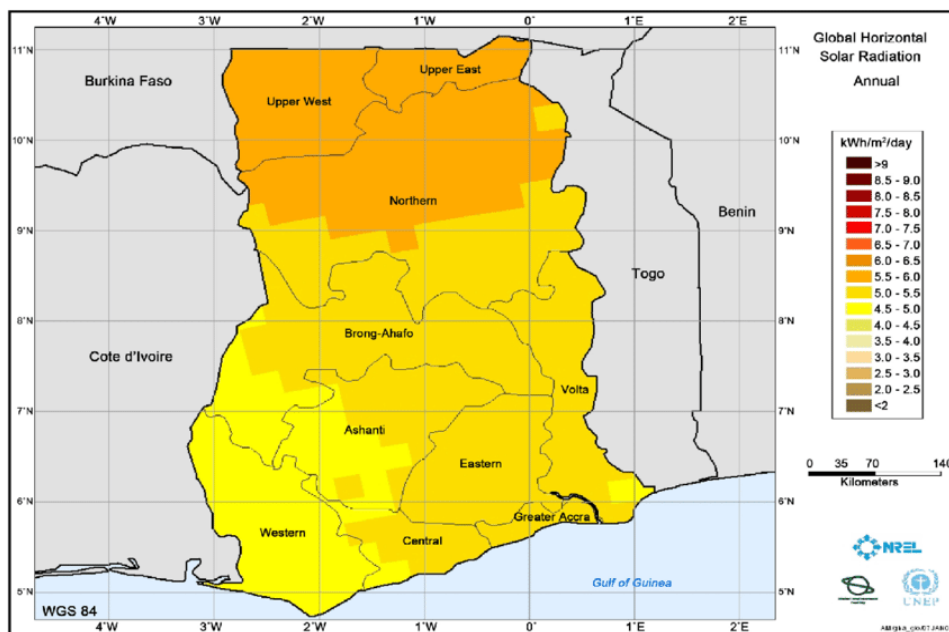


Figure 3. Annual daily average global horizontal irradiance plot for Ghana

Source: Adopted from Ababio et al. (2021)

Evidence from Sub-Saharan Africa shows that high upfront investment costs, limited access to credit, fragmented supply chains, and weak after-sales services are the most common barriers to solar-powered irrigation uptake (Durga et al. 2024). Replicating such bundled service models in Ghana's underserved cocoa regions could therefore help address parallel gaps by integrating technology provision with farmer training, maintenance services, and market linkages. This approach would not only reduce the risks borne by individual farmers but also create more sustainable pathways for scaling solar-powered irrigation in support of climate-smart cocoa production.

Land and farm characteristics further mediate irrigation potential. Cocoa farms in Ghana typically range from 1–3 hectares, often fragmented and interspersed with shaded trees, which poses challenges for fixed irrigation infrastructure. Secure tenure is also a key variable. Donkor et al. (2023) find that land titling significantly increases farmers' likelihood to invest in irrigation, a pattern also echoed in cross-country analysis by Adu-Baffour et al. (2021), which shows land ownership as a critical predictor of SPIS adoption. In contrast, in South Asia and Sahelian West Africa, larger average field sizes and flatter terrains facilitate mobile irrigation units and broader mechanization (Faye and von Braun, 2024). However, Ghana's landscape offers room for adaptive design: drip or hose-based systems with flexible layout are often more suitable than sprinkler or pivot models in tree-dense cocoa agroforests (Baidoo et al. 2024). Designing terrain, farm size, and crop geometry is thus essential in avoiding the one-size-fits-all pitfalls that have undermined adoption in other regions.

The Ghanaian case also reveals how physical and resource constraints intersect with economic viability. Falchetta et al. (2023), using a pan-African spatial model, estimate that up to 55 million hectares of smallholder land in SSA could be economically irrigated with SPIS. But they caution that without guardrails such as water abstraction regulation and energy governance, widespread adoption could jeopardize aquifer sustainability. This aligns with earlier warnings by Namara et al. (2014), who emphasized the need for water resource management policies to evolve in parallel with technological scale-up.

4.1.2 Service environment (enabling conditions)

Irrigation development in Ghana is increasingly shaped by its evolving policy and institutional landscape. However, the enabling environment for solar-powered irrigation systems (SPIS) and farmer-led irrigation development (FLID) remains partial, fragmented, and insufficiently adaptive to the unique demands of decentralized irrigation systems. A growing body of literature reveals persistent regulatory and institutional constraints that limit scale, equity, and sustainability despite demonstrated farmer demand and private-sector innovation.

At the regulatory level, there is currently no unified national framework that licenses third-party irrigation service providers (IAS providers) or offers clear guidelines for their operation. While large-scale irrigation projects fall under the Ghana Irrigation Development Authority (GIDA), decentralized, mobile, or solar-based services often operate in a regulatory vacuum. Lal (2023) highlights that in such contexts, the absence of formal recognition for service-based irrigation providers leads to inconsistency in service quality, pricing, and long-term viability. Moreover, current tax structures and import tariffs have not been optimized for SPIS expansion. As Agyapong and Anto (2023) observe, high duties on solar components, along with exchange rate volatility, severely undermine affordability and investor confidence despite Ghana's long history of off-grid solar experimentation. The exclusion of SPIS from key subsidy schemes or energy tariffs has also limited adoption. IWMI (2023) notes that in countries where solar irrigation is bundled with financial and regulatory incentives such as import waivers, abstraction permits, or service registration uptake is significantly higher. In Ghana, however, policy frameworks continue to prioritize grid-based energy systems or capital-heavy infrastructure, rather than incentivizing modular, private systems aligned with FLID. Minh et al. (2020) further argue that Ghana's irrigation policies lack clear mandates or funding streams to support FLID pathways, resulting in an uncoordinated patchwork of pilots, often dependent on donor support and lacking scale-out mechanisms.

Beyond formal policy gaps, institutional coordination is weak across the sectors that govern irrigation, energy, agriculture, and local governance. Obuobie et al. (2023) show that fragmented roles between MoFA, GIDA, the Energy Commission, and decentralized local governments result in overlaps, inefficiencies, and the neglect of operational issues such as maintenance, water permitting, and SPIS repair services. In practice, this fragmentation means that farmers and service providers must navigate multiple bureaucracies, none of which have clear mandates to support solar irrigation holistically. Institutional support for irrigation service delivery is similarly underdeveloped. Agricultural extension officers are rarely trained in SPIS operation, energy scheduling, or water abstraction calculations. As Adu-Baffour et al. (2021) demonstrates through multi-country regression analysis, access to extension is a significant predictor of SPIS adoption, along with education and land ownership. In Ghana, however, SPIS training is inconsistently delivered and rarely integrated into MoFA's mainstream programs. Lal (2023) argues that for irrigation-as-a-service (IAS) to function effectively, technical training must be extended not only to farmers but also to service providers and pump operators, especially in mobile and PAYG delivery contexts. Equity in training and institutional outreach remains a key concern. Van Koppen et al. (2013) and Kwoyiga (2024) both highlight systemic gender disparities in access to training, land rights, and irrigation decision-making. Although women in cocoa and vegetable systems often possess indigenous knowledge about water access, plot conditions, and pump scheduling, they are frequently excluded from cooperative ownership structures or training programs dominated by male leaders. In a recent Ghana-based study, Katic (2024) finds that irrigation access yields varied livelihood benefits depending on age and gender group, with

young women gaining significantly less than young men under existing irrigation models. These findings suggest that, beyond general equity goals, irrigation strategies must intentionally differentiate support based on demographic characteristics to achieve poverty reduction and equitable livelihood impacts.

Public–private partnerships (PPPs) and bundled service models offer a promising route to scale, but they require enabling regulation and policy support. IWMI (2023) reports that in Ethiopia, bundling hardware, finance, and training through PPPs significantly improved uptake and sustainability of SPIS. The potential for replication in Ghana is high, particularly in high-priority zones for cocoa irrigation. Yet without institutional frameworks to guide PPP design and implementation, such initiatives risk fragmentation or elite capture. Lal (2023) and Minh et al. (2020) both emphasize the need for cross-sector alignment between agriculture, energy, finance, and local governance to ensure SPIS and FLID scale equitably and sustainably.

4.1.3 IAS Business Model Design

The success of irrigation-as-a-service (IAS) models in Ghana is increasingly shaped by the structure of the service enterprise, the modality of delivery, and how cost recovery is structured. While early smallholder irrigation relied primarily on farmer ownership of pumps or informal group sharing, emerging models now range from cooperative-owned assets to PAYG (pay-as-you-go) systems and third-party providers offering professional irrigation services. Across Sub-Saharan Africa, these models vary in maturity, scale, and inclusivity but Ghana is now seeing increasing experimentation and convergence around flexible, bundled service structures.

In terms of service structure, cooperative ownership remains one of the most promoted approaches, especially among vegetable farmers in the Northern and Upper East Regions. Akrofi et al. (2019) report that shared ownership models lower entry barriers for resource-constrained farmers but are often hampered by challenges like repayment defaults and governance disputes over scheduling and maintenance. In contrast, studies from Burkina Faso and Niger show that community-led models succeed when paired with clear rules and support from extension officers and local governments (Sally 2002). A growing trend in Ghana and elsewhere is the rise of provider-operated IAS models, where entrepreneurs or cooperatives own and maintain equipment, delivering irrigation as a paid service. Lal (2023) emphasizes that this model reduces the financial burden on farmers while creating employment opportunities, particularly when paired with digital tools and structured maintenance plans.

Service delivery mechanisms in Ghana vary from fixed infrastructure (reservoir-linked schemes) to mobile pump services that are deployed on demand. Minh et al. (2022) highlight that mobile SPIS units in Ghana’s Upper East Region are especially attractive for smallholder vegetable growers with fragmented land holdings. Similarly, the IWMI (2023) bundling pilots in Ethiopia show that mobility and bundling (pump + tank + hose + operator) increase system utilization and expand access to farmers who cannot afford their own equipment. The comparison between fixed and mobile models is instructive: fixed systems tend to benefit larger landholders or cocoa cooperatives with permanent boreholes, whereas mobile units provide flexibility and scalability in mixed landscapes like Ghana’s cocoa belt.

Drip versus hose delivery systems reflect another layer of business model differentiation. Drip systems are more water-efficient and compatible with solar pumps but require upfront planning and infrastructure, making them better suited for long-term investments or higher-

value crop zones (Baidoo et al. 2024). Conversely, hose-based systems are cheaper, easier to deploy, and preferred by many mobile service providers operating under seasonal contracts (Owusu 2016).

On the issue of pricing and cost recovery, IAS models are evolving from flat-rate, per-season fees toward more granular and adaptive pricing schemes. Studies by Davuluri (2019) and Pelizan et al. (2019) show that PAYG models, supported by mobile payments, are effective in rural Ghana when bundled with agent support and basic financial literacy training. These approaches have been particularly successful among vegetable farmers with variable income streams but can also be adapted for cocoa growers during dry-season flowering periods. However, as Durga et al. (2024) argue, PAYG models are vulnerable to breakdown in areas with poor network coverage or limited access to mobile banking, constraints common in remote cocoa zones.

Subsidy access and credit schemes also play a central role in service provider sustainability. While few public subsidies currently target SPIS service models in Ghana, IWMI (2023) and Minh et al. (2024) stress that bundling hardware with financial services such as credit guarantees or seasonal loan windows can drastically improve adoption and reduce default risks. Comparative examples from Ethiopia and Kenya further illustrate how public-private partnership (PPP) models that share capital costs and risks between governments, donor programs, and entrepreneurs can enable broader SPIS access across demographic groups (IWMI 2023a).

4.1.4 IAS Market and Supply Chain

The development and sustainability of irrigation-as-a-service (IAS) in Ghana are deeply tied to the strength and inclusiveness of its market and supply chain ecosystem. This includes not only the actors involved in technology delivery and support but also the packaging of services and equipment in accessible formats, and the responsiveness of the market to evolving demand, particularly for off-grid, climate-smart irrigation technologies.

A growing number of actors now participate across Ghana's solar irrigation value chain, reflecting an increasingly decentralized and entrepreneurial approach. Technology suppliers are typically importers or distributors of solar pumps, storage tanks, drip kits, and power inverters, often concentrated in urban centers like Accra and Kumasi. Yet, local technicians crucial for installation and maintenance are unevenly distributed and often undertrained, which limits service reliability in rural cocoa-growing areas (Glitse et al. 2018). In more mature markets like Kenya and Ethiopia, bundling training and certification into distribution programs has improved after-sales service quality and market confidence (IWMI 2023a). Ghana is now seeing the rise of private entrepreneurs and youth-led cooperatives that act as irrigation service providers, operating mobile SPIS units across farms, especially for vegetable farmers in the northern transition zones. These actors serve as critical intermediaries between technology suppliers and smallholders, often combining technical delivery with financial intermediation and customer support.

Closely related to market actors is the bundling of products and services into packages that are more user-friendly and financially viable. A typical solar irrigation bundle may include a pump, hose or drip system, storage tank, and sometimes an operator. Minh et al. (2022) and IWMI (2023b) emphasize that bundling not only enhances service uptake but also enables targeted training, increases ease of maintenance, and lowers risk perception among farmers. In Ghana, the bundling approach is especially useful for mobile service providers, who lease or rent SPIS kits to farmers under flexible terms. The “bundle + service” model has proven

effective in reducing market entry barriers, particularly for female farmers and tenant cocoa growers who might otherwise lack capital or technical knowledge (Katic 2024). In Nigeria and Ethiopia, solar pump bundling with embedded training and access to finance has been instrumental in boosting rural adoption, demonstrating the replicability of this strategy in Ghana.

Teferi *et al.* (2024) highlight that irrigation businesses often struggle with substandard products, counterfeit pumps, shortages of genuine spare parts, and poor-quality after-sales service. These problems erode farmer trust and weaken demand. In addition, policy and regulatory hurdles such as import duties, foreign currency shortages, and inefficient tax exemption systems drive up equipment costs and delay supply. Many firms also face limited access to finance, weak market data, and low business capacity to scale operations. These lessons are directly relevant for Ghana, where fragmented supply chains and uneven technician training already constrain service delivery. Integrating stronger quality assurance, financing options, and regulatory support into Ghana's IAS ecosystem could therefore help avoid similar pitfalls while fostering more sustainable irrigation growth.

The IAS market is also shaped by clear and accelerating trends, particularly the growing demand for off-grid irrigation solutions. Gbodji *et al.* (2023) find that cocoa farmers in Ghana are increasingly willing to pay for SPIS, especially those with larger landholdings or access to credit. This mirrors adoption patterns in vegetable sectors across East Africa, where targeted PAYG financing has enabled smallholders to irrigate seasonally or contractually (Falchetta *et al.* 2023). Furthermore, diversified crop markets are driving demand: while cocoa irrigation remains nascent, dry-season vegetable production, especially tomatoes, onions, and leafy greens relies heavily on SPIS in Ghana's Upper East and Northern Regions (Baidoo *et al.* 2024). This inter-crop spillover effect is helping to normalize solar irrigation and expand supplier footprints.

Still, significant supply chain challenges persist. These include high costs due to import taxes, fragmented distribution networks, lack of spare parts in remote regions, and a scarcity of trained repair agents. Baidoo *et al.* (2024) note that business models must integrate cost-sharing and risk-reduction features to thrive in such fragmented environments. Lessons from Ethiopia reinforce that without regulatory reforms, product quality controls, and investment in business capacity, these barriers will continue to undermine market growth (Teferi *et al.* 2024). The emerging consensus is that a combination of public-private partnerships, regional distribution hubs, and integrated logistics planning will be needed to build a resilient IAS supply chain. Lessons from Rwanda and India suggest that national-level subsidies tied to verified supplier networks can reduce costs and improve quality control strategies worth exploring in Ghana (Dekker 2015; Kayitare *et al.* 2023).

4.1.5 Farmer Demand and Investment Behaviour

The uptake of irrigation-as-a-service (IAS), particularly through solar-powered systems, is strongly mediated by smallholder farmers' willingness to adopt and pay, their ability to afford services, and their preferences for how those services are delivered. In Ghana and across Sub-Saharan Africa, increasing climate variability, the allure of dry-season production, and exposure to success stories are driving interest in solar irrigation. However, this interest is often tempered by concerns over affordability, access to credit, and trust in service reliability.

Gbodji *et al.* (2023) provide a benchmark analysis of cocoa farmers' willingness to invest in solar-powered irrigation pumps (SPIPs) in Ghana using a contingent valuation method with 523 respondents. The study reveals that effective demand is highly stratified by farmer

resource endowment. Resource-rich farmers are far more likely to adopt SPIPs, while the resource-poor and resource-limited exhibit demand gaps due to financial constraints. Willingness to pay is significantly influenced by income, land ownership, education level, credit access, and extension services. This finding aligns with evidence from Falchetta et al. (2023), who estimate that solar irrigation has strong profit potential across SSA, but uptake is constrained by affordability and financing bottlenecks. These studies highlight the critical importance of designing flexible pricing models, such as pay-as-you-go (PAYG), and bundling irrigation with value-added services like training or maintenance to increase trust and reliability.

Affordability remains a central barrier, especially for cocoa farmers who face seasonal income cycles and low liquidity during dry periods. Akrofi (2019) shows that farmers in Ghana value supplemental irrigation highly, but adoption is sensitive to cost structure average willingness-to-pay for small-scale systems was just under \$7 per acre per season. Similarly, Martey et al. (2023) found that access to simple irrigation scheduling tools is limited not only by cost but by information gaps, particularly among women and low-income farmers. Notably, women, youth, and higher-income earners were more likely to pay for such tools when they received adequate information and training. Gendered dimensions of affordability were further emphasized by Katic (2024), who found that female and youth farmers often face greater hurdles accessing credit and are more likely to rely on shared or seasonal service models than on equipment ownership.

Credit access is repeatedly flagged as a determinant of IAS investment behaviour. Kyire et al. (2023) confirm that credit intensity among irrigated rice farmers in Ghana is positively influenced by access to extension services and contract farming. When credit is available, especially through mobile platforms or informal savings groups, adoption increases significantly. This is corroborated by Davuluri (2019) and Pelizan et al. (2019), who showed that bundling mobile money repayment plans with agent support improves farmer commitment to PAYG solar irrigation schemes.

When it comes to service preferences, farmer demand tends to cluster around flexible, seasonally aligned services. Yussif et al. (2017) report that Ghanaian farmers are willing to pay for private irrigation services up to GHS 35.60 per acre on average but prefer services that align with dry-season crop cycles and allow for on-demand usage. Trust in service reliability is a crucial factor: farmers express concern over maintenance support, pump downtime, and water access during peak periods. According to Baidoo et al. (2024), smallholders are more likely to adopt when services come bundled with training, post-sale maintenance, and access to real-time water supply data or operator assistance. Ensuring broad-based access to solar-powered irrigation systems in Ghana requires exploring innovative ownership models that address capital constraints, equity concerns, and system sustainability. One increasingly viable approach is group or cooperative ownership, where smallholder farmers pool resources to acquire and manage shared irrigation assets. This model promotes economies of scale and peer-to-peer learning but depends heavily on strong governance structures and conflict resolution mechanisms to manage shared responsibilities like scheduling, maintenance, and payments (Akrofi et al. 2019). Alternatively, Pay-As-You-Go (PAYG) and leasing models have gained traction in Ghana's off-grid energy sector, offering smallholders the ability to pay for solar systems in manageable installments via mobile money platforms. This flexible arrangement, already proven effective in household solar energy access (Davuluri 2019); (Pelizan et al. 2019), holds significant promise for solar irrigation, particularly if supported by rural banks or microfinance institutions.

Public-Private Partnerships (PPPs) represent another promising avenue, where governments or development agencies co-invest private firms to lower costs and deliver irrigation infrastructure to underserved regions. Evidence from Ghana shows that such PPPs can accelerate solar deployment when structured transparently and aligned with local agricultural priorities (Awuku et al. 2021; Glitse et al. 2017). Another emerging model is community-owned infrastructure with private access rights, where collective systems (like boreholes and storage tanks) are jointly maintained, while individual farmers invest in smaller distribution assets such as drip lines or hoses for their own plots (Akudugu and Issahaku 2013). Regardless of the model, sustainable scaling of solar irrigation technologies demands supportive ecosystems, including access to affordable finance, technical training, land tenure security, and coherent cross-sectoral policy frameworks (Aboubacar 2023). Without these foundational elements, even well-designed ownership models may struggle to deliver equitable and lasting benefits to smallholder farmers.

4.1.6 Systemic Barriers and Opportunities

Despite growing interest and evidence of the viability of solar-powered irrigation systems (SPIS), Ghana's irrigation development landscape continues to face systemic constraints that hinder equitable scaling and sustainability. Many of these barriers also apply to the development of irrigation-as-a-service (IAS), since both models rely on similar enabling conditions in markets, policy, and service ecosystems. The barriers that emerge from this review are best understood across four thematic domains as displayed in Table 2: knowledge and awareness, institutional coordination, technical capacity, and policy/financial frameworks.

Knowledge and awareness: A prominent barrier is the low awareness and limited understanding of SPIS and IAS options among many smallholder farmers. Studies, such as those by Martey et al. (2023), show that while nearly all surveyed farmers expressed a willingness to pay for irrigation scheduling tools once introduced, baseline awareness of such technologies was minimal, especially among women and lower-income groups. This reflects a broader issue of weak extension outreach and technology diffusion, which disproportionately excludes vulnerable farmers from innovation cycles. IAS models, which depend on farmer trust in service providers, are equally constrained by these gaps in awareness and information flow.

Institutional coordination: Another critical challenge lies in governance and coordination failures. Obuobie et al. (2023) and Minh et al. (2022) highlight how fragmentation between agriculture, energy, and water governance structures has led to duplicated efforts, inconsistent policy frameworks, and poor integration of SPIS into national irrigation planning. These governance gaps undermine both investor confidence and farmer uptake. The same applies to IAS, which requires clear frameworks on service provision, regulation of private providers, and alignment with rural electrification and water-use planning. Without institutional clarity, IAS markets risk remaining fragmented and unregulated.

Technical capacity: A persistent barrier is the shortage of skilled technicians and reliable service providers. Without adequate technical support, especially in rural zones, many SPIS systems become non-functional due to simple maintenance issues. Baidoo et al. (2024) observed that farmer-managed solar drip systems often failed without structured training or bundled support services. Limited technician networks also constrain the scalability of IAS models, particularly mobile and pay-as-you-go schemes that depend on responsive local maintenance. Similarly, the scarcity of localized data for site-specific irrigation planning remains a cross-cutting issue. While Akpoti et al. (2023) have mapped groundwater

availability in the cocoa belt using GIS tools, this data has not been widely mainstreamed into planning frameworks or farmer-facing tools. Both SPIS and IAS models face challenges in targeting suitable sites and ensuring technical viability.

Policy and financial frameworks: Perhaps the most systemic barrier, though often underemphasized, is the policy environment. Import tariffs on solar pumps, inefficient subsidy targeting, and inconsistent donor financing raise costs and increase market uncertainty (Durga et al. 2024). IAS businesses are vulnerable to policy gaps: without clear quality standards, certification frameworks, and financing incentives, many service providers struggle to expand. Lessons from Ethiopia show how substandard products, regulatory inefficiencies, and weak business capacity erode farmer trust and market stability (Teferi et al. 2024). Without proactive policy reforms, IAS in Ghana risks encountering the same systemic bottlenecks.

These systemic barriers also point to several emerging opportunities. One of the most promising is the advent of digital tools that enable scheduling, payment, and performance monitoring. Systems using mobile money and apps for irrigation service coordination enable transparent pricing and usage tracking in remote communities (Minh et al. 2024). Such tools can reduce information asymmetry, build trust, and support adaptive pricing for resource-poor farmers. Expansion of community-based and youth-led service models, i.e., youth-managed irrigation initiatives, enhance both rural employment and irrigation service delivery, reinforcing the value of supporting entrepreneurial youth groups through incubation and financing strategies (Katic 2024). These initiatives simultaneously address rural employment and irrigation access, offering scalable templates for cocoa zones and off-grid areas.

Finally, a strategic policy opening exists through climate adaptation and donor programming windows. International actors and national climate-smart cocoa (CSC) initiatives are increasingly recognizing the need for water solutions. While current CSC programs often overlook irrigation (Forest Trends, 2019), there is growing momentum to embed SPIS and IAS into broader climate resilience and sustainable intensification strategies. This creates a fertile ground for cross-sectoral collaboration, results-based financing, and integrated support for service-based irrigation models.

Table 2: Summary of barriers and opportunities for SPIS in Ghana

Thematic Domain	Barriers	Opportunities / Pathways	Relevance to SPIS & IAS
Knowledge & Awareness	<ul style="list-style-type: none"> - Low awareness of SPIS/IAS options among smallholders. - Weak extension and diffusion, especially for women and low-income farmers. - Limited trust in service providers for IAS. 	<ul style="list-style-type: none"> - Digital tools (apps, mobile money) for scheduling, payment, and monitoring. - Targeted extension campaigns and inclusive training programs. 	<ul style="list-style-type: none"> - Both SPIS and IAS rely on farmer knowledge, and trust awareness-building is foundational.
Institutional Coordination	<ul style="list-style-type: none"> - Fragmentation across agriculture, energy, and water sectors. - Duplicated efforts, weak policy alignment, and lack of integration into irrigation planning. 	<ul style="list-style-type: none"> - Cross-sectoral collaboration platforms. - Integration of SPIS/IAS into national irrigation and climate-smart cocoa strategies. 	<ul style="list-style-type: none"> - IAS especially requires regulatory clarity on service provision and private provider roles.

Technical Capacity	<ul style="list-style-type: none"> - Shortage of skilled technicians and after-sales service. - SPIS breakdowns due to poor maintenance. - Weak technician networks constrain IAS mobile/PAYG models. - Lack of localized hydro-geological data. 	<ul style="list-style-type: none"> - Bundled service models (training + installation + maintenance). - Youth-led technical enterprises for SPIS/IAS services. - Expansion of suitability mapping into farmer-facing tools. 	<ul style="list-style-type: none"> - Both models need stronger local technical ecosystems - IAS models depend more heavily on responsive maintenance.
Policy & Financial Frameworks	<ul style="list-style-type: none"> - High import tariffs on solar pumps and inconsistent subsidies. - Inconsistent donor financing. - Lack of quality standards and certification for IAS providers. 	<ul style="list-style-type: none"> - Results-based financing and risk-sharing models. <ul style="list-style-type: none"> - Public-private partnerships to de-risk investments. - Embedding SPIS/IAS into climate-smart cocoa and adaptation programs. 	<ul style="list-style-type: none"> - Policy clarity and financial innovation are critical leverage points for scaling IAS and SPIS.

Source: Author's Construct (2025)

4.2. Pathway Development for Scaling IAS (Irrigation-As-A-Service)

The successful scaling of irrigation-as-a-service (IAS) in Ghana requires the design of context-sensitive pathways that accommodate the diverse needs, capacities, and constraints of smallholder farmers. Broadly, three farmer segments emerge from empirical and valuation studies: resource-rich, resource-limited, and resource-poor, each requiring a different model of engagement.

4.2.1. Resource-rich farmers

For farmers with larger cocoa or vegetable farms, stronger land tenure, and better access to credit and extension services, ownership-based models are most viable. This group shows higher willingness and ability to pay for SPIS, with adoption likelihood strongly correlated with landholding size and income (Gbodji et al. 2023). Yet even these farmers face high upfront costs and unreliable service support. Bundled solutions, combining equipment with technician training, financing, and maintenance, can reduce risks while positioning this group as local service providers. Models piloted in East Africa and Ethiopia show that resource-rich farmers often become informal irrigation vendors, renting systems to neighbors or acting as embedded entrepreneurs (Lal 2023; Minh et al. 2022). Supporting such farmer-to-farmer service spillovers could strengthen Ghana's IAS ecosystem.

4.2.2. Resource-limited farmers

For smallholders with fragmented plots and irregular cash flows, full ownership is less feasible. Semi-service or shared models, such as cooperative ownership of pumps or group-based PAYG leasing, lower the capital barrier. However, these arrangements often face governance challenges like scheduling conflicts and repayment defaults (Akrofi et al. 2019). Here, the barrier of weak coordination becomes an opportunity: digital platforms and bundled training, as tested in Ethiopia and Ghana, can enhance reliability, support transparent

scheduling, and enable mobile payments (IWMI 2023; Minh et al. 2024). Cooperatives, women's groups, and rural associations can serve as key intermediaries, especially if backed by dispute-resolution mechanisms and accountability frameworks.

4.2.3. Resource-poor farmers

For land-insecure, income-constrained farmers, especially women and marginalized households, fully outsourced IAS models are essential. These models address barriers of affordability and risk by transferring system ownership to service providers who deliver irrigation on demand or via contracts. While capital-intensive, viability improves when irrigation is bundled with complementary services such as input supply, training, and microfinance (Minh and Ofosu 2022; Falchetta et al. 2023). Here, private entrepreneurs, youth-led pump service enterprises, and NGOs play critical roles as direct providers. Mobile money-enabled platforms can further reduce transaction frictions and allow flexible micro-payments.

4.2.4. Cross-cutting pathways

Across all farmer segments, bundling emerges as a central strategy for addressing systemic barriers. By integrating irrigation hardware with financing, extension, and maintenance, bundling directly tackles the challenges of high upfront costs, weak technical support, and low awareness. At the same time, multi-stakeholder partnerships are indispensable. Public-private partnerships (PPPs) linking governments, NGOs, solar tech providers, and farmer organizations help de-risk private investments, provide co-financing, and strengthen extension (IWMI 2023; Baidoo et al. 2024). Gender- and youth-focused programs add another layer of opportunity: women farmers, despite systemic barriers, show high returns when provided access to SPIS (van Koppen et al. 2013; Kwoyiga 2024), while youth-led irrigation services (Katic 2024) simultaneously expand coverage and generate rural employment. Finally, spatially explicit planning tools that integrate groundwater, solar irradiance, road access, and crop suitability (Akpoti et al. 2023; Adhikari et al. 2021) are vital for matching service models to local realities, thereby reducing technical risks and guiding investment.

4.3 Gaps and Opportunities for Solar-Based Irrigation in Ghana

The literature review reveals both a growing recognition of its potential and persistent gaps that continue to constrain its equitable scaling (see Table 3). Across the cocoa belt and wider smallholder farming systems, irrigation development is shaped less by physical scarcity than by systemic weaknesses in knowledge, governance, technical ecosystems, and policy frameworks. At the same time, emerging innovations and institutional openings suggest clear pathways for overcoming these challenges and positioning solar irrigation as a transformative element of climate-smart agriculture.

The first gap lies in knowledge and awareness. Despite evidence of farmers' willingness to pay for irrigation technologies once they are introduced, baseline knowledge of SPIS and IAS remains extremely low, particularly among women and resource-poor groups. Weak extension services, limited diffusion of technologies, and a lack of inclusive outreach perpetuate these knowledge asymmetries. In the case of IAS, which depends heavily on trust in service providers, poor awareness and information flows act as a direct barrier to farmer participation. This indicates that awareness-raising, extension reform, and targeted inclusion strategies are critical starting points for scaling both ownership and service-based models.

Second, the literature points to entrenched institutional coordination challenges. Irrigation development is often undermined by fragmented governance across agriculture, energy, and water institutions, resulting in duplicated programs, inconsistent policy signals, and a lack of integration of SPIS into national irrigation plans. For IAS, these coordination failures create even sharper risks, as service provision requires clear regulatory frameworks that define roles for private providers, align with water-use planning, and harmonize with rural electrification strategies. Without greater institutional clarity, the promise of both SPIS and IAS is unlikely to translate into large-scale adoption.

A third systemic gap concerns technical capacity and infrastructure support. Multiple studies highlight the shortage of trained technicians, the uneven distribution of local repair agents, and the absence of reliable after-sales services, particularly in rural zones. These deficiencies mean that even technically viable SPIS systems often become non-functional due to minor maintenance problems. IAS models that rely on mobile or pay-as-you-go schemes are equally constrained by the lack of responsive maintenance networks. The scarcity of site-specific hydro-geological and suitability data adds another layer of constraint, limiting both private investment targeting and farmer decision-making. While GIS-based mapping of groundwater and solar potential exists, these insights are not yet widely embedded into planning frameworks or accessible to end users.

Finally, the review highlights significant weaknesses in policy and financial frameworks. High import tariffs on solar pumps, poorly targeted subsidies, inconsistent donor financing, and the absence of quality standards or certification schemes raise costs and introduce uncertainty into the market. IAS providers, in particular, are vulnerable to policy gaps: without clear standards, regulatory oversight, and financing incentives, many struggle to build sustainable businesses or gain farmer trust. Lessons from other sub-Saharan African countries demonstrate how poor regulation and weak business capacity can erode market stability risks that Ghana must address proactively.

Despite these barriers, literature also points to important opportunities and pathways for innovation. Digital tools, including mobile apps and mobile-money-enabled platforms, are being piloted to support scheduling, payments, and performance monitoring. These tools have the potential to reduce information asymmetry, build transparency, and increase trust between farmers and service providers. Similarly, bundled service models that package pumps with training, financing, and after-sales maintenance have shown effectiveness in reducing adoption risks, particularly for smallholders with limited resources. In parallel, youth- and community-led service initiatives demonstrate how entrepreneurial models can address rural employment gaps while also building reliable technical capacity and expanding service coverage.

At the policy level, a strategic opening exists through climate adaptation and donor programming windows. Climate-smart cocoa (CSC) initiatives, as well as broader national climate adaptation frameworks, increasingly recognize the need for reliable water solutions. While irrigation has historically been overlooked in these programs, there is growing momentum to embed SPIS and IAS as central pillars of resilience and sustainable intensification strategies. This alignment creates an opportunity for results-based financing, stronger public-private partnerships, and cross-sectoral collaboration that can de-risk investments and accelerate adoption.

Table 3. Theme-based gaps and opportunities for scaling solar irrigation in Ghana

Thematic Domain	Key Gaps/Barriers	Emerging Opportunities/Pathways
Knowledge and Awareness	• Low farmer awareness and understanding of SPIS and IAS	• Farmer-targeted sensitization and training programs

	<p>options</p> <ul style="list-style-type: none"> • Weak extension outreach and limited inclusion of women and youth • Low trust in service-based models due to poor information flow 	<ul style="list-style-type: none"> • Strengthening of digital extension and peer learning platforms • Inclusion-focused outreach through women's and youth groups
Institutional Coordination	<ul style="list-style-type: none"> • Fragmented governance among agriculture, water, and energy sectors • Duplication of efforts and inconsistent policy direction • Lack of clear regulatory framework for IAS and private service provision 	<ul style="list-style-type: none"> • Creation of multi-sectoral coordination platforms • Integration of SPIS into national irrigation and energy plans • Development of quality assurance and service regulation standards
Technical Capacity and Infrastructure	<ul style="list-style-type: none"> • Shortage of trained technicians and maintenance networks • Weak supply chains and limited access to spare parts • Lack of site-specific hydrogeological and solar resource data 	<ul style="list-style-type: none"> • Promotion of youth-led technical enterprises • Bundled service models combining technology, training, and maintenance • GIS-based data integration for irrigation planning
Policy and Financial Frameworks	<ul style="list-style-type: none"> • High import tariffs and inconsistent subsidy mechanisms • Absence of certification standards and poor regulation • Limited access to affordable finance for farmers and service providers 	<ul style="list-style-type: none"> • Policy reforms to streamline tariffs and standards • Results-based financing and blended investment mechanisms • Integration of SPIS and IAS in climate adaptation and CSC programs

Source: Author's Construct (2025)

4.4. Proposed scaling pathways for solar-based irrigation

The successful scaling of solar-based irrigation in Ghana demands a deliberate and inclusive strategy that aligns technical feasibility with institutional readiness, market incentives, and social equity as seen in Figure 4. Given the heterogeneity of Ghana's smallholder farming systems, particularly within cocoa-growing landscapes, no single model cannot meet the diverse needs of farmers. Instead, scaling pathways must be differentiated by farmer resource capacity, land tenure status, and access to complementary services, while aiding grounded in broader climate and development goals. Table 4, provides a summary of the proposed scaling pathways for IAS in Ghana.

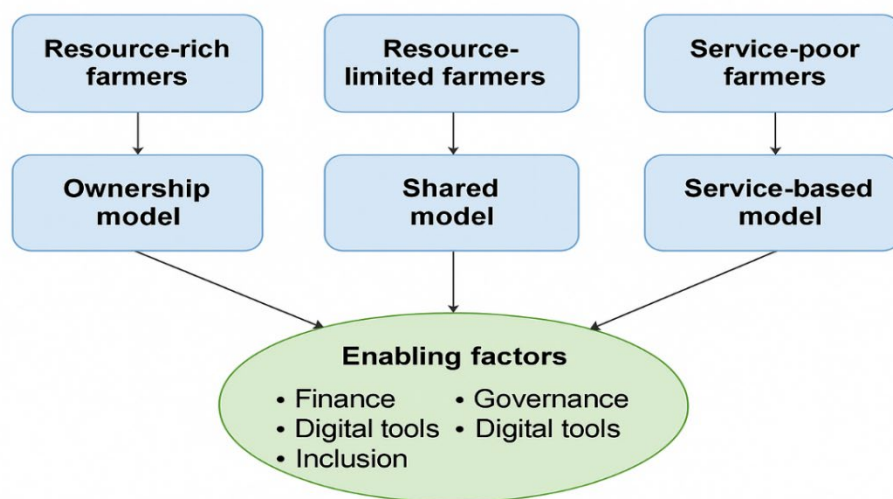
4.4.1 Farmer Segmentation and Tailored Engagement Models

Empirical evidence suggests three primary farmer categories: resource-rich, resource-limited, and resource-poor, each requiring a different scaling approach.

- *Resource-rich farmers, typically owning medium to large plots and possessing access to credit and extension services, are best suited for ownership models. These farmers demonstrate higher willingness and ability to pay for solar-powered irrigation systems (SPIS), often viewing them as long-term productivity investments. They also hold potential to become local irrigation service providers by renting their systems to neighboring smallholders, thereby expanding irrigation access within communities.*
- *Resource-limited farmers, who cultivate smaller plots and face irregular cash flows, benefit most from shared or cooperative-based models. This includes group ownership, cooperative PAYG (Pay-As-You-Go) leasing, or seasonal rental schemes*

that distribute costs and reduce capital burdens. Digital platforms can further enhance coordination by managing scheduling, payments, and usage tracking, while bundled services (training, maintenance, and financial literacy) help sustain such collective arrangements.

- Resource-poor farmers, often land-insecure and highly vulnerable, require fully serviced irrigation-as-a-service (IAS) models. Under these arrangements, third-party providers own and operate SPIS units, delivering irrigation through contract-based or on-demand services. This approach ensures inclusive access without imposing upfront investment burdens, especially for women, tenants, and marginalized farmers.



Proposed scaling pathways for solar-based irrigation

Figure 4 (conceptual diagram) illustrating scaling pathways.

Source: Author’s Construct (2025)

4.4.2 Bundled and Service-Oriented Pathways

Bundled models are central to addressing multiple systemic barriers simultaneously: technical, financial, and informational. The bundling approach, successfully piloted in Ethiopia, pairs irrigation technology with capacity building, input supply, and tailored financing. Such integration reduces technology failure rates, improves repayment performance, and increases trust in service models. In the Ghanaian context, bundling could combine solar pumps with agronomic training, digital extension, and market linkages within existing programs like the Climate-Smart Cocoa Initiative or Planting for Food and Jobs. This would also align with national energy access strategies by leveraging distributed renewable infrastructure for productive uses.

4.4.3 Institutional Partnerships and Governance Reform

Scaling solar irrigation requires coherent institutional arrangements that bridge the traditional silos between water, agriculture, and energy governance. Effective scaling will rely on public–private partnerships (PPPs) that combine government coordination with private-sector efficiency and NGO facilitation. Government agencies should focus on establishing

enabling policies such as import duty exemptions for solar equipment, quality certification standards, and access-to-finance mechanisms, while private actors deliver technology and after-sales services. NGOs and research institutions can strengthen local capacity and ensure gender and youth inclusion through training and monitoring. The creation of an Inter-Ministerial Taskforce on Solar Irrigation could further ensure alignment between irrigation planning, renewable energy policy, and climate adaptation objectives.

4.4.4 Financing and Incentive Mechanisms

The transition to solar irrigation will depend on innovative financing mechanisms that lower upfront costs and distribute risk. Blended finance instruments, combining concessional public funds with private capital, can de-risk investments and incentivize service providers to target smallholder segments. Results-based financing (RBF) and leasing schemes could also encourage the private sector to expand IAS operations in rural zones. In parallel, financial inclusion initiatives that integrate mobile-money payments, credit guarantees, and microinsurance would enable smallholders to participate sustainably in SPIS markets. The government, development banks, and climate funds (e.g., the Green Climate Fund) can play catalytic roles by co-financing pilots and supporting market development.

4.4.5 Digital and Data-Driven Support Systems

Digital technologies can play a transformative role in enabling efficiency, transparency, and scalability. Mobile applications and remote-sensing platforms can support irrigation scheduling, payment tracking, and system monitoring. Integration of geospatial data on groundwater, solar irradiance, and crop suitability into planning systems can help target investments more effectively. Expanding digital literacy among farmers, technicians, and local service providers will further enhance the adoption and sustainability of solar irrigation systems.

4.4.6 Equity, Gender, and Youth Inclusion

Equitable access must remain central to all scaling strategies. Women, youth, and land-insecure farmers often face compounded barriers, including limited collateral, exclusion from training programs, and social constraints on technology use. Mainstreaming gender-responsive design, inclusive financing, and youth entrepreneurship within solar irrigation programs is therefore essential. Youth-led service enterprises, in particular, present a dual opportunity expanding rural employment while improving local maintenance capacity. Tailored financing, business incubation, and mentorship programs can foster a new generation of “rural green entrepreneurs” who drive both energy transition and agricultural resilience.

4.4.7 Spatial Planning and Environmental Safeguards

Finally, spatially explicit planning is needed to ensure that scaling solar irrigation does not compromise ecosystem integrity or water balance. Using GIS-based assessments of groundwater potential, solar radiation, and land suitability, planners can identify priority zones where irrigation expansion aligns with environmental sustainability. Integrating environmental safeguards such as sustainable water abstraction limits and soil management practices into solar irrigation policies will ensure long-term viability and resilience.

Table 4 Proposed Scaling Pathways for Solar-Based Irrigation in Ghana

Farmer Segment / Context	Recommended Model	Core Features / Bundles	Key Support Actors	Expected Outcomes
Resource-rich farmers	Ownership / Vendor Model	Direct purchase or financed acquisition; potential to rent out services; bundled training & maintenance	Private sector, rural banks, MoFA, extension services	Localized service expansion and demonstration effects
Resource-limited farmers	Cooperative / Shared Model	Group-based PAYG, shared pump ownership, digital coordination, conflict-resolution support	Cooperatives, NGOs, digital providers, IWMI	Cost-sharing, inclusive access, improved governance
Resource-poor farmers	Full Service (IAS) Model	Providers own/operate SPIS; irrigation on-demand or contract basis; mobile-money payments	Private service providers, NGOs, donors	Inclusive access, zero upfront costs, improved equity
Cross-cutting support	Bundled Service & PPP Pathways	Integration of finance, training, and input supply; risk-sharing via blended finance	Government, development banks, private firms	Systemic scalability, reduced technology failure
Cross-cutting enablers	Digital & Climate Integration	Mobile apps, geospatial targeting, CSC alignment, gender/youth inclusion	Research institutions, MoFA, Energy Commission	Smart scaling, climate resilience, social inclusion

Source: Author’s Construct (2025)

5. CONCLUSION

Irrigation development in Ghana is entering a pivotal phase, shifting from traditional, centralized, and donor-driven models toward decentralized, farmer-led, and market-based systems. This transition reflects broader structural changes driven by climate variability, the rising demand for water security in cocoa and vegetable production, and the expanding feasibility of solar-powered irrigation technologies. This review highlights that while the adoption of solar-powered irrigation is steadily increasing particularly through bundled service models and informal entrepreneurial initiatives systemic challenges continue to limit equitable scaling. Key constraints include weak extension support for solar irrigation, fragmented and underdeveloped supply chains, persistent gender and youth access barriers, and limited policy recognition of emerging Irrigation-as-a-Service (IAS) models. The evidence underscores the importance of differentiated business models tailored to farmer resource levels: ownership-based systems for wealthier farmers, shared or cooperative approaches for middle-income groups, and fully serviced or pay-as-you-go (PAYG) models for resource-poor households. Complementary investments in technical capacity, infrastructure, and financial innovation are equally critical to sustaining adoption. At the same time, Ghana’s opportunities for scaling solar irrigation are substantial. Spatial mapping of groundwater and solar potential, growing private sector participation, and the emergence of youth- and community-led service models point to a fertile innovation landscape. Strategic public–private partnerships (PPPs) and digital tools for payment, scheduling, and monitoring further enhance prospects for inclusive expansion.

Realizing this potential, however, will require a coherent and coordinated policy framework that bridges the water–energy–agriculture nexus while embedding financial inclusion and

climate resilience. Integrating solar irrigation more explicitly within the Climate-Smart Cocoa (CSC) agenda and expanding its relevance from high-value vegetables to perennial crops like cocoa will be vital to building long-term adaptation capacity and strengthening rural livelihoods. With the right mix of enabling policies, investment, and institutional alignment, solar irrigation can serve as a transformative lever for sustainable agricultural intensification and equitable growth in Ghana's smallholder systems.

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APPENDIX

Table A1 Literature Review Matrix

#	Citation	Focus Area	Methodology	Key Findings	Relevance
1	Gbodji et al., 2023	Solar irrigation demand for cocoa	Contingent valuation with 523 farmers	Demand varies by wealth tier; resource-rich farmers more likely to invest; credit, education, and extension services increase WTP	Core study on SPIP adoption behavior and investment needs
2	Agbenyo et al., 2022	Impact of CSA practices on income	Endogenous switching regression	Irrigation raises cocoa income by 8.6–11.1%; credit access critical	Validates economic case for solar irrigation as CSA
3	Yiridomoh et al., 2022	Agronomic adaptation by cocoa farmers	Mixed-method + regression	Land access, credit, and extension determine adaptation success	Highlights enabling environment needs for FLID
4	Hashmiu, 2020	Agroforestry adoption in cocoa	Survey + regression	Perceived resilience of shade trees influences agroforestry uptake	Supports link between farmer perceptions and climate-smart choices
5	Arhin et al., 2020	Agroforestry willingness in cocoa areas	Qualitative survey of 100 households	Despite positive perceptions, barriers (e.g., cost, tree management) limit participation	Suggests need for technical and institutional support in climate-smart cocoa

#	Citation	Focus Area	Methodology	Key Findings	Relevance
6	Yamoah & Kaba, 2022	Gender-inclusive agroforestry and composting	Field training & interviews	Women's capacity building led to stronger adoption of shaded cocoa and composting	Emphasizes gender equity in climate-smart innovations
7	Asare et al., 2014	Cocoa agroforestry and forest connectivity	GIS + economic modeling	Agroforestry helps connect forest zones but financial incentives needed to justify adoption	Supports policy and ecosystem services rationale for CSA
8	Afriyie-Kraft et al., 2020	Climate adaptation in cocoa	Household survey of 313 farmers	90% report impacts; 25% lack response strategies	Identifies large adaptation gaps among cocoa farmers
9	Maguire-Rajpaul et al., 2020	Role of agricultural information in adaptation	48 interviews, 12 FGDs	Extension access improves adaptation; social factors matter	Underscores importance of info access for effective tech adoption
10	Tham-Agyekum et al., 2024	Extension service delivery models	Binary probit on 385 farmers	Private extension perceived more responsive; access shaped by land, credit, gender	Reinforces the value of tailored, inclusive support models
11	Akpoti et al., 2023	Groundwater suitability for cocoa zones	GIS + multi-criteria analysis	80% of cocoa-growing areas have good-to-excellent groundwater potential	Strong evidence for targeting borehole-fed SPIS
12	Baidoo et al., 2024	Solar drip irrigation + soil carbon	Field trial	High economic returns and soil health improvements when biochar added to drip irrigation	Shows viability of bundled CSA strategies with irrigation
13	Akrofi et al., 2019	FLID service payment models	Qualitative, 6 communities	Shared irrigation models effective but challenged by group dynamics, repayment defaults	Illustrates social trade-offs in group-based irrigation models
14	Lagger, 2011	BoP irrigation access	Market model review	The "4As" (Affordability, Accessibility, Acceptability, Awareness) crucial for uptake	Strong foundation for inclusive solar irrigation design principles
15	Glitse et al., 2017	State of irrigation systems	Institutional review	Irrigation coverage <2%; many systems obsolete or poorly maintained	Underscores need for decentralized, farmer-led alternatives
16	Donkor et al., 2023	Tenure & cocoa investment	Structural equation modeling	Farmers with land titles more likely to invest in irrigation and fertilizer	Direct link between secure land and willingness to adopt SPIS
17	Naah, 2018	Distributed solar (energy access)	Survey + impact evaluation	Users value low operating costs, but raise concerns over maintenance access	Relevant lessons for off-grid solar irrigation design
18	Agyapong & Anto, 2023	Energy transition & solar adoption	Policy and market review	Unstable currency, taxes, and fragmented supply chain hinder private adoption	Clarifies barriers in solar pump market and logistics chain
19	Davuluri, 2019	PAYG solar model in Ghana	Business model analysis	PAYG makes solar affordable, but repayment depends on mobile network coverage and seasonal income	Transferable insights for PAYG-based SPIS financing in rural areas
20	Pelizan et al., 2019	Mobile-enabled solar access	Case study + interviews	PAYG is effective when bundled with user training and agent support	Highlights importance of service support in solar tech models
21	IWMI, 2023	Solar irrigation bundles (Ethiopia)	PPP implementation case	Bundled hardware + training + finance boosts adoption	Transferable bundle design lessons for SPIS in Ghana
22	Amoah & Torvikey, 2024	Climate-smart cocoa equity	Policy framework review	Gender and tenancy gaps persist; need for inclusive investment design	Direct relevance to IAS targeting and climate-smart planning
23	Kumeh, 2024	Agroecology in cocoa	Narrative review	Agroecology improves resilience but constrained by land tenure laws	Adds context for integrating irrigation into CSC pathways
24	Forest Trends, 2019	Cocoa Carbon Initiative (Ghana)	Case analysis	Focus on shade trees/carbon excludes irrigation despite water stress	Highlights gaps in CSC policy scope for irrigation inclusion

#	Citation	Focus Area	Methodology	Key Findings	Relevance
25	Glitse et al., 2018	Barriers to small-scale irrigation	Field survey + institutional analysis	Encroachment, poor funding, lack of skilled technicians limit scalability	Documents systemic barriers to irrigation expansion
26	Obuobie et al., 2023	Capacity building for SPIS	Institutional capacity survey	Weak cross-sector coordination undermines solar irrigation scaling	Confirms institutional limitations in enabling environment
27	Adu-Baffour et al., 2021	SPIS adoption in SSA	Multinational regression	Education, access to extension, and credit key predictors of adoption	Confirms behavior/institutional levers for Ghana's smallholders
29	Khatun et al., 2021	CSC governance critique	Political economy analysis	Donor-driven models reinforce inequality; top-down design limits effectiveness	Calls for farmer-inclusive, bottom-up irrigation governance
30	Danso & Dietzen, 2025	Solar suitability for crop evapotranspiration	Energy-agro model	Solar radiation matches dry-season ET needs in many cocoa zones	Strong technical case for off-grid SPIS in cocoa agroecologies
31	Gbodji et al., 2023	Cocoa farmers' demand for SPIS	Contingent valuation	Wealth and access to credit drive solar pump demand	Key evidence on willingness-to-pay and segmentation
32	Akpoti et al., 2023	Groundwater mapping for cocoa irrigation	GIS + MCA	80% of cocoa belt suitable for groundwater-fed irrigation	Essential for spatial targeting of SPIS interventions
33	van Koppen et al., 2013	Gender dynamics in groundwater adoption	Farm-level survey	Gender inequality in access to pumps, ownership, and water use	Critical to inform equitable FLID models
34	Kwoyiga, 2024	Women's irrigation knowledge	Qualitative interviews	Women play key roles in access, planning, and food security	Strong gender insight for inclusive IAS strategies
35	Kwoyiga & Stefan, 2018	Local knowledge in well drilling	Case study	Farmers use environmental indicators for well placement	Grounds FLID in indigenous knowledge systems
36	Asare et al., 2014	Cocoa agroforestry & incentives	GIS + economic modeling	Agroforestry supports carbon goals but needs premium price incentives	Adds environmental logic to CSC-linked irrigation shifts
37	Glitse et al., 2017	Public irrigation capacity	Infrastructure audit	Centralized systems outdated; decentralization via SPIS needed	Justifies move toward FLID and private models
38	Wereko-Brobby & Opam, 1988	Solar PV history in Ghana	National pilot reviews	Ghana has early experience in off-grid solar telecom & pumping	Historical foundation for solar irrigation transitions
39	Lefore et al., 2021	Inclusive solar irrigation models	Cross-country framework	Presents models for bundling tech, training, finance, and equity	Global framework adaptable to Ghana's IAS pathways
40	Yamoah & Kaba, 2022	Gender and compost in cocoa	Field-based training + interviews	Female cocoa farmers benefited from organic compost + shaded systems	Reinforces intersection of gender, agroforestry, irrigation
41	Baidoo et al., 2024	Solar + biochar integration	Field trials + profitability analysis	Solar drip irrigation + biochar highly profitable for dry-season farming	Highlights financial viability of bundled CSA solutions
42	Barnie et al., 2014	Groundwater quality	Hydrochemical analysis	Water is generally safe for irrigation, but magnesium hazard exists	Essential for assessing groundwater-fed SPIS viability
43	Salifu et al., 2017	Irrigation water suitability	Water quality indices	Groundwater mostly good for irrigation with minor limitations	Strengthens technical foundation for borehole use in FLID
44	Agbenyo et al., 2022	CSA impact on income	Endogenous regression	Irrigation improves cocoa income by 8.6–11.1%	Confirms economic impact of IAS adoption
45	Bastakoti et al., 2020	Solar pump governance (India/Nepal)	Policy case studies	PAYG + community-based SPIS effective; governance critical	Informative for PPPs and ownership models in Ghana

#	Citation	Focus Area	Methodology	Key Findings	Relevance
46	Namara et al., 2011	Smallholder groundwater use	Regional case studies	Farmers self-develop shallow wells, limited policy support	Validates farmer-led trends and institutional gaps
47	Worqlul et al., 2018	Small-scale irrigation impacts	Integrated Decision Support System	SPIS viable but groundwater alone not always sufficient; mix with surface water needed	Encourages integrated resource planning for IAS scale-up
48	Nkpeebo & Mavimbela, 2023	Climate resilience with Bhungroo irrigation	Mixed-method + ARIMA analysis	Hybrid irrigation + solar PAYG improves resilience in flood-prone areas	Provides model for adaptive service design in vulnerable zones
49	Yoshida, 2008	Full-sun cocoa vs agroforestry	Fieldwork + interviews	Intensified cocoa threatens sustainability; agroforestry needed	Aligns irrigation with shade cocoa and land-use reforms
50	Pelizan et al., 2019	PAYG solar models in Ghana	Field interviews + monitoring	Bundled PAYG + agent support enhances solar adoption in rural areas	Lessons applicable to SPIS business models for cocoa
51	Obuobie et al., 2023	Institutional support for SPIS	Stakeholder interviews + capacity survey	Weak inter-agency coordination hinders solar irrigation scale-up	Highlights enabling environment issues in IAS rollout
52	Adu-Baffour et al., 2021	Solar irrigation adoption	Regression across multiple SSA sites	Education, land ownership, and extension drive adoption	Empirical drivers relevant to Ghana's cocoa-growing zones
53	Minh et al., 2020	FLID coordination in Ghana	Stakeholder engagement study	Farmer-led expansion needs clearer roles, long-term financing	Key governance insights for FLID integration in policy
54	Asare-Kumi et al., 2023	Youth-led irrigation businesses	Field survey + case profiles	Youth-managed pump services increase irrigation access + employment	Promotes youth-inclusive scaling pathways for IAS
55	Akudugu & Issahaku, 2013	Tenure and investment	Qualitative survey	Customary land systems reduce tenant incentive to invest	Central to farmer willingness to adopt irrigation in cocoa areas
56	IWMI, 2023	Bundled SPIS delivery	Project-level review	Bundles (tech + training + finance) accelerate adoption	Strong cross-applicability to Ghanaian rural SPIS scaling
57	Glitse et al., 2018	Barriers to small-scale irrigation	Mixed methods	Tech failure, maintenance gaps, low skills hinder scalability	Reinforces need for technician training and after-sales service
58	Awuku et al., 2021	PPPs in solar sector	Policy analysis	Clear incentives needed for private sector to serve rural zones	Important for PPP-based SPIS delivery models
59	Khatun et al., 2021	CSC governance critique	Political economy study	Top-down models reinforce inequity and farmer exclusion	Grounds the need for participatory irrigation planning
60	Dittoh et al., 2020	National FLID trends	Literature synthesis + institutional analysis	FLID widespread, but poorly integrated into irrigation policy	Landmark study justifying decentralized IAS support
61	Gbodji et al., 2023	SPIP demand for cocoa	Contingent valuation (523 farmers)	WTP linked to income, land, credit, and extension; resource-rich farmers more likely to adopt SPIPs	Strong basis for segmentation and adoption models in FLID design
62	Akpoti et al., 2023	Groundwater mapping	Remote sensing + MCA	80% of cocoa-growing zone has moderate-high groundwater potential; surface water declining	Spatial planning data for borehole-based cocoa irrigation
63	Agbenyo et al., 2022	Climate-smart cocoa income impact	Endogenous switching regression	Irrigation increases income by 8.6–11.1%; credit access critical to adoption	Empirical income benefit for SPIS-supported CSC
64	Yiridomoh et al., 2022	Drivers of CSA adoption	Mixed methods (259 cocoa farmers)	Access to land, credit, extension services shape soil/pruning/adaptation choices	Foundational insights on behavioral factors in CSA adoption
65	Yamoah & Kaba, 2022	Gender and climate tech	Community workshops + compost trials	Women benefit from compost/agroforestry training; improves livelihood and agency	Supports inclusive climate-smart cocoa innovation strategies

#	Citation	Focus Area	Methodology	Key Findings	Relevance
66	Buxton, 2020	Farmer adaptation strategies	Survey (444 farmers)	Extension + behavioral adjustments (pruning, variety change) key to resilience	Adds historical baseline for adaptation decision drivers
67	Tham-Agyekum et al., 2024	Extension delivery comparison	Probit regression + 385 farmer interviews	Private extension excels in access/support; public better for environment/training	Informs design of blended service delivery for IAS uptake
68	Afriyie-Kraft et al., 2020	Perennial crop climate adaptation	Household survey + econometrics	25% of farmers still lack adaptation strategies; cocoa dominance limits diversification	Suggests need for FLID pathways to complement perennial crop traps
69	Amfo et al., 2021	Soil water management in cocoa	3SLS + Tobit models (400 farmers)	Practices like mulching, shade trees, and compost increase productivity	Strengthens link between soil water techniques and IAS synergies
70	Asare et al., 2014	Cocoa agroforestry corridors	GIS + economic analysis	Agroforestry + timber offsets yield loss; market incentives required	Frames irrigation within wider climate-smart ecosystem restoration
71	Gbodji et al., 2023	Cocoa irrigation demand	Contingent valuation	Willingness to invest in SPIPs increases with income, land, credit	Strong basis for market segmentation in FLID expansion
72	Akpoti et al., 2023	Groundwater mapping	GIS + MCA	80% of cocoa belt has high groundwater potential	Technically supports borehole-fed IAS
73	Yamoah & Kaba, 2022	Women's agro-innovation	Community-based project	Organic compost + shaded cocoa improved women's livelihoods	Promotes inclusive climate-smart strategies
74	Hashmiu, 2020	Agroforestry perception	Survey (240 HHs)	Positive perceptions drive agroforestry adoption; social networks matter	Social behavior insights for scaling CSC practices
75	Agbenyo et al., 2022	Irrigation impact on income	Regression modeling	Irrigation improves cocoa income by up to 11.1%	Quantifies income benefits of IAS adoption
76	Yiridomoh et al., 2022	CSA adoption factors	Mixed methods	Credit, land, and extension services determine CSA uptake	Useful for enabling environment analysis
77	Frimpong et al., 2024	Gender and sustainability	Probit regression (401 farmers)	Gender shapes adoption behavior; both cite lack of extension support	Supports gender-aware IAS program design
78	Mills et al., 2024	Cocoa agroforestry adoption	Probit model + χ^2 analysis	Extension, knowledge of climate change, and group membership boost adoption	Aligns with community-based CSC scaling
79	Baidoo et al., 2023	REDD+ and agroforestry	Mixed-methods	Motivators: climate resilience & food security; barriers: finance, logistics	Deepens understanding of farmers' agroforestry decisions
80	Wongnaa & Babu, 2020	Cocoa adaptation/resilience	PSM analysis	Credit, extension, and off-farm income increase adoption and productivity	Confirms systemic enablers of CSA and IAS adoption
81	Gbodji et al., 2023	Demand for solar irrigation	Contingent valuation	Resource-rich farmers more willing/able to adopt SPIPs; credit and extension drive uptake	Anchors market segmentation for solar irrigation models
82	Yamoah & Kaba, 2022	Gender + CSA training	Field project evaluation	Organic compost adoption improved women's livelihood in cocoa	Demonstrates co-benefits of CSA and gender empowerment
83	Agbenyo et al., 2022	CSA income impact	Endogenous switching regression	Irrigation raises cocoa incomes by 8.6–11.1%; credit essential	Validates economic justification for FLID/IAS scale-up
84	Frimpong et al., 2024	Gender and sustainability	Probit regression (401 cocoa HHs)	Women and men cite extension gaps; age and cocoa system type drive adoption	Useful for equitable IAS design
85	Yiridomoh et al., 2022	Agronomic CSA adoption	Mixed-methods (259 farmers)	Land access, credit, and extension are key enablers	Highlights enabling conditions needed for IAS uptake

#	Citation	Focus Area	Methodology	Key Findings	Relevance
86	Buxton, 2020	Cocoa climate responses	Survey of 444 farmers	Farmers use behavioral and institutional adaptation, but are limited by resources	Adds insight to farmer decision drivers under stress
87	Afriyie-Kraft et al., 2020	Perennial trap in cocoa	Survey (313 HHs) + econometrics	Cocoa farmers lack viable off-farm adaptation; need livelihood alternatives	Underlines IAS as a tool for climate-smart intensification
88	Torvikey & Dalaa, 2024	Inclusive CSC governance	Document + qualitative synthesis	Calls for structural changes to address gender inequalities in cocoa sector	Provides a rights-based framework for CSC–IAS linkage
89	Denkyirah et al., 2017	Adaptation strategy choice	Logit modeling (240 HHs)	Gender, education, and credit access shape CSA strategies	Key for targeting IAS promotion by farmer profile
90	Asante et al., 2017	Cocoa–climate transitions	Field + FGDs (200 cocoa farmers)	Farmers shifting between cocoa and cereals; adaptive innovations emerging	Grounds CSC and IAS within shifting rural realities
91	Attiogbé et al., 2024	Cocoa–drought adaptation	Survey + regression	Drought perception tied to adaptation gaps; farm management is the only strategy improving yield	Supports urgency of IAS adoption in cocoa belt
92	Jamal et al., 2021	Gendered adaptation	Mixed methods	Gender influences adaptation preferences (planting dates, drought hybrids); similar perceptions but different practices	Validates gender-informed service models
93	Yiridomoh et al., 2022	Agronomic CSA practices	Mixed methods	Adoption driven by land access, credit, extension services	Confirms enabling environment factors for IAS
94	Oyekale, 2021	Cocoa rehabilitation + adaptation	PCA + 2-stage probit	Ownership model and income drive adaptation/rehabilitation	Useful for segmenting IAS ownership pathways
95	Maguire-Rajpaul et al., 2020	Info gaps + adaptation	FGDs + interviews	Agricultural info boosts capacity but informal networks underutilized	Reinforces role of extension in scaling FLID
96	Wanger et al., 2018	Response to cocoa monoculture study	Method critique	Agroforestry should not be abandoned despite shade-related risks; monoculture misguides adaptation	Validates agroforestry–IAS balance
97	Abdulai et al., 2018	Cocoa income + shade	Climate gradient study	Cocoa in dry zones has low yield; farmers diversify to survive	Strengthens case for climate zoning in IAS scale-up
98	Yamoah & Kaba, 2022	Female-focused CSA	Project + field eval	Women benefit from shaded cocoa + compost innovation	Reinforces gender-sensitive IAS strategies
99	Ehiakpor et al., 2016	Perception–adaptation link	Heckman model	Farmer perceptions influence adaptation; FBO membership matters	Grounds FLID and extension models in behavioral insight
100	Inkoom et al., 2024	Climate-smart adoption	Multivariate probit	Extension, CSA awareness, and zone effects influence farmer behavior	Synthesis-ready for enabling conditions matrix

Stakeholders in the Solar-Powered Irrigation Supply Chain in Ghana

Overview Solar-powered irrigation systems (SPIS) are gaining traction in Ghana as a sustainable, climate-resilient solution for smallholder agriculture. This brief outline the key actors in Ghana's SPIS value chain and their roles.

Table A2 Key Stakeholders and Roles

Stakeholder Group	Role in the Supply Chain	Example Actors	Key Needs or Challenges
Farmers & Cooperatives	End users managing and operating SPIS	Smallholder cocoa/vegetable/rice farmers	Access, training, affordability

Well Drillers & Technicians	Provide boreholes and maintain pumps	Joissam Ghana Limited, Global Water Ghana Limited, Geosource Drilling Technologies Ltd, Mint Borehole Drilling Services etc.	Variable quality, lack of training
Technology Suppliers	Import and distribute solar panels, pumps, and kits	Pumptech Ghana, Anseco, Futurepump	High import cost, limited local production
Distributors & Retailers	Sell, install, and offer after-sales service	Agro-input shops, regional solar vendors	Weak rural logistics, inconsistent servicing
Finance Providers	Provide credit, PAYG, lease-to-own services	Rural banks, VSLAs, Opportunity Int'l	Collateral issues, high interest rates
IAS Providers	Deliver irrigation services without farmer ownership	Pilot service hubs, mobile pump renters	Viable pricing, logistics
Research Institutions	Test systems, generate evidence, guide policy	IWMI, CSIR, KNUST	Technology adaptation, policy engagement
NGOs & Development Partners	Fund pilots, train farmers, support scale-up	GIZ, SNV, FAO	Long-term support, sustainability
Government Agencies	Policy setting, regulation, subsidies, and oversight	GIDA, MoFA, COCOBOD, Energy Commission	Coordination gaps, policy exclusion of cocoa
Community Leaders	Support land access, mobilize communities	Chiefs, assembly members	Often left out of planning

Table A3 Well Drilling & Pump Service Providers

Company Name	Services Provided	Regions Served
Massoud I.S.S Ventures	Borehole drilling, plumbing, pump installations	Kumasi and surrounding areas
Joissam Ghana Limited	Drilling, water treatment, hand/mechanized pumps	Nationwide
Global Water Ghana Limited	Borehole drilling, solar borehole services, pump installs	Multiple regions
Geosource Drilling Technologies Ltd	Borehole excavation, surveys, pump installs/services	All major regions
Mint Borehole Drilling Services	Drilling, rehabilitation, pump installations/tests	Takoradi, Tamale
MMesh Borehole Drilling Co. Ltd	Drilling, water testing, pump installations & repair	All regions across Ghana

Table A4 Solar Irrigation Distributors & Retailers in Ghana

Stakeholder Group	Role in Supply Chain	Example Actors in Ghana	Key Notes / Challenges
Technology Suppliers / Distributors	Import, distribute, and install SPIS kits and components	Pumptech Ghana (LORENTZ pumps); Hatoum Trading (Futurepump)	Key local partners handling branded solar pump distribution (ResearchGate , ilssi.tamu.edu)
Local Retailers / Agrodealers	Sell and deliver solar pump packages, manage after-sales service	HTC Depot (Reapp Ghana), SupplyMaster Accra	Reach broader urban/rural markets; delivery infrastructure varies (Reapp , Supply Master , Supply Master)
Market Expansion Networks	Support supplier-farmer linkages and workshops	IWMI & ILSSI dialogue initiatives, Pumptech outreach	Build rural sales/service networks and farmer exposure (ilssi.tamu.edu , ilssi.tamu.edu)
Asset Finance Platforms	Provide PAYG or leasing for retail customers	PEG Africa (PAYG solar energy and irrigation)	Combine pump financing with solar systems for affordability (Wikipedia)

Table A5 NGOs & Development Partners in Ghana's Solar Irrigation Supply Chain

Organization	Role in Supply Chain	Key Contributions	Challenges / Needs
GIZ (German Agency for International Cooperation)	Pilot solar irrigation systems, provide training	- Established SPIS demonstration farms at UDS and Ho Technical University- Integrated SPIS into vocational education- Trained technicians and farmers	Ensuring long-term system maintenance and policy mainstreaming
SNV (Netherlands Development Organisation)	Support rural solar infrastructure for agriculture and WASH	- Installed solar-powered water systems for rural communities- Supports inclusive energy and agriculture access strategies	Limited agriculture-specific focus in some projects; sustainability beyond donor cycles
FAO (UN Food and Agriculture Organization)	Promote climate-smart irrigation and solar water access	- Supports solar irrigation in smallholder climate-resilient farming- Conducts water governance assessments and irrigation suitability studies	Needs to scale pilot interventions into national frameworks
World Bank / IFC	Finance renewable energy and solar-agriculture linkages	- Funds SPIS feasibility studies under climate-smart agriculture programs- Supports PPPs in off-grid irrigation finance	Requires strong local implementation partners to deliver impact
IWMI (International Water Management Institute)	Lead research and innovation on solar-powered irrigation	- Pilots automated solar irrigation systems- Convened FLID (Farmer-Led Irrigation Development) platform- Supports data, training, and policy reform	Need for greater coordination with private sector and district-level institutions

Table A6 **Technology Suppliers in Ghana's Solar Irrigation Supply Chain**

Organization / Actor	Role in Supply Chain	Key Contributions	Challenges / Needs
Pumptech Ghana	Official distributor of LORENTZ solar pumps	- Supplies SPIS kits (panels, pumps, controllers)- Offers installation and after-sales services- Partners with IWMI and NGOs on outreach	High import duties, rural distribution limitations
Anseco Group	Solar irrigation and energy solutions provider	- Distributes a range of off-grid solar water systems- Supplies to agri-business and donor projects	Limited local assembly and service infrastructure
Futurepump Ghana Partners (e.g., Hatoum Trading)	Import low-cost SF1 pumps for smallholders	- Supplies surface solar pumps for vegetable and smallholder farmers- Builds reseller networks in northern Ghana	No in-country manufacturing, limited technical support
Wadfow & AquaPro (via SupplyMaster, HTC Depot)	Retail solar irrigation kits online and in shops	- Offer plug-and-play kits online with cash or mobile payments- Reach both urban and peri-urban farmers	After-sales support and repair networks are weak



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