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Solar irrigation for adapting to climate change in cocoa farming: A choice experiment approach identifying Ghanaian farmers' preferences

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ABSTRACT

Future climate conditions will be characterized by substantial uncertainty in weather patterns. For cocoa production, adapting to climate change will require securing water application and soil moisture by investing in irrigation infrastructure. In Ghana, government and private sector organizations have introduced solar-powered groundwater irrigation solutions to address the challenges. However, high upfront costs, limited access to institutional finance, and hydro-geological uncertainties constrain demand. We employed a discrete choice experiment approach to examine cocoa farmers' willingness to adopt solar-based irrigation, surveying 550 farmers across seven regions depending on type of ownership, incentivized loans, and cutbacks on drilling uncertainties. The study revealed that cocoa irrigation investment decision depends primarily on access to longer-term loans, followed by cost reduction through group ownership, with the last factor being the reduction of uncertainties associated with borehole drilling. However, there are differences in farmers' stated preferences based on wealth resources, gender, farm access, cocoa farm size, and household size. These findings suggest that policymakers should prioritize initiatives that alleviate financial constraints through longer-term loans to promote climate-resilient and sustainable agriculture. In addition, it indicates that a one-size-fits-all approach to promoting solar irrigation investment is unlikely to be effective, due to substantial heterogeneity in preferences amongst farmers. Instead, targeted policies are needed to increase solar pump adoption among marginalized groups like women and resource-poor farmers.

1. Introduction

Climate change and variability remain significant global challenges, particularly for developing nations (Abdallah et al., 2019; Pörtner et al., 2022). These countries, with economies dependent on climate-sensitive sectors, face heightened vulnerability due to limited adaptation capacity (Asfaw et al., 2021). Agriculture is the main economic activity in many African nations, including Ghana, with overreliance on rainfall and small-scale, low-input farming (Mekonnen et al., 2021). The region's high levels of poverty, food insecurity, and low productivity are exacerbated by limited agricultural technology adoption and the adverse impacts of climate change (Stuch et al., 2021). Therefore, raising farmers' awareness of climate change and implementing innovative adaptation strategies are essential to mitigate its harmful effects (Khonje et al., 2018).

Cocoa, which contributes about 10 % to Ghana's GDP and employs about 800,000 farm families (Ghana Cocoa Board, 2024), is experiencing yield drops due to climate change effects, affecting the livelihood of many smallholder farm families. Zuidema et al. (2005) demonstrated through simulations that water limitations can result in substantial yield gaps in cocoa, reaching as high as 50 % in some cases. As cocoa production continuously faces the threat of adverse climate change through increasing temperatures and declining precipitation (Ofori-Boateng and Insah, 2014), Ofori-Boateng et al. (2015) suggested that adaptation strategies should focus on investment in irrigation infrastructure to combat the varying effects of climate change in cocoa-producing countries. Consequently, in Ghana, irrigation solutions have been introduced by both government and private sector organizations to mitigate the

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adverse effects of climate change on cocoa production (Sarpong et al., 2022). Some recent accounts have suggested that; under irrigation, cocoa farmers could significantly withstand climate-induced water stress while improving their yields owing to an enhanced ability to produce cocoa throughout the calendar year (Carr and Lockwood, 2011).

Solar-powered irrigation systems (SPIS) are gaining recognition as a promising innovation in cocoa production, distinguished by their climate mitigation potential, energy efficiency and cost savings. For instance, in a study by Mishra et al. (2024), SPIS was shown to be a more cost-effective and suitable alternative to electricity-based water pumping systems due to its low operational and maintenance (O&M) costs. More so, the operation and maintenance (O&M) costs of diesel pumps was reported to be two to four times higher than those of solar photovoltaic pumps. In comparison to traditional irrigation methods, SPIS is an attractive solution for cocoa farmers aiming to improve and secure yields while minimizing environmental impacts (Gebrezgabher et al., 2021; Awafo and Owusu, 2022; Hamidinasab et al., 2023). Moreover, a recent study by Gbodji et al. (2023) employing contingent valuation methodology found that Ghanaian cocoa farmers are willing to invest in solar-based irrigation systems.

Despite these emerging demands, Durga et al. (2024) found that uncovered risks, lack of incentives, and lack of capacity are the key factors limiting the adoption of solar-powered irrigation. One such risk is the risk associated with borehole drilling, reported as a limiting factor hindering the adoption of groundwater solar-powered irrigation in Ethiopia (Balasubramanya et al., 2023). Bunn et al. (2019) argued that high irrigation technology prices may hamper adoption and subsequent scaling to a wider range of cocoa farmers. In addition, Minh and Ofosu (2022) and Gbodji et al. (2023) mentioned that Ghanaian cocoa farmers face significant financial constraints, limiting their ability to invest in solar-powered irrigation systems. Furthermore, Thompson et al. (2022) observed that even under certification schemes that guarantee stable and high cocoa revenues, smallholder farmers opt out of irrigated farming, indicating that their incomes are insufficient to support irrigation investments. These findings underscore the need for innovative solutions to address the financial barriers hindering the adoption of sustainable irrigation practices in Ghana's cocoa sector, to promote inclusive investment.

Balasubramanya et al. (2023) reported the significant positive role that access to subsidies plays on farmers' irrigation investment decisions in their work on scaling irrigation in Ethiopia. Moreover, Owusu (2016) suggested that the Government of Ghana, Non-Governmental Organizations, and key stakeholders in the irrigation sector should provide subsidies and flexible micro-credit facilities to small-scale private pump irrigators in Ghana to alleviate financial constraints and promote growth and sustainability in the irrigation subsector. However, subsidy programs in Ghana focus largely on fertilizers and pesticides, with no provision for the irrigation equipment subsector (Dittoh, 2020). In the absence of subsidies in Ghana's pump and equipment market, alternative cost-sharing investment models are necessary to reduce the high upfront costs of irrigation investments. One potential strategy is group ownership[1] of irrigation facilities, which could lessen the financial burden of acquisition and maintenance among cocoa farmers. However, this approach also presents challenges, including risks and complexities related to farm size, maintenance, flexibility, and control, which could lead to conflicts among group members. In addition, the availability, accessibility, and affordability of finance have been shown to empower smallholder farmers to purchase, operate, and maintain new technologies (Fisher and Carr, 2015; Akrofi et al., 2019; Habtemariam et al., 2019; Makate et al., 2019; Fadeyi et al., 2022).

Institutional credit can support cocoa farmers in adopting solar-powered irrigation systems, as licensed financial institutions have advantages in mobilizing liquidity, reaching more borrowers, and mitigating risks compared to other sources (Agbenyo et al., 2022; Sarpong et al., 2022). However, despite the expansion of financial services to rural communities, institutional credit to cocoa farmers remains low (World Bank, 2019). Moreover, household and farm factors like poor bookkeeping, illiteracy, and default rates constrain access to credit (Essel and Newsome, 2000), while agricultural lending products have features such as loan repayment structures, high interest rates, minimum deposit requirements, and harsh collateral conditions (Martin and Hurley, 2019) which hinder access to finance for most farmers. In Ghana, most financing programs offer small loans for short periods at high real interest rates, which do not respond to the needs of cocoa farmers to invest in irrigation (Sarpong et al., 2022).

The adoption of SPIS requires a steady water source. However, surface water pollution, largely caused by illegal mining in Ghana's cocoa-producing regions, necessitates groundwater extraction for cocoa irrigation (Akpoti et al., 2023). MacDonald et al. (2009) and Mensah et al. (2022) posited that although groundwater recharge can be influenced by evaporation, resulting in poor infiltration, it is generally better buffered against evaporation, droughts, and climate change/variability as compared to surface water. Meanwhile, this shift to groundwater is accompanied by significant uncertainties, including the risk of inadequate groundwater availability, which may result in dry or low yield boreholes; technical issues such as borehole collapse, clogging, or poor water quality due to improper construction; and financial risks stemming from the high cost of drilling with no assurance of a successful outcome (Carter et al., 2006). According to Balasubramanya et al. (2023), risk-reducing borehole drilling policies are essential to promote groundwater irrigation investments, however, none of such policies currently exist in Ghana. Liddle and Fenner (2018) found that the level of uncertainty associated with borehole drilling methods varies, with different techniques carrying distinct risks and uncertainties.

In the absence of such risk-reducing policies in Ghana, we investigated how two distinct borehole drilling methods in Ghana - professional-drilled and local-drilled, differing in risk and cost levels - influence cocoa farmers' decisions on irrigation investment choices. Professionally drilled boreholes incorporate many measures to mitigate the risk of not getting a yield. For instance, before the drilling, a hydrogeological investigation or siting is conducted to ensure that there is a high potential for water availability at the location. This is done using advanced technology, whereas those drilled by local artisans use traditional methods such as the growth of certain plant species and experience to indicate water availability; this has a high chance of failure. After drilling, an airlift is done adequately as a risk-mitigating strategy against clogging of driplines to improve flow rate, ensuring clean water is produced from the borehole. Airlift means washing the borehole to ensure that all construction arrangements of pipes settle in, debris and gravel are removed, and all aquifers are clean. In addition, professional borehole drillers use the correct number and length of pipes to line and case the drill. Improper lining of the borehole can lead to structural collapse and the production of muddy water, which negatively affects both the flow rate and the performance of the driplines.

Cocoa cultivation requires significantly more water than vegetables and other commonly irrigated crops, necessitating borehole depths of around 60–100 m. Such depths may exceed the capabilities of local drillers. Although professional drilling services offer greater technical capacity and lower operational risks, they tend to be significantly more

[1] In this study, 'group ownership' refers specifically to small, informal clusters of 2–5 farmers who voluntarily come together for the sole purpose of jointly purchasing and using irrigation equipment. These clusters are formed on mutual trust, proximity, and shared interest in irrigation, with no formalized leadership, no institutional fees, and no obligations beyond the shared management of the jointly-owned asset. They are distinct from formal organizations or groups such as cooperatives or Farmer-Based Organizations (FBOs), and are not intended to provide broader governance, service delivery, or representation, which come with major challenges. Their sole function is to facilitate cost- and risk-sharing through joint ownership.

expensive than local drillers (Lukawski et al., 2016). However, local artisans may still be suitable for borehole construction in areas with high water tables, where sufficient water can be accessed at shallower depths.

Designing best-fit irrigation investment modalities requires knowledge of farmers' preferences, given the associated trade-offs regarding ownership, credit access, and drilling. The study thus proposes a move away from SPIS as 'silver bullets' and towards a systems approach of designing context-specific solutions to address risks, incentives, and capacity challenges. As such, we employed a choice experiment approach to examine cocoa farmers' willingness to adopt smallholder farmer-led irrigation bundles in response to (i) group ownership, (ii) access to incentivized loans, and (iii) reductions in uncertainties associated with borehole drilling.

The article provides a comprehensive framework for analyzing cocoa farmers' investment preferences for solar irrigation and their implications for the adoption of solar irrigation technologies for cocoa production. The findings also provide insights into resource-segment-specific cocoa irrigation investment preferences and an understanding of gender-differentiated preference patterns for solar irrigation technologies.

The remainder of the article is organized as follows. The second section describes the method, including the study areas, design, and implementation of the experiment, theoretical framework, and empirical model. The results follow after the method, whereas the discussion and conclusion sections conclude the paper.

2. Methods

2.1. The study areas and sampling

A total of seven regions, 18 districts, and 32 communities participated in the survey, as shown in Fig. 1. These communities lie within the deciduous, semi-deciduous, and rainforest agro-ecological zones in southern Ghana, where rainfall is between 1000 and 1500 millimeters per year. The study areas were selected based on their groundwater potential (or availability), classified as very low, low, moderate, high, and very high (Fig. 2). Only areas with high and very high groundwater potential were included in the study. The assessment is premised on multi-criteria analysis (MCA), where groundwater occurrence influencing factors were combined to determine groundwater availability potential zones (Akpoti et al., 2023). This criterion was crucial since the scalability of irrigation technologies for cocoa production relies heavily on groundwater extraction, given the widespread pollution of surface water resources in cocoa-producing regions due to illegal mining activities. By focusing on areas with significant groundwater potential, we aimed to assess the feasibility of irrigation technologies in regions where surface water is no longer a viable option. The edaphic and climatic conditions in these zones, characterized by suitable soil types, good drainage, extensive vegetation cover, and adequate rainfall regimes, create a favourable environment for the cultivation of tree crops, including cocoa. However, the suitability of these areas for cocoa production is threatened by climate change, which has led to records of erratic rainfall and dry spells, causing production shocks.

Regarding the sampling strategy, we employed a multistage sampling method. Initially, seven regions were purposively selected based on their significance as major cocoa-producing areas in Ghana, ensuring comprehensive representation. Following a thorough assessment of groundwater potential, 18 districts (at least two per region) and 32 communities (at least one per district) were purposively selected. Within these communities, 564 cocoa farmers were randomly drawn for face-to-face interviews, from an initial target of 580 respondents (16 were absent during survey administration).[2] To achieve a representative distribution of responses, regions with higher cocoa producers (Ashanti and Western North) were allocated more districts, communities, and respondents. Initially, the study aimed to select two communities per district; however, due to the limited number of cocoa farmers in some districts, additional districts (Afigya Kwabre North and Asutifi North) were included, with new communities (Tetrem and Gambia No.1) added to the sample to ensure adequate representation.

2.2. Study conceptualization

2.2.1. Design and implementation of the experiment

This study employed the discrete choice experiment (DCE) framework to examine farmers' preferences for attributes of solar-based cocoa irrigation investment bundles and the trade-offs among these attributes, thereby informing the drivers of adoption decisions. DCE is a widely applied stated preference elicitation method in various fields, including agriculture, marketing, and health. In recent years, DCE has gained prominence in ex-ante agricultural technology adoption studies, providing valuable insights for designing, refining, and delivering demand-driven cropping technologies and management practices tailored to the needs of smallholder farmers (Ortega et al., 2016; Waldman et al., 2015; Jourdain et al., 2020; Silberg et al., 2020; Kotu et al., 2022; Balasubramanya et al., 2023).

The design and implementation of the DCE involved a four-stage approach. Initially, we conducted an extensive literature review and background studies to identify and understand the key attributes influencing the adoption of irrigation technologies in cocoa production. This review focused on existing agricultural financing schemes, irrigation supply business models, and drilling, providing a comprehensive understanding of the context. Additionally, a cost-benefit analysis was conducted to demonstrate the economic viability of solar irrigated cocoa farming. This analysis aimed to inform farmers of the potential financial benefits associated with investing in the intervention. The Results show that the technology adds net value in present terms to cocoa farming, but it is sensitive to the prevailing producer price. With an investment of about USD 20,000[5] per hectare over a 25-year period, farmers can achieve a Net Present Value (NPV) of \$4183 and an internal rate of return (IRR) of 18.21 %, assuming a 15 % discount rate and the 2022/23 producer price of \$185.76 per 64-kg bag of cocoa. Monte Carlo simulations indicate that under these baseline conditions, only 31.7 % of scenarios yield a positive incremental NPV. However, if the discount rate declines to 9 % and cocoa prices rise by at least 20 % (to $\geq$\$223/bag), the likelihood of positive NPV increases to 70 %. Notably, the official 2023/24 producer price rose by 49.8 % to \$278.19 per bag, substantially improving the economic case for investing in solar-powered irrigation systems (SPIS). Secondly, a co-design workshop was organized to present the background studies and potential attributes

[2] Subsequent data cleaning and quality control led to the exclusion of 14 responses due to inconsistencies (*See explanation in Section 2.2*) in choice responses, resulting in a final sample size of 550 for the analysis.

[5] An earlier cost–benefit analysis (CBA) was conducted to inform the selection of attributes for the discrete choice experiment on solar irrigation adoption among cocoa farmers. As the CBA was not the main focus of this study, its results were not initially included in the manuscript but were added following peer-review feedback for completeness. While the attribute levels in the choice experiment reflect prices prevailing during the 2022/2023 cocoa season, the key CBA findings reported here are based on updated input and output prices and exchange rates consistent with current market conditions, which form part of an ongoing standalone CBA study. Accordingly, any discrepancies between prices embedded in the choice experiment attributes (Section 2.2.2 and Table 2) and those reported in the CBA results reflect temporal price updates rather than analytical inconsistencies. Importantly, the qualitative conclusions remain unchanged, with cocoa irrigation investments yielding positive net present values and attractive internal rates of return.

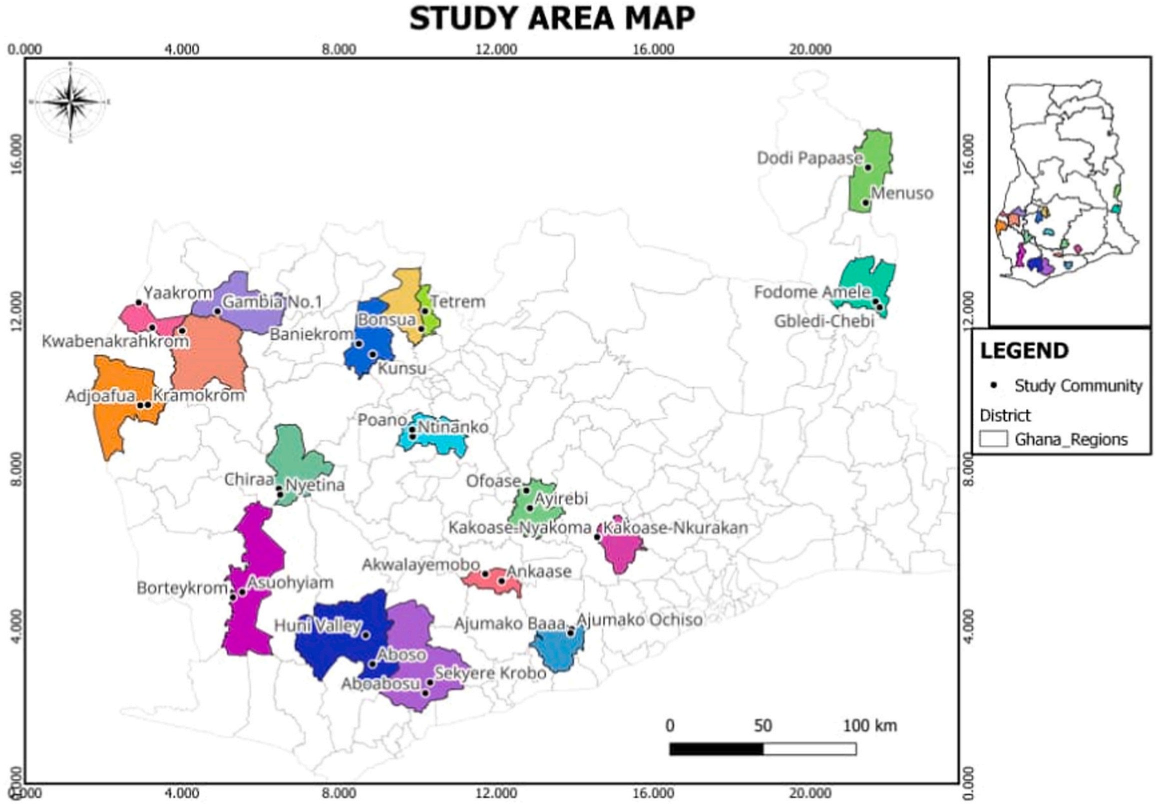

Fig. 1. The study area map.

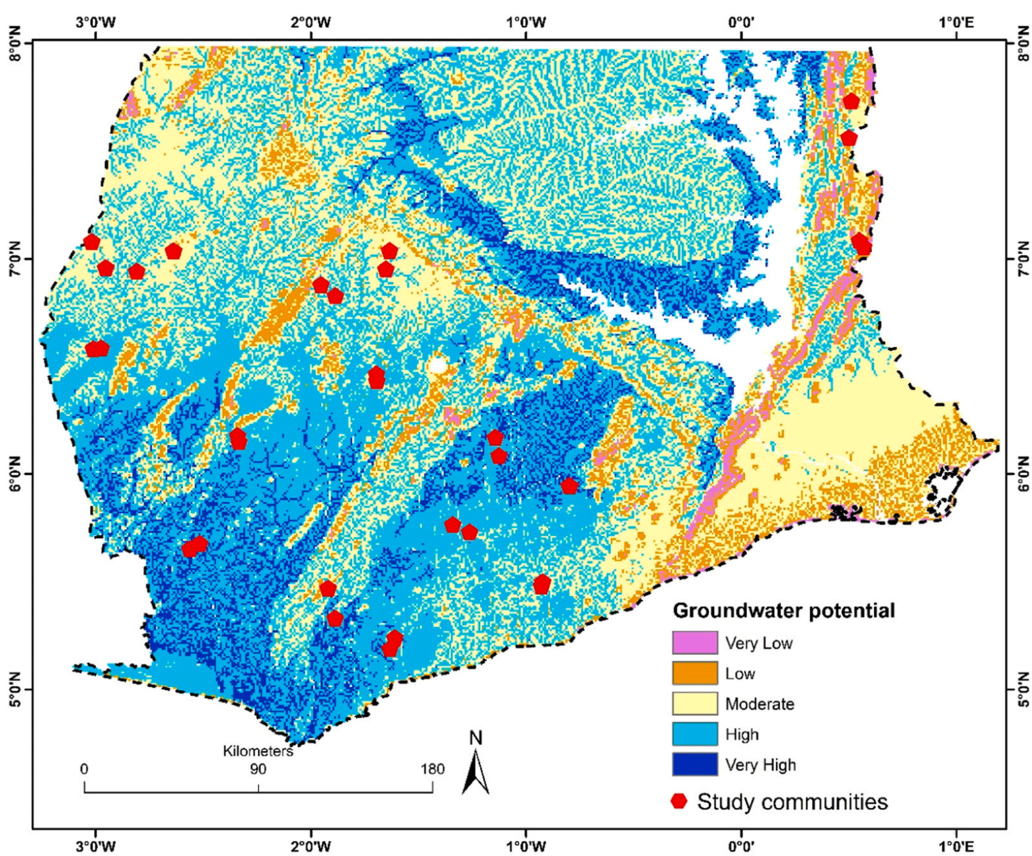

Fig. 2. Map showing groundwater potential of study communities.

to stakeholders for validation. Stakeholders from financial institutions, irrigation equipment suppliers, borehole drillers, farmers, researchers, and the Ghana Cocoa Board (Industry regulators) were present. The final list of attributes includes ownership type, borehole drilling, and financing options, intending to soften capacity, risk, and incentive challenges (Fadeyi and Aziz, 2022; Durga et al., 2024).

The ownership attribute has three levels namely individual, 3-member group, and 5-member group. The inclusion of two group levels of 3 and 5 was meant to be proxies for small and large groups. The group sizes of three and five individuals were selected based on the typical number of neighboring farms proximal to a cocoa farm, which averages 3 and ranges up to 5. Additionally, group size may influence water distribution efficiency, as larger groups require increased pump capacities and pipe diameters, potentially entailing prohibitively high costs for smallholder farmers. Moreover, increasing group size can lead to diminished control and coordination among farmers, potentially resulting in conflicts over irrigation system usage, as decision-making becomes more complex and individual interests may diverge.

The second attribute, designed to capture the uncertainties associated with borehole drilling, is defined by two levels: professional-drilled (mechanized or excavated) and local-drilled.

The last attribute, 'financing option', describes the source and type of finance available for irrigation investments. This is defined by four levels, namely, no loan, short-term loan, medium-term loan, and long-term loan (Table 3). The loan options were designed such that there is an incentive to repay the loan in a shorter term at a lower interest rate instead of repaying the loan in the long term with flexibility but at a higher interest rate. The rates and repayment period were designed based on local market conditions in Ghana. Ghana's credit market, particularly for smallholder farmers and rural communities, faces several structural and practical challenges that affect access to financing. These include limited access to formal credit due to low financial inclusion and poor collateral availability, which makes it difficult for farmers to meet traditional lending requirements (Balana et al., 2022). High interest rates, often exceeding 25–30 % annually, further discourage borrowing. In addition, many available loan products are not designed to align with agricultural production cycles, making them poorly suited to farmers' needs (Sarpong et al., 2022). The rural banking infrastructure is underdeveloped, with many areas lacking adequate financial services. As a result, farmers frequently rely on informal lending sources such as moneylenders, cooperatives, and community savings groups, which can offer more flexible terms but often lack sufficient capital needed to finance productivity–enhancing but costly technologies such as solar irrigation systems.

We developed loan term models based on two prevailing interest rate structures in the agricultural sector: the commercial rate (32 %) and the development rate (18–22 %). The latter is a subsidized rate offered to farmers for agricultural investments, primarily in the form of input credit. To incentivize banks to offer loans at this preferential rate, we incorporated a shorter repayment period, contingent on timely loan repayments, to mitigate lender risk and encourage participation. The maximum repayment period for agricultural equipment loans in Ghana is about 7 years.

The third stage of the experimental design involved constructing choice sets (using Stata software), that were orthogonal (Appendix Table A2), balanced (Appendix Table A3), and efficient (D-efficiency = 2.14), with minimal overlap. As our design was near optimal (Trade-off between the degrees of orthogonality and balance), we selected the most efficient design based on the measure of D-efficiency (Carlsson and Martinsson, 2003; Burgess and Street, 2005; Kuhfeld, 2005). The design therefore generated a total of 16 choice sets, which were subsequently randomized and divided into two blocks of eight choice sets each (Table A1). This was done to minimize the cognitive burden of evaluating too many choice sets (Hensher et al., 2005). We employed a randomized ordering of attribute levels to mitigate potential biases arising from the presentation order of choice sets or attribute descriptions (Kjaer et al., 2006). In addition, to facilitate respondent understanding, we created 16 laminated choice cards with visual aids, including pictures and symbols, explanation sheets, and translated questionnaires into local languages (Hanson et al., 2005). Each card presented two hypothetical alternatives without an opt-out option, as the study aimed to identify key attributes promoting irrigation adoption, not willingness to pay. The explanation sheet and a sample choice card are shown in Table 2 and Fig. 3, respectively.

To ensure logical and consistent responses, we included a dominated choice card in which the finance option was varied, comparing no loan and a long-term loan, while the other attributes were held constant with individual ownership for ownership levels and professionally drilled for borehole drilling. Respondents who failed to answer this card correctly were excluded from the analysis, but this exclusion did not impact the study's final results (see robustness check, Appendix A4). Also, to mitigate hypothetical bias in our choice experiment, we reminded participants of their option to opt out if they felt uncomfortable or perceived the scenarios as unrealistic. Additionally, budget reminders were provided to reinforce financial constraints and encourage consideration of the real-world implications of their choices. As a robustness check, the computer-assisted personal interviewing (CAPI) software was programmed to capture the time a respondent would take to complete each choice card. It is believed respondents would typically spend more time answering the first card since the experiment is new, with a decline in time as the experiment progresses (Balasubramanya et al., 2023). A pilot survey was conducted before data collection to assess the enumerator and respondent's understanding of the questions, the selection and definition of attributes and their levels, and other inefficiencies in the survey tool (Hall et al., 2004).

Finally, prior to the administration of the DCE, respondents were randomly selected and assigned to one of the two blocks, ensuring an equal distribution of blocks across all communities. To ensure respondents were fully informed, an onboarding process was conducted, which included a detailed explanation of the attributes and levels of the irrigation bundle. Any confusion or questions were addressed during this session to ensure respondents clearly understood the choices before making their selections. Along with the DCE, respondents were administered semi-structured questionnaires.

Table 1
Distribution of sampled respondents.

Region	District	Number of Communities	Sampled farmers
Ashanti	Bekwai Municipal	2	36
	Ahafo Ano South-East	2	36
	Afigya Kwabre North	1	16
	Offinso Municipal	1	18
Brong Ahafo	Dormaa West	2	36
	Asutifi North	1	18
	Asunafo North	1	16
Central	Assin Central	2	33
	Ajumako-Enyan-Essiam	2	36
Eastern	Akyemansa	2	34
	West Akim	2	36
Western North	BibianiAnhwiaso Bekwai	2	36
	Bia West	2	30
Volta	Kadjebi	2	36
	Hohoe Municipal	2	36
Western South	Prestea-Huni Valley	2	27
	Wassa Amenfi West	2	34
	Wassa East	2	36

Source: Field survey, 2022/2023 cocoa season. Regions represent the cocoa region, not the new administrative regions.

Table 2
Description of attributes and levels.

Attributes	Levels	Explanation
Ownership type	Individual	The individual owns a solar-powered irrigation facility including the solar pump, panels, other accessories, and drip pipes covering at least 1 hectare at GHS 85,000. Cost of drilling covered fully by the farmer. The individual owner caters for associated costs and risks. Full control.
	3-member group	Irrigation system covering 3 ha for 3 farmers, each irrigating 1 ha plot at GHS 48,000. Drilling cost shared by 3 farmers. Group caters to maintenance costs. Price is at least 43 % lower than individual ownership, and 15 % higher than a 5-member group. Shares associated cost and risk. Joint liability in case of loan. Partial control.
	5-member group	Irrigation system covering 5 ha for 5 farmers, each irrigating 1 ha plot at GHS 41,000. Drilling cost shared by 5 farmers. Group caters to maintenance costs. Price is at least 52 % lower than individual ownership. Shares associated costs and risk Joint liability in case of loan. Partial control.
Borehole drilling	Drilled by local artisans	Drilled by local artisans. No or limited risk tests before drilling. Drill may not yield required amount of water; reach the required depth or may collapse. Shorter lifespan It is cheaper (GHS 15,000).
	Professional-drilled	Drilled by professionals with due consideration for risk factors. Farmer or group bears risk-associated costs including hydro-geological investigations/siting, full lining, airlift, and pumping test. Greater chance of hitting water; drill may yield required water amount. Longer lifespan. More expensive.
Financing option	No loan	The farmer uses their own income and savings to pay for the irrigation system and other associated costs.
	Short-term loan	Farmer or group receives a short-term loan covering the total cost of the irrigation facility and a borehole. Farmer or group repays the loan at a reduced rate (18 %) within 2 years, monthly. Irrigation system serves as collateral.
	Medium-term loan	Farmer or group receives a medium-term loan covering the total cost of the irrigation facility and a borehole. Farmer or group repays the loan at a reduced rate (22 %) within 4 years, monthly. Irrigation system serves as collateral.
	Long-term loan	Farmer or group receives a long-term loan covering the total cost of the irrigation facility and a borehole. Farmer or group repays the loan at the prevailing bank rate (32 %) monthly, within 7 years. Irrigation system serves as collateral.

Note: 1GHS = 0.084 USD during the time of the survey.

2.2.2. Ownership structures and cost modeling for solar-based irrigation systems in cocoa farming

Ownership of the solar-based irrigation system was conceptualized at both the individual and group levels. We adopted this approach to reflect the diverse resource endowments of cocoa farmers. While some are financially capable of independently acquiring the irrigation bundle, others, particularly resource-constrained farmers, may only be able to afford the system through shared ownership, even when credit options are available. However, group ownership may only be feasible among farmers with adjacent plots due to the spatial limitations of the system's reach. Moreover, group size was deliberately restricted to mitigate excessive usage pressure that could compromise the efficiency and longevity of the system. Against this backdrop, we modeled two group configurations: a three-member group and a five-member group.

In modeling the cost of irrigating a cocoa farm, we include the solar pump, switch, controllers, accessories, and drip irrigation pipes. Recognizing that technology adoption typically occurs in stages, the choice experiment was conducted to model farmers' preferences based on their willingness to invest in irrigating a minimum of one hectare of cocoa. The cost components were derived from prevailing market prices (at an exchange rate of GHS 1 = USD 0.084). Cost of the water lifting technology (solar pump and accessories) was estimated at GHS 55,000 (USD 4620), while water conveyance (drip pipes) cost GHS 30,000 (USD 2520) per hectare. The cost of borehole construction, required as a water source, varied by drilling method: GHS 25,000 (USD 2100) for professional drilling and GHS 15,000 (USD 1260) for local drilling. However, the ownership cost analysis presented in Table 2 included only the cost of the water lifting and conveyance components, assuming the final system cost would depend on the borehole drilling option selected. As such, the cost of borehole drilling was modeled as part of the drilling attribute and presented separately to the respondents. The total cost of installing the irrigation system per hectare, excluding borehole costs, was therefore GHS 85,000.

For group ownership models, drip pipes were scaled with the number of farmers, given that each additional hectare required its own drip pipe setup. Importantly, the capacity of the selected solar pump was sufficient to irrigate up to five hectares, and thus its cost remained fixed regardless of group size. Cost-sharing models were then developed for each group type. For instance, a three-member group incurred a total system cost of GHS 144,000, comprising one solar pump (GHS 55,000) and drip pipes for three hectares (GHS 90,000). This total was equally divided, resulting in a per-farmer cost of about GHS 48,000 for irrigating one hectare. This figure represents a 43 % reduction in cost compared to individual ownership, though it is approximately 15 % higher than the per-farmer cost in a five-member group.

While the base system cost was estimated at GHS 85,000, total investment could rise to GHS 110,000 with professionally drilled boreholes or GHS 100,000 with locally drilled ones. Transportation and installation labor costs were included in these estimates. Operational and maintenance expenses, although not explicitly modeled, are expected to be low (Mishra et al., 2024) and are to be borne by the farmers.

2.3. Theoretical framework and the empirical model

The study draws on the theoretical foundations of Lancaster's (1966) characteristics theory of consumer behaviour, McFadden's (1974) random utility maximization (RUM) theory, and Ben-Akiva and Lerman's (1985) introduction of alternative-specific variables. This foundation has been widely applied in empirical analyses of consumer and producer decision-making (Ruto and Garrod, 2009; Asche et al., 2015; Waldman and Kerr, 2015; Carlucci et al., 2017; Santeramo et al., 2017; Kotu et al., 2022; Balasubramanya et al., 2023). Analogous to how consumers evaluate differentiated products based on a bundle of quality attributes, we assumed that farmers perceive cocoa irrigation investments as comprising various intrinsic and extrinsic attributes that contribute to their overall value. We model the effect of three attributes, ownership type, borehole drilling, and financing options, on irrigation bundle choice, using the conditional logit (CL) and the random parameter logit (RPL).

The utility obtained by individual n from the irrigation bundle alternative i at time t is assumed as $[U_{nit}]$. We assume that each decision maker maximizes their utility by selecting the most preferred alternative from a finite choice set of J options. The utility associated with

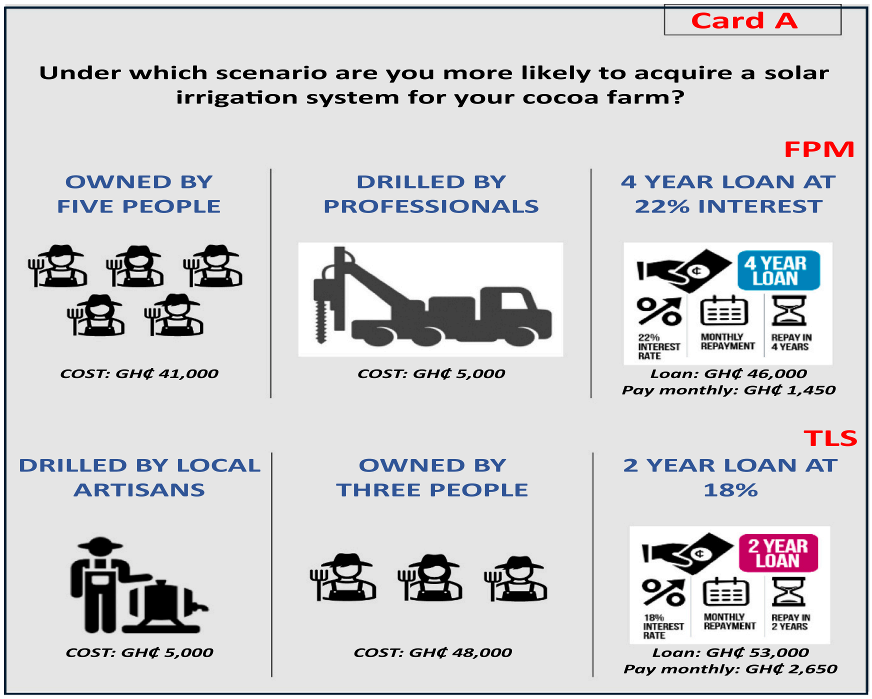

Fig. 3. Example of a choice card used in the experiment.

alternative i can be represented as the sum of two components: a deterministic component [V_{nit}], which is a function of the attribute mix, and a stochastic component [ε_{nit}], which accounts for the random and unobserved influences on decision maker preference:

$$U_{nit} = V_{nit} + \varepsilon_{nit}$$

The decision rule for individual n involves selecting the alternative that maximizes utility through a pairwise comparison of the full set of alternatives. Alternative i is chosen over j if [U_{nit}] > [U_{njt}], [$\forall j \neq i$]. Given the stochastic nature of the utility function, the choice is modeled as a probabilistic maximization problem. Individual n chooses alternative i if it yields the highest utility among the J options. The choice probability [P_{nit}] represents the likelihood that alternative i's utility will be the highest for decision maker n:

$$P_{nit} = Prob\left[(V_{nit} + \varepsilon_{nit}) > \left(V_{njt} + \varepsilon_{nit}\right)\right] > 0; \forall j \neq i, \forall J$$

Suppose the stochastic components [ε_{nit}] are independently and identically distributed (IID) with a type I extreme value distribution. In that case, the conditional logit model can be represented by the following closed-form equation:

$$P_{nit} = \frac{\exp(V_{nit})}{\sum_j \exp(V_{njt})}$$

If βX_{nit} represents the deterministic component of the utility of alternative i for individual n, where β is a vector of coefficients that weights the importance of each attribute or level, in this case, attribute levels professional drilling, 3-member group, 5-member group, short-term, medium-term and long-term loans, the expanded closed-form equation is:

$$P_{nit} = \frac{\exp(\beta X_{nit})}{\sum_j \exp(\beta X_{njt})}$$

Building on the understanding that individual preferences are as diverse as individual characteristics (Janssen and Hamm, 2014; Carlucci et al., 2017), we advance our approach by adopting the random parameter logit model. This model is well-suited to accommodate heterogeneous preferences, as demonstrated in numerous empirical choice studies (Tonsor and Wolf, 2011; Carlucci et al., 2017; Kotu et al., 2022; Balasubramanya et al., 2023). The RPL model offers exceptional flexibility and is capable of approximating any random utility model (RUM) by relaxing the homogeneity assumption inherent in traditional logit models. By allowing for preference variations within the sample (McFadden and Train, 2000), the model can maintain a linear relationship between the deterministic component of the utility function [V_{nit}] and product attributes:

$$V_{nit} = \beta' X_{nit}$$

where β' is a vector of random parameters, with known mean and variance (McFadden and Train, 2000), which represent individual preferences; X_{nit} is a vector of attributes or characteristics of alternative i for individual n. Following Train (2009), the probability of individual, n, choosing alternative, i, at a given time, t, is computed as follows:

$$P_{nit} = \int \frac{[\exp(\beta' X_{nit})]}{\left[\sum_j \exp(\beta' X_{njt})\right]} f(\beta) d\beta$$

The density function $f(\beta)$ characterizes the distribution of the random coefficients β, which are assumed to be normally distributed and independent. By emphasizing the random variation in β, we shift the focus away from the error term. We estimated the random parameters model by employing the mixlogit command in Stata (Hole, 2007), specifying uncorrelated coefficients. To further improve estimation accuracy, we utilized a Bayesian estimation method, incorporating a Monte Carlo simulation with a Halton sequence of 1000 draws to simulate the density function $f(\beta)$.

We applied the method outlined in Revelt and Train (2000) to estimate individual-specific coefficients (β) for each of the 550 participants in our sample, leveraging their observed choices and the estimated distribution of random coefficients from the random parameters logit model. These individual-level coefficients represent the conditional expectation of β given the response pattern (y_n) and choice options (x_n) in the sample, denoted as $E(\beta \mid y_n; x_n)$. We utilized the *mixlbeta* command in Stata (Hole, 2007) to estimate these coefficients, following the *mixlogit* command. The individual-level coefficients serve as a valuable tool for assessing model specification and testing heterogeneity in coefficient estimates (Train, 2003).

Apart from the total sample (550) estimation, we also explored factors that accounted for preference heterogeneity by disaggregating the data into small, medium, and large farmers based on farm size, a proxy for poor, limited versus rich farmers. Farm size is commonly proxied to income (Wozniak, 1993), given that directly capturing information on farmers' income is difficult (Anderson et al., 1999). Farm size below the 25th percentile (<4.1 acres) is defined as small-sized, those within the interquartile range (4.1 – 11.9 acres) are classified as medium-sized, and those above the 75th percentile (>11.9 acres) are considered large-sized. In addition to conducting a gender-disaggregated analysis to examine preference heterogeneity, we also incorporated interactions between selected household characteristics and the attribute variables. This was intended to assess whether distinct segments within the population exhibit varying levels of preference. The gender-disaggregation analysis is grounded in existing research, which suggests that males and females exhibit distinct preferences and decision-making patterns regarding investment and resource management (Mudhara et al., 2003; Murage et al., 2015; Michalscheck et al., 2018).

Lastly, given that the choice probabilities are nonlinear functions of the estimated coefficients (β), the marginal effects of attribute changes on irrigation package choices are not directly equal to the coefficients. Therefore, we computed marginal effects using the estimated coefficients and evaluated them at each observation. The average marginal effects for each attribute were then reported, with standard errors estimated through bootstrapping (500 replications). These marginal effects represent the average change in the probability of selecting an irrigation package when a given attribute is present, relative to the omitted category, holding all else constant.

3. Results

3.1. Descriptive results

Fig. 4 presents the average duration of each choice in the discrete choice experiment. The results show that respondents completed the choice experiment section of the survey in an average time of 16.58 min. Notably, the average time spent on each choice card decreased as respondents progressed through the experiment, indicating a learning effect. Specifically, the first-choice card required the most time; the ninth card required the least time, suggesting that respondents became more efficient in their decision-making as they gained experience with the experiment.

The results of the summary statistics of variables used in the study are presented in Table 3 for the pooled sample, resource segments, and gender. Columns 2–12 show the results of the sub-samples while columns 13–14 show the results for the pooled sample. We found that the respondents were mostly men (81 %) with an average age of 55 years, which in the context of Ghana with a life expectancy of 63.8 (World Bank, 2021) can be considered relatively high. On average respondents spent 9 years in school. From the sample of respondents, a typical cocoa household has about 5 members and the average cocoa farm size is about 10 acres, yielding about 18 bags[3] a year.

Significant differences exist among the three resource segments regarding most variables used in the descriptive analysis. Notable among the resource segments is that large-sized cocoa farmers are on average older with larger household sizes. They are also characterized by large cocoa farms averaging about 24 acres, with a cocoa output of about 44 bags a year, and mostly involved in other off-farm income-generating activities. We also found notable differences in respondents' knowledge and experience concerning various climate and irrigation-related indicators. Interestingly, a majority of respondents show a keen understanding of their local environment, perceiving high to very high groundwater potential on their farms. This perception aligns with the study's focus on areas known for their high groundwater potential.

There is also a high consensus that climate change in the form of water stress can negatively impact cocoa yield. Additionally, there is a general agreement that borehole drilling may be risky. However, regarding previous experience with borehole drilling, a relatively small number of cocoa farmers were previously involved in drilling, with no statistically significant difference between the resource segments. In terms of previous experience with irrigation, the majority of the respondents had no experience, but compared to the other resource segments, a larger proportion of the small-sized farmers had previously irrigated. Perhaps with smaller farms, and lower incomes, this resource segment perceives sustainable intensification practices such as irrigation as insurance against yield losses, ensuring all-year-round production for increased incomes. Professional or mechanized drilling methods can only be possible if the machines can access the farm, as such, we also collected information on whether these drilling machines can be sent to the farm. The results show a relatively high percentage of access.

Using a *t*-test, we also identified some differences for gender, with notable differences in almost all the variables except off-farm activity, age of the cocoa trees, number of neighboring farms, knowledge of groundwater potential, and irrigation experience. Male-headed households reported an output-land ratio of 1.88 bags while female-headed households reported a lower ratio of 1.58, which indicates that men are more technically efficient.

3.2. Econometric results of attribute effects on the choice of irrigation investment bundles

3.2.1. Cocoa farmers' irrigation investment preferences

To achieve the primary objective of identifying farmers' irrigation investment preferences, we employed both conditional logit (CL) and random parameter logit (RPL) models and compared their results. The Wald Chi-square test revealed a high level of significance for both models, indicating that the selected attributes collectively contribute significantly to explaining the choice behavior related to cocoa irrigation investment. Notably, all parameters exhibited consistent signs across the two models, suggesting that either model can adequately explain farmers' choice behaviors, although the robustness of the results may differ between models. From the results (Table 4), all six attribute levels including professional-drilled boreholes, 3-member group, and 5-member group ownership, short-term, medium-term, and long-term loans show statistical significance among the two models. However, in addition to the higher log-likelihood of the RPL, the significant standard deviation of some of the variables in the model shows preference heterogeneity in the study population about the technology attributes, which implies that the RPL is superior to the CL model in terms of our study setting. Thus, we continued the rest of our analysis using the RPL model. From the standard deviations, it can be observed that there are differences in preference for four attribute levels including the professional-drilled borehole, 5-member group, medium-term loans, and long-term loans, with greater heterogeneity observed in the drilling and 5-member group attributes.

Since the marginal effects of changes in attributes on irrigation investment choices cannot be directly inferred from the coefficients to give a meaningful explanation, we computed the marginal effects (Table 4, column 5) using the estimated coefficients from the RPL (Balasubramanya et al., 2023). As such, the results from the marginal effect show that the most important attributes for cocoa irrigation investments are the loan attributes, with longer-term loans (medium-term and long-term) most preferred. This is consistent with farmers' explanations that apart from the high cost of the technology which demands longer payback periods, cocoa is a permanent crop with a relatively stable output price and ready market, yielding for a long period, which provides security for obtaining longer-term loans with flexible payment

[3] Bag is the commonly used unit to measure cocoa yields in Ghana. Each bag is equivalent to 64.5 kg.

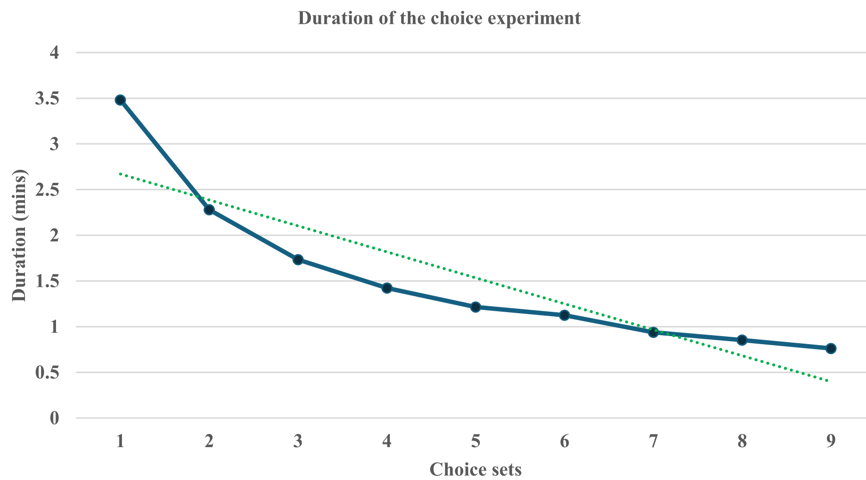

Fig. 4. Time taken to complete the choice experiment.

Table 3
Summary statistics of study variables.

Variables	Resource segments							Gender of household head					Total	
	Small Farms		Medium Farms		Large Farms		F-value	Male-headed		Female-headed		t-value		
	Mean	Std.	Mean	Std.	Mean	Std.		Mean	Std.	Mean	Std.		Mean	Std.
Household-specific factors														
Gender (Men=1)	0.70	0.46	0.84	0.37	0.90	0.31	11.17***						0.81	0.39
Age[1] (Years)	52.67	13.14	55.10	12.55	58.19	12.97	6.75***	54.61	12.49	57.56	14.65	-2.09**	55.16	12.96
Household size (#)	4.49	2.51	4.89	2.45	6.10	2.94	15.35***	5.29	2.65	4.14	2.52	4.02***	5.07	2.66
Education (Years)	7.66	4.64	8.74	4.50	9.80	4.99	7.65***	9.39	4.53	5.66	4.33	7.57***	8.69	4.72
Bank account (Yes=1)	0.41	0.49	0.46	0.50	0.64	0.48	9.48***	0.53	0.50	0.30	0.46	4.30***	0.49	0.50
Resource-endowment factors														
Farm size (Acres)	2.91	1.01	7.51	2.03	24.44	15.43	310.82***	10.79	10.84	8.41	13.23	1.92*	10.35	11.35
Cocoa output (# bag)	6.44	6.77	13.76	12.65	43.58	41.46	111.51***	20.29	27.84	13.30	20.37	2.40**	18.98	26.72
Off-farm activity (Yes=1)	0.37	0.48	0.40	0.49	0.43	0.50	0.87	0.40	0.49	0.40	0.49	-0.04	0.40	0.49
Farm-specific factors														
Age[2] (Years)	17.01	11.93	19.49	12.20	22.09	12.95	6.20***	19.53	12.49	18.93	12.22	0.44	19.42	12.43
Neighboring farms (#)	3.34	1.46	3.48	1.59	3.69	2.12	1.53	3.48	1.73	3.53	1.58	-0.28	3.49	3.35
Access for drilling machine (Yes=1)	0.62	0.49	0.67	0.47	0.75	0.44	2.78*	0.69	0.46	0.59	0.49	1.93*	0.67	0.47
Climate and irrigation-related factors														
Climate-risk perception (strongly agree/agree=1)	0.94	0.23	0.96	0.19	0.99	0.12	1.77	0.97	0.17	0.93	0.25	1.75*	0.96	0.19
Groundwater potential (Very High/ High/moderate=1)	0.95	0.22	0.96	0.19	0.99	0.09	2.18	0.97	0.18	0.96	0.19	0.26	0.97	0.18
Drilling-risk perception (Yes=1)	0.65	0.47	0.70	0.46	0.76	0.43	1.87	0.72	0.45	0.60	0.49	2.42**	0.70	0.46
Drilling experience (Yes=1)	0.34	0.47	0.35	0.48	0.36	0.48	0.03	0.37	0.48	0.24	0.43	2.52**	0.35	0.48
Irrigation experience (Yes=1)	0.13	0.33	0.11	0.31	0.02	0.15	5.55***	0.10	0.30	0.06	0.24	1.34	0.09	0.29
N	158		257		135			447		103			550	

Note: Age1 =Age of household head, Age2 =age of the cocoa tree. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. The mean values for all the dummy variables should be interpreted in percentages.

terms. They explained that the unpredictability of agriculture necessitates a more flexible payback structure, allowing ample time to recover from crop failures. They further noted that the benefits of irrigation are not immediate and may take time to materialize, making flexible loan terms essential.

While the loan terms rank first, as the most important attributes, group ownership (3-member and 5-member group) comes second, reaffirming the need to build farmers' financial capacity to adopt capital-intensive technologies like solar irrigation in cocoa. We found that the magnitude of the marginal effects for the small (3-member group) and large (5-member group) group ownership attributes were similar (a difference of 0.01). The indifference in the marginal effects could be interpreted as that farmers' choice of a group type could be context-specific, depending on several factors. The cutbacks in borehole drilling risk through professional drilling ranks as the least important factor. This outcome aligns with the attribute rankings revealed in the descriptive statistics (Fig. 5), providing further evidence for the observed pattern.

3.2.2. *Test of preference heterogeneity*

The study further investigates the factors contributing to differences in attribute preferences, with a focus on resource levels (farm size). The results reveal significant variations in preference for most irrigation investment attributes across the three resource segments (Tables 6 and 7; Fig. 7). Notably, loan attributes (short-term, medium-term, and long-term) were the most influential factors for all segments, but the small-sized farmers showed a stronger preference for longer-term loans (medium-term and long-term) compared to the large-sized farmer segment. Furthermore, while group ownership is the second most important attribute for the resource-constrained segments (small-sized and medium-sized farmers), reduction in uncertainties related to borehole drilling is the second most critical pathway for scaling irrigation investments among the large-sized farmers. The marginal effects of professional drilling vary substantially across segments, with large-sized

Table 4
Econometric estimates from CL and RPL Models for the sample population.

Choice	Model 1		Model 2			
	Conditional Logit		Random Parameter Logit			
	Coefficient	Robust s.e.	Coefficient	Robust s.e.	dy/dx	Bootstrap s.e.
Mean						
Professional[1]	0.34***	0.05	0.53***	0.08	0.08***	0.01
3-member[2]	0.46***	0.05	0.64***	0.07	0.09***	0.01
5-member[2]	0.51***	0.07	0.74***	0.10	0.10***	0.01
Short-term[3]	0.90***	0.06	1.42***	0.10	0.18***	0.01
Medium-term[3]	1.35***	0.08	2.09***	0.13	0.28***	0.01
Long-term[3]	1.36***	0.08	2.06***	0.13	0.28***	0.01
Standard deviation						
Professional-drilled			1.29***	0.10		
3-member			0.02	0.05		
5-member			1.25***	0.11		
Short-term			0.01	0.01		
Medium-term			0.56***	0.21		
Long-term			0.49***	0.16		
Log-likelihood	-2534.66		-2362.32			
Wald Chi-sq (6)	402.84***		307.15***			
AIC	5081.31		4748.65			
BIC	5123.81		4833.64			
N	8800		8800			

Notes: CL stands for Conditional logit, RPL stands for Random parameter logit, dy/dx = marginal effects. An average of the marginal effects is calculated for each observation using coefficient estimates from the random parameter model; standard errors are estimated using bootstrapping (500 replications, 8800 observations); Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. [1]Reference category is locally drilled, [2]Reference category is individual ownership, [3]Reference category is no loan.

Table 5
Comparison of individual-level coefficients with population parameter estimates.

Choice	First moment	First moment / Population Parameter Estimate
Mean		
Professional[1]	0.53	1.00
3-member[2]	0.64	1.00
5-member[2]	0.74	1.00
Short-term[3]	1.42	1.00
Medium-term[3]	2.09	1.00
Long-term[3]	2.06	1.00
Standard deviation		
Professional-drilled	1.02	0.79
3-member	0.00	0.03
5-member	0.88	0.70
Short-term	0.00	0.03
Medium-term	0.19	0.34
Long-term	0.17	0.34

[1]Reference category is locally drilled, [2]Reference category is individual ownership, [3]Reference category is no loan. [4]To evaluate model specification, test heterogeneity, and compare individual-level preferences with population-level preferences, we present the estimates in Table 5. Individual-level parameter estimates (mean and standard deviation) are presented in Table 5, column 1. The ratio of individual-level means (Table 5, column 1) to population means (Table 4, column 1) is reported in Table 5, column 2, revealing a mean ratio of unity across all attribute levels. This indicates that individual-level preferences align with population preferences, suggesting a well-fitting model with the implication that the preferences and behavior of the individuals in the sample are representative of the population. Furthermore, heterogeneity tests, represented by the ratio of individual-level standard deviations to population standard deviations (Table 5, column 2), show similar trends to population estimates. Notably, greater preference heterogeneity is observed for drilling and 5-member group attributes, as visually depicted in Fig. 6, where more heterogeneous attributes display multiple distinct peaks. In contrast, the ratio of standard deviations for the 3-member group and short-term loan attributes approaches zero, indicating negligible preference heterogeneity.

farmer segments exhibiting a 13 %age point effect, followed by medium-sized (7 %age points) and small-sized farmers (5 %age points).

Additionally, it is noteworthy that, among the large-sized segment, the 5-member group was statistically insignificant, whereas the 3-member group attribute exhibited a significant effect (5 %), albeit with a substantially smaller marginal effect compared to the small-sized and medium-sized segments. In addition, we examined the effect of farm size on ownership attribute preferences by interacting farm size with 3-member and 5-member group ownership within the pooled sample. This analysis was necessary to capture the overall pattern and generalizable findings, rather than relying solely on the resource-disaggregated data, which may obscure the broader relationship by overemphasizing segment-specific variations. Our results show that the relationship between farm size and the two group ownership attributes is negatively correlated and statistically significant at the 5 % level (Table 10). This could be argued in two folds that, with greater resources, larger farmers could afford the technology alone or in a much smaller group. Secondly, larger farm sizes may preclude group formation due to increased water requirements and reduced proximity to neighboring farms, making collective ownership technically less feasible. While we observed differences in preferences for most attributes across the segments, there were some similarities regarding preferences for short-term loans, with zero preference heterogeneity observed among the small-sized and medium-sized segments for all attributes.

We conducted a second heterogeneity test to examine the influence of gender on irrigation investment preferences, comparing male-headed and female-headed households. The results show similarities in preferences for almost all the irrigation investment attributes except professional drilling and 5-member group ownership (Table 8 & 9). The preference for professional drilling is greater for male-headed households, statistically significant at 1 %, while that of female-headed households is significant at 10 %. Regarding group ownership attributes, preferences are homogenous among the two types of households. However, the test of difference in marginal effect among the households shows a statistically significant difference, with the female-headed households showing a greater preference for the 5-member group ownership.

Beyond resourcefulness and gender, we explored additional sources of variation in farmers' preferences by incorporating interaction terms between selected explanatory variables and the attributes examined in this study. Our results reveal that multiple factors, including farm access, household size, and farm size contribute to variations in preferences for irrigation investment attributes (Table 10). Notably, farmers

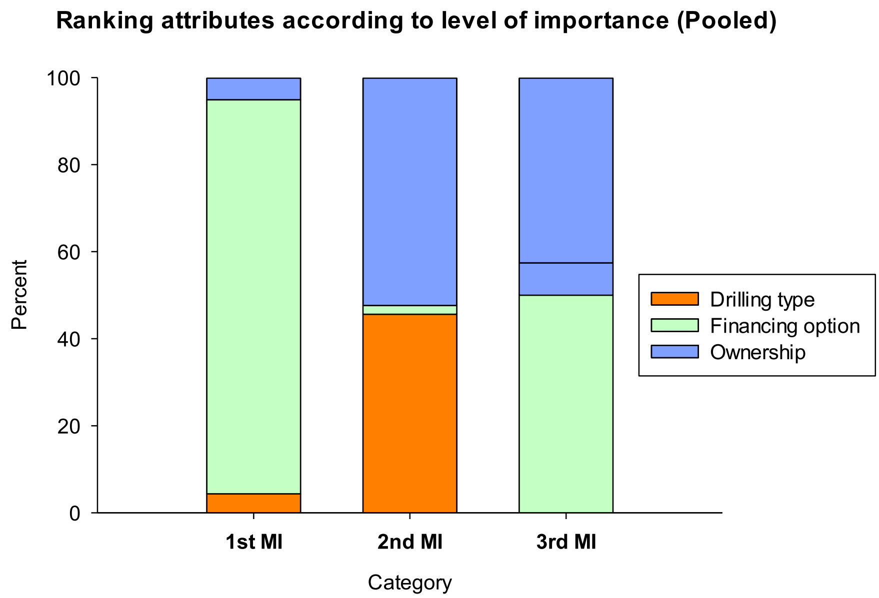

Fig. 5. Attribute ranks for the pool sample. MI = Most important.

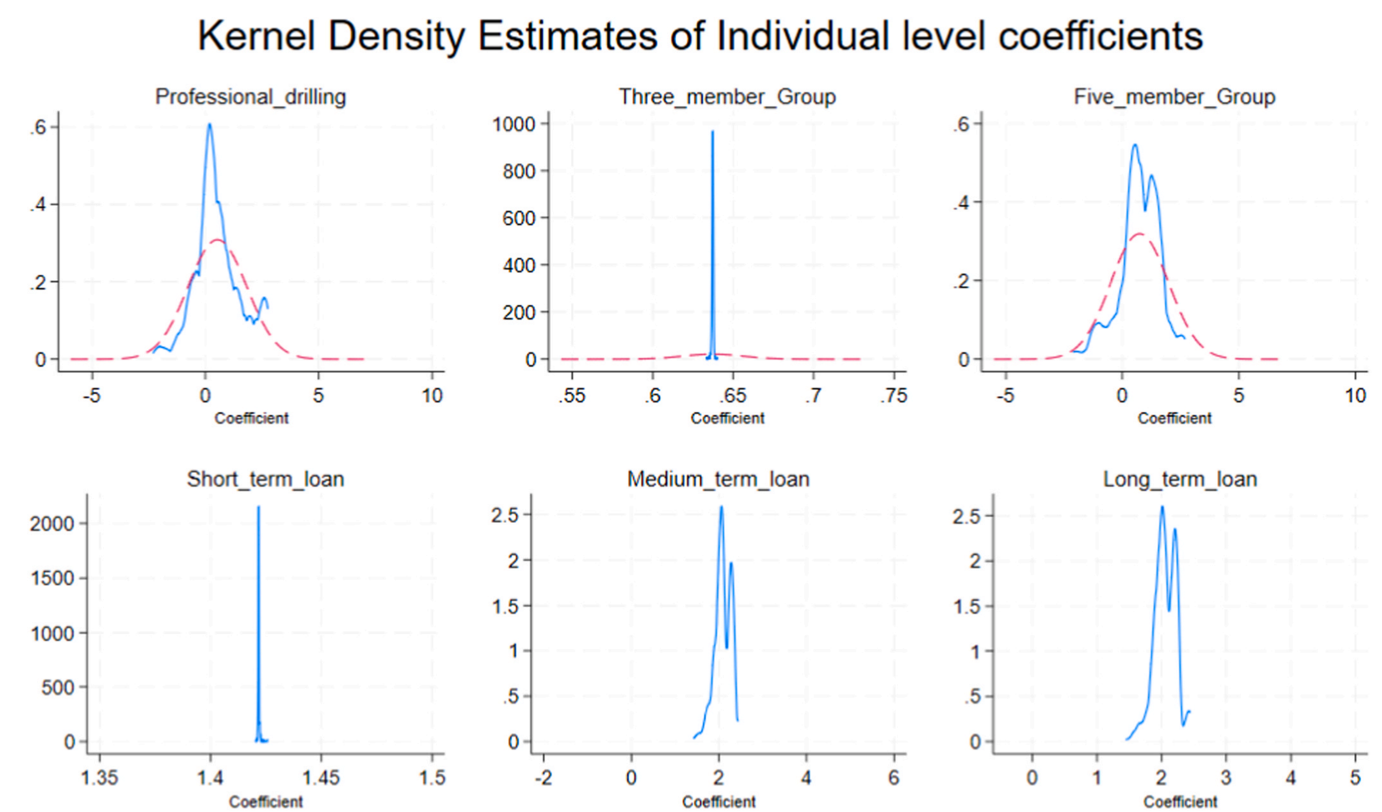

Fig. 6. Kernel density estimates of individual-level coefficient.

with better farm access show a stronger preference for professional drilling methods, likely due to large excavators and mechanized drilling machines requiring easier access to the farm to operate. Conversely, larger households indicate less preference for large group ownership.

4. Discussion and conclusion

Our study provides insights into the key pathways for scaling solar irrigation in cocoa farming. First, the results show that access to financing tools such as loans is the most important factor for cocoa farmers to consider in their irrigation investment decisions. We found that access to any incentivized loan is of greater importance than any other attribute, but with a higher preference for longer-term loans that better respond to repayment capacity, technology costs, and the features of cocoa farming. The findings align with existing literature on technology adoption in Sub-Saharan Africa, which highlights the crucial role of access to finance in facilitating the adoption of new technologies (Mudhara et al., 2003; Diagne, 2009; Habtemariam et al., 2019; Makate et al., 2019). The importance of finance in technology adoption is further emphasized by a recent review of 128 articles, which found that

Table 6
RPL estimates for a test of heterogeneity in preferences for attributes, by resource segment.

Choice	Small-sized				Medium-sized				Large-sized			
	Coef.	Rob. se	dy/dx	Boot. s.e	Coef.	Rob. s.e	dy/dx	Boot. s.e	Coef.	Rob. s.e	dy/dx	Boot. s.e
Mean												
Professional[1]	0.34***	0.13	0.05***	0.02	0.46***	0.10	0.07***	0.01	1.12***	0.25	0.13***	0.02
3-member[2]	0.80***	0.13	0.10***	0.02	0.70***	0.10	0.10***	0.01	0.41**	0.18	0.04**	0.02
5-member[2]	0.81***	0.16	0.10***	0.02	0.90***	0.14	0.12***	0.02	0.37	0.28	0.04	0.03
Short-term[3]	1.61***	0.20	0.19***	0.02	1.42***	0.15	0.18***	0.01	1.41***	0.26	0.14***	0.02
Medium-term[3]	2.41***	0.29	0.30***	0.02	2.04***	0.18	0.28***	0.02	2.17***	0.31	0.22***	0.02
Long-term[3]	2.32***	0.24	0.30***	0.02	2.07***	0.18	0.28***	0.02	2.13***	0.30	0.22***	0.02
Standard deviation												
Professional	1.06***	0.19			1.19***	0.14			2.08***	0.30		
3-member	0.04	0.04			0.02	0.03			1.01***	0.26		
5-member	0.88***	0.21			1.15***	0.15			2.20***	0.39		
Short-term	0.00	0.02			0.02	0.02			0.01	0.08		
Medium-term	1.36***	0.31			0.32	0.38			0.01	0.04		
Long-term	0.71**	0.30			0.65***	0.18			0.05	0.08		
Log-likelihood	-652.39				-1094.69				-570.70			
Wald Chi-sq (6)	106.00***				153.17***				60.27***			
AIC	1328.78				2213.38				1165.41			
BIC	1398.81				2289.24				1233.54			
N	2528				4112				2160			

Note: RPL = Random parameter logit, Rob. s.e =Robust standard error, Boot. s.e = Bootstrap standard error. dy/dx = marginal effects. An average of the marginal effects is calculated for each observation using coefficient estimates from the random parameter model; standard errors are estimated using bootstrapping (500 replications); Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. [1]Reference category is locally drilled, [2]Reference category is individual ownership, [3]Reference category is no loan.

Table 7
Test of differences in marginal effects, by resource segment.

Choice	Resource segments		
	SF (I) - MF (J)	SF (I) - LF (J)	MF (I) - LF (J)
	Diff	Diff	Diff
Professional	-0.02	-0.08***	-0.06***
3-member	0.00	0.06***	0.06***
5-member	-0.02	0.06***	0.08***
Short-term	0.01	0.05	0.04
Medium-term	0.02	0.08***	0.06
Long-term	0.02	0.08***	0.06

Note: SF=Small-sized farmers, MF=Medium-sized farmers, LF=Large-sized farmers. Diff = marginal effect (I) – marginal effect (J); Post-hoc test: Tukey's HSD, with Bonferroni adjustment for multiple tests. Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

finance was a key factor in 81 of the studies (Fadeyi et al., 2022). The preference for longer-term loans is even more pronounced among the small-sized farmers. However, in Ghana, most financing programs for smallholder farmers offer relatively small loans for short periods and often at high real interest rates (Sarpong et al., 2022). Meanwhile, cocoa irrigation requires a relatively large initial investment since cocoa irrigation technologies are capital-intensive.

We included three attributes to capture the cost dimension of the technology and its institutional model: i.e., individual, a 3-member group, and a 5-member group ownership. Farmers were sensitive to cash outlays, and, *ceteris paribus* selected ownership types that significantly reduced their cost, given the capital-intensive nature of the technology (Michalscheck et al., 2018; Senyolo et al., 2018), lack of subsidies (Owusu, 2016), absence of tax incentives and limited access to credit (Fadeyi et al., 2022; Sarpong et al., 2022). The preference for the two group ownership attributes in the pooled sample is significant, and

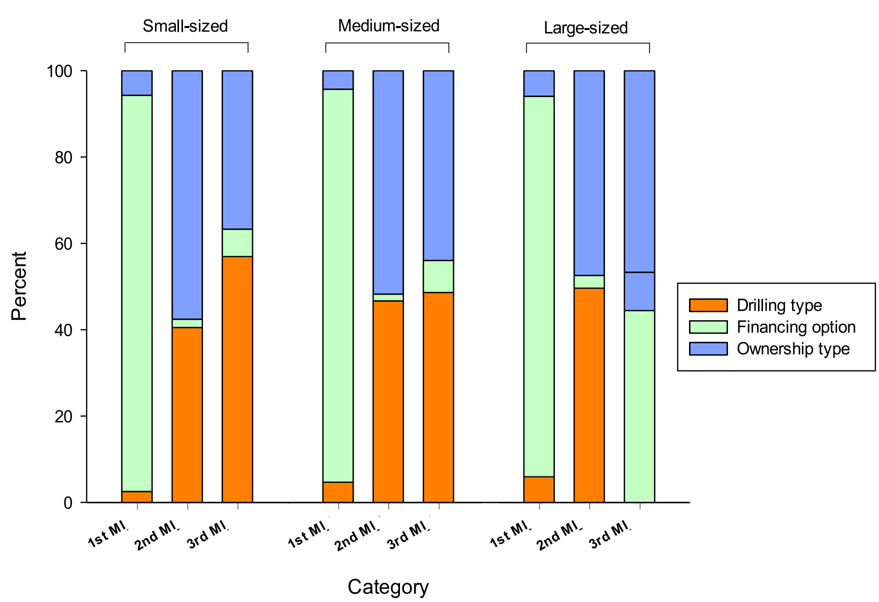

Fig. 7. Attribute ranks by resource level. MI = Most important.

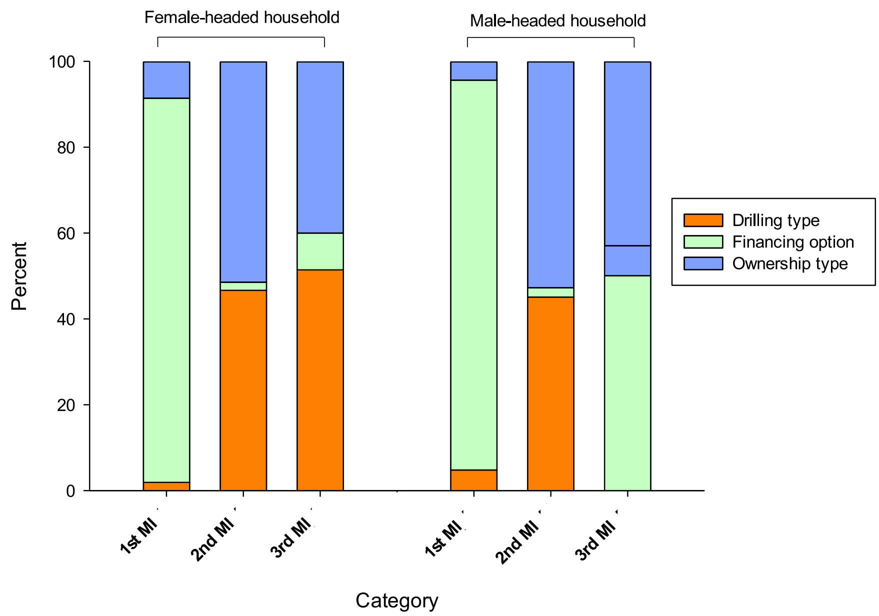

Fig. 8. Attribute ranks by gender. MI = Most important.

Table 8
RPL estimates for a test of heterogeneity in preferences for attributes, by gender.

Choice	Male-headed household				Female-headed household			
	Coef.	Rob. s.e.	dy/dx	Boot. s.e.	Coef.	Rob. s.e.	dy/dx	Boot. s.e.
Mean								
Professional[1]	0.57***	0.08	0.08***	0.01	0.33*	0.18	0.04*	0.02
3-member[2]	0.58***	0.08	0.08***	0.01	0.92***	0.18	0.11***	0.02
5-member[2]	0.61***	0.11	0.08***	0.01	1.34***	0.25	0.16***	0.02
Short-term[3]	1.44***	0.11	0.19***	0.01	1.31***	0.26	0.15***	0.02
Medium-term[3]	2.04***	0.14	0.27***	0.01	2.25***	0.33	0.28***	0.03
Long-term[3]	1.99***	0.13	0.27***	0.01	2.37***	0.34	0.29***	0.02
Standard deviation								
Professional	1.29***	0.11			1.29***	0.26		
3-member	0.01	0.02			0.27	0.46		
5-member	1.26***	0.12			1.09***	0.22		
Short-term	-0.00	0.01			-0.01	0.08		
Medium-term	-0.50*	0.26			0.71	0.48		
Long-term	-0.40**	0.20			0.82**	0.36		
Log-likelihood	-1939.57				-411.80			
Wald Chi2 (6)	256.18***				60.24***			
AIC	3903.14				847.60			
BIC	3985.65				912.48			
N	7152				1648			

Notes: RPL = Random parameter logit, Rob. s.e =Robust standard error, Boot. s.e = Bootstrap standard error. dy/dx = marginal effects. An average of the marginal effects is calculated for each observation using coefficient estimates from the random parameter model; standard errors are estimated using bootstrapping (500 replications); Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. [1]Reference category is locally drilled, [2]Reference category is individual ownership, [3]Reference category is no loan.

Table 9
Test of differences in marginal effects, by gender.

Choice	Male-headed household (I)	Female-headed household (J)	Diff	t-value
Professional	0.08	0.04	0.04	2.36**
3-member	0.08	0.11	-0.03	-1.47
5-member	0.08	0.16	-0.08	-3.55***
Short-term	0.19	0.15	0.04	1.64
Medium-term	0.27	0.28	-0.01	-0.33
Long-term	0.27	0.29	-0.02	-0.53

Note: Diff = marginal effect (I) – marginal effect (J) Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

consistent across the gender sub-sample and the two resource-constrained segments (small-sized and medium-sized). However, the result of the gender-wise disaggregated analysis showed that female-headed households were more interested in a 5-member group (larger group ownership) compared to their male counterparts. This could be attributed to several reasons such as social and cultural norms (Croppenstedt et al., 2013) and risk aversion. Women may prefer the security and shared risk of group ownership models.

Apart from these social and behavioral factors, there may be gender differences in preferences for ownership type due to economic factors. Lower yields and incomes are expected to lead women farmers to favor investments in larger groups, as their reduced financial capacity makes collective investment more appealing. Many researchers reported that women achieve lower yields than men in agriculture, translating into lower incomes (Udry et al., 1995; Udry, 1996; Tiruneh et al., 2001;

Table 10
Parameter estimates of RPL with interactions between irrigation investment attributes and household characteristics.

Variable	Coefficient	Robust std. err.
Mean		
Professional[1]	0.11	0.13
3-member[2]	1.06***	0.16
5-member[2]	1.44***	0.24
Short-term[3]	1.43***	0.10
Medium-term[3]	2.11***	0.13
Long-term[3]	2.08***	0.13
Professional * Farm access	0.63***	0.15
3-member * Household size	-0.04	0.03
5-member * Household size	-0.08*	0.04
3-member * Farm size	-0.02**	0.01
5-member * Farm size	-0.03**	0.01
Standard deviation		
Professional	1.27***	0.10
3-member	0.04	0.04
5-member	1.24***	0.11
Short-term	-0.01	0.01
Medium-term	0.60***	0.22
Long-term	0.54***	0.16
Log-likelihood	-2335.81	
Wald Chi2 (11)	315.02***	
AIC	4705.61	
BIC	4826.01	
N	8800	

Note: RPL = Random parameter logit, Std. err. = Standard error. Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. [1]Reference category is locally drilled, [2]Reference category is individual ownership, [3]Reference category is no loan. The interaction terms are not associated with standard deviation parameters, as they were assumed to be fixed.

Akresh, 2005; Horrell and Krishnan, 2007; Goldstein and Udry, 2008). Even within the same household, significant yield differences were observed for the two gender groups with lower yields recorded by female farmers (Akresh, 2005; Goldstein and Udry, 2008). The differences in yield were mainly attributed to men having greater access to inputs, resources, and services. These empirical findings are consistent with our results which found significant differences in land ownership, credit access, and cocoa output (Table 3). Though group ownership could be an attractive strategy for cost reduction, careful consideration and planning are required to make group ownership a viable and sustainable solution. Policy advocacies can strengthen existing farmer groups or cocoa cooperatives by providing training and capacity building on management and leadership, and technical assistance, enabling them to support smaller groups in forming collective investments in solar irrigation for cocoa.

Interestingly, our study found that reducing the risk associated with borehole drilling was the least important factor influencing cocoa farmers' irrigation investment decisions, contrary to the findings of Balasubramanya et al. (2023). In their study, Ethiopian farmers cited geological uncertainty as a major deterrent to irrigation adoption, ranking it as a highly important attribute. Ghanaian cocoa farmers did not prioritize risk reduction, likely due to the high groundwater potential in the selected study areas. Farmers' awareness of this potential may have led them to perceive borehole drilling as a relatively low-risk venture, despite its inherent risks. As a result, the perceived risk associated with drilling in their locations was lower, making risk reduction a less pressing concern. Additionally, the higher cost of professional drilling may outweigh the benefits of reduced risk, leading farmers to prefer alternative options. Our results showed that only large-sized farmers and male-headed households preferred professional drilling, despite. Furthermore, farm access emerged as a crucial factor influencing farmers' preference for professional drilling, with large-sized segments and male-headed households reporting higher access rates. These findings suggest that drilling risk-reduction preferences are influenced by a complex interplay of factors, including resource availability, gender, and farm access.

To conclude, the following messages can be drawn from our study. First, while farmer-led irrigation is a viable option for reducing the threat of water stress, financial capacity remains a key challenge. From this analysis, we found that access to longer-term loans, cost reduction through group ownership, and cutbacks on uncertainties related to borehole drilling are key pathways to promote the scaling and adoption of solar irrigation technologies among Ghanaian cocoa farmers. Second, we observed heterogeneity in farmers' preferences, depending on resource level, gender, farm size, household size, and access to the farm, suggesting that development actions like inclusive irrigation investments are more likely to succeed when they consider such heterogeneities and adapt to local conditions. As such, there is a need for agricultural researchers to shift from traditional reductionist approaches, which focus on one attribute at a time, to more comprehensive and multidimensional technology assessment frameworks that consider the complex interplay of various factors. In this context, bundling irrigation equipment with tailored financial products, flexible cost-reduction options, and innovative institutional models can be an effective strategy to reconcile trade-offs and leverage synergies among key technology attributes, ultimately enhancing the adoption of cocoa irrigation technologies among smallholder farmers. Third, the results indicate a negative correlation between farm size and preference for group ownership, suggesting that the cost-reducing benefits of group ownership may be more applicable to smallholder farmers. Consequently, larger farms may require alternative financial support mechanisms, such as subsidies or blended finance approaches, to facilitate the adoption of irrigation technologies. Lastly, our study reveals that small and medium-sized farmers identified access to finance and group ownership as their first and second most important attributes, respectively, while large-sized farmers prioritize finance first and drilling risk reduction then. This indicated that financial considerations drive cocoa irrigation investments among all cocoa farmers. As compared to other types of irrigated crops, cocoa farms are typically larger and require bigger irrigation equipment and greater investments to meet the crop's high water demands, posing a significant barrier for smallholder farmers. Therefore, policymakers and practitioners such as banks should propose customized financial products to cocoa farmers that prioritize longer-term loans to facilitate the adoption of solar irrigation technology and allow joint liability, especially to target smallholder and women farmers.

From a practical standpoint, the promotion of joint irrigation ownership among cocoa farmers can be facilitated through existing COCOBOD extension officers. These officers can help identify and organize farmers whose farms are geographically close and who demonstrate the capacity to collaborate based on mutual trust. To meet the requirements of financial institutions, such farmer groups should be formally registered, as banks typically require registered entities with proper record-keeping to assess creditworthiness and ensure loan security. Moreover, the Ghana Cocoa Board (COCOBOD) can play a critical role by providing government-backed guarantees to reduce lending risks and enable joint-owner farmer groups to access more affordable loans. Once financing is secured, banks—working in collaboration with COCOBOD—should implement a robust monitoring system to track farm-level practices, including yield and income records. This can be efficiently done by leveraging existing COCOBOD structures, such as the

Cocoa Management System[4] (CMS), to mitigate the risk of loan default, ensure accountability, and enhance the long-term success of the initiative. In addition, the loan disbursement process should be structured to minimize the risk of fund misallocation. Rather than transferring the loan amount directly to the farmers, payments should be made directly to the accredited irrigation equipment providers upon successful installation of the system. This approach would help to ensure that the funds are used solely for their intended purpose and reduce the likelihood of diversion toward unrelated personal or social expenses, such as weddings, funerals, or other non-agricultural activities.

5. Limitations and future research

While this study addresses key barriers to solar irrigation investment in cocoa production, it also opens important opportunities for future research. Our proposed group ownership model introduces a simplified, informal approach to shared irrigation investment; however, challenges commonly associated with collective action in Ghana, such as trust, accountability, and long-term sustainability, may still arise. Future research should examine how these informal clusters develop over time and assess their effectiveness relative to more formal group structures. Further investigation is also needed to explore how various collective models, including ours, can be adapted or scaled to overcome persistent implementation challenges.

6. CRediT authorship contribution statement

William Quarmine: Writing – review & editing, Conceptualization. **Kekeli Kofi Gbodji:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Petra Schmitter:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Archisman Mitra:** Writing – review & editing, Formal analysis. **Marie-Charlotte Buisson:** Writing – review & editing, Supervision, Formal analysis.

Declaration of Competing Interest

The authors reported no potential conflict of interest.

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Appendix

Table A1
Fractional factorial design of discrete choice experiment

Ownership type	Borehole drilling	Financing option	Choice set	Alternative	Block	Code
Five-member	Professional	Medium	1	1	1	FPM
Three member	Local	Short	1	2	1	TLS
Five-member	Local	Short	6	1	1	FLS
Individual	Professional	No	6	2	1	IPN
Five-member	Professional	Medium	7	1	1	FPM
Individual	Local	No	7	2	1	ILN
Individual	Local	Long	8	1	1	ILL
Three member	Professional	No	8	2	1	TPN
Five-member	Local	Medium	9	1	1	FLM
Three member	Professional	Short	9	2	1	TPS
Three member	Professional	Medium	13	1	1	TPM
Five-member	Local	No	13	2	1	FLN
Individual	Professional	Short	15	1	1	IPS
Three member	Local	Long	15	2	1	TLL
Three member	Local	No	16	1	1	TLN
Five-member	Professional	Long	16	2	1	FPL
Individual	Local	Long	2	1	2	ILL
Three member	Professional	Short	2	2	2	TPS
Five-member	Local	Short	3	1	2	FLS
Individual	Professional	No	3	2	2	IPN
Five-member	Local	Medium	4	1	2	FLM
Three member	Professional	Long	4	2	2	TPL
Individual	Professional	Long	5	1	2	IPL
Five-member	Local	No	5	2	2	FLN
Five-member	Professional	No	10	1	2	FPN
Three member	Local	Medium	10	2	2	TLM
Three member	Professional	Medium	11	1	2	TPM
Individual	Local	Short	11	2	2	ILS
Individual	Local	Medium	12	1	2	ILM
Five-member	Professional	Long	12	2	2	FPL

(*continued on next page*)

[4] The Cocoa Management System (CMS) is a comprehensive national database developed by the Ghana Cocoa Board (COCOBOD) to digitize and streamline the management of Ghana's cocoa sector. It captures detailed information on cocoa farmers, including their identities, farm ages and sizes, locations, yields, income levels, and farmer demographics. The CMS also records and tracks purchasing clerks, service providers, and suppliers of key production inputs such as fertilizers and pesticides, along with their capacities and pricing. Registered farmers have Cocoa Identification Cards, linked to the national identification system (Ghana Card), which will serve as their official ID within the cocoa sector. The system is also designed to enhance traceability, transparency, and accountability across the value chain, laying the foundation for improved planning, resource allocation, and long-term sectoral development.

Table A1 (*continued*)

Ownership type	Borehole drilling	Financing option	Choice set	Alternative	Block	Code
Three member	Local	Long	14	1	2	TLL
Individual	Professional	Short	14	2	2	IPS

Table A2
Orthogonality test

	Ownership type	Borehole drilling	Financing option
Ownership type	1.0000		
Borehole drilling	-0.0395	1.0000	
	(0.8281)		
Financing option	0.0161	0.0000	1.0000
	(0.9300)	(1.0000)	

Table A3
Test of Balance

Attribute	Level	Frequency		
		Block 1	Block 2	Total
Ownership type	Individual	4	6	10
	3-member	6	5	11
	5-member	6	5	11
Borehole drilling	Local	8	8	16
	Professional	8	8	16
Financing option	No	5	3	8
	Short-term	4	4	8
	Medium-term	4	4	8
	Long-term	3	5	8

Table A4
RPL estimates for the full dataset

Variable	Coefficient	Robust std. err.
Mean		
Professional[1]	0.52***	0.07
3-member[2]	0.60***	0.07
5-member[2]	0.70***	0.10
Short-term[3]	1.39***	0.10
Medium-term[3]	2.05***	0.13
Long-term[3]	2.01***	0.12
Standard deviation		
Professional	1.27***	0.10
3-member	0.05	0.09
5-member	1.26***	0.10
Short-term	0.01	0.01
Medium-term	0.47**	0.24
Long-term	0.45***	0.17
Log-likelihood	-2437.08	
Wald Chi2 (11)	313.33 ***	
AIC	4898.16	
BIC	4983.45	
N	9024	

Note: Robustness checks using the entire dataset (564) including wrongly answered dominated choice cards. RPL = Random parameter logit, Std. err. = Standard error. Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. [1]Reference category is locally drilled, [2]Reference category is individual ownership, [3]Reference category is no loan.

Data availability

Data will be made available on request.

References

Abdallah, A.H., Ayamga, M., Awuni, J.A., 2019. Impact of agricultural credit on farm income under the savanna and transitional zones of Ghana. Agric. Financ. Rev. 79 (1), 60–84. https://doi.org/10.1108/AFR-02-2018-0009.

Agbenyo, W., Jiang, Y., Jia, X., Wang, J., Ntim-Amo, G., Dunya, R., Siaw, A., Asare, I., Twumasi, M.A., 2022. Does the adoption of climate-smart agricultural practices impact farmers' income? Evidence from Ghana. Int. J. Environ. Res. Public Health 19 (7), 3804.
Akpoti, K., Dembélé, M., Forkuor, G., Obuobie, E., Mabhaudhi, T., Cofie, O., 2023. Integrating GIS and remote sensing for land use/land cover mapping and groundwater potential assessment for climate-smart cocoa irrigation in Ghana. Sci. Rep. 13 (1), 16025.
Akresh, R., 2005. "Understanding Pareto Inefficient Intrahousehold Allocations." IZA Discussion Paper No. 1858. Institute for the Study of Labor (IZA), Bonn, Germany.
Akrofi, N.A., Sarpong, D.B., Somuah, H.A.S., Osei-Owusu, Y., 2019. Paying for privately installed irrigation services in Northern Ghana: the case of the smallholder Bhungroo irrigation technology. Agric. Water Manag. 216, 284–293.
Anderson, P.D., Wilson, N.P., Thompson, D.G., 1999. Adoption and diffusion of level fields and basins. J. Agric. Resour. Econ. 24 (1), 186–203.
Asche, F., Larsen, T.A., Smith, M.D., Sogn-Grundvåg, G., Young, J.A., 2015. Pricing of eco-labels with retailer heterogeneity. Food Policy 53, 82–93.
Asfaw, A., Bantider, A., Simane, B., Hassen, A., 2021. Smallholder farmers' livelihood vulnerability to climate change-induced hazards: agroecology-based comparative analysis in Northcentral Ethiopia (Woleka Sub-basin). Heliyon 7 (4).
Awafo, E.A., Owusu, P.A., 2022. Energy and water mapping of the cocoa value chain in Ghana. Sustain. Prod. Consum. 29, 341–356.
Balana, B.B., Mekonnen, D., Haile, B., Hagos, F., Yimam, S., Ringler, C., 2022. Demand and supply constraints of credit in smallholder farming: evidence from Ethiopia and Tanzania. World Dev. 159, 106033.
Balasubramanya, S., Buisson, M.C., Mitra, A., Stifel, D., 2023. Price, credit or ambiguity? Increasing small-scale irrigation in Ethiopia. World Dev. 163, 106149.
Ben-Akiva, M., Lerman, S.R., 1985. Discrete choice analysis: theory and application to travel demand. The MIT Press, Cambridge Massachusetts.
Bunn, C., Läderach, P., Quaye, A., Muilerman, S., Noponen, M.R., Lundy, M., 2019. Recommendation domains to scale out climate change adaptation in cocoa production in Ghana. Clim. Serv. 16, 100123.
Burgess, L., Street, D.J., 2005. Optimal designs for choice experiments with asymmetric attributes. J. Stat. Plan. Inference 134, 288–301.
Carlsson, F., Martinsson, P., 2003. Design techniques for stated preference methods in health economics. Health Econ. 12, 281–294.
Carlucci, D., Devitiis, B.D., Nardone, G., Santeramo, F.G., 2017. Certification labels versus convenience formats: What drives the market in aquaculture products? Mar. Resour. Econ. 32 (3), 295–310.
Carr, M.K.V., Lockwood, G., 2011. The water relations and irrigation requirements of cocoa (Theobroma cacao L.): a review. Exp. Agric. 47 (4), 653–676. FAO, F.S.P., 2015. World food and agriculture. *Food and Agriculture Organization of the United Nations*.
Carter, R., Belete, E., Berhe, E., Defere, E., Horecha, D., Negussie, Y., 2006. Reducing the costs of borehole drilling in Africa: insights from Ethiopia. WATERLINES-LOND.- 25 (1), 7.
Croppenstedt, A., Goldstein, M., Rosas, N., 2013. Gender and agriculture: inefficiencies, segregation, and low productivity traps. World Bank Res. Obs. 28 (1), 79–109.
Diagne, A., 2009. Technological Change in Smallholder Agriculture: Bridging the Adoption Gap by Understanding its Source.
Dittoh, S., 2020. Assessment of farmer-led irrigation development in Ghana. World Bank.
Durga, N., Schmitter, P., Ringler, C., Mishra, S., Magombeyi, M.S., Ofosu, A., Pavelic, P., Hagos, F., Melaku, D., Verma, S., Minh, T., 2024. Barriers to the uptake of solar-powered irrigation by smallholder farmers in sub-Saharan Africa: a review. Energy Strategy Rev. 51, 101294.
Essel, T.T., Newsome, M.A., 2000. Effectiveness of institutional credit for rural development in Africa: a control-case study of rural banks in Ghana. J. Sustain. Dev. Afr. 2 (1).
Fadeyi, O.A., Ariyawardana, A. and Aziz, A.A., 2022. Factors influencing technology adoption among smallholder farmers: a systematic review in Africa.
Fisher, M., Carr, E.R., 2015. The influence of gendered roles and responsibilities on the adoption of technologies that mitigate drought risk: the case of drought-tolerant maize seed in eastern Uganda. Glob. Environ. Change 35, 82–92.
Gbodji, K.K., Quarmine, W., Minh, T.T., 2023. Effective demand for climate-smart adaptation: a case of solar technologies for cocoa irrigation in Ghana. Sustain. Environ., 2258472 https://doi.org/10.1080/27658511.2023.2258472.
Gebrezgabher, S., Leh, M., Merrey, D.J., Kodua, T.T., Schmitter, P., 2021. Solar photovoltaic technology for small-scale irrigation in Ghana: suitability mapping and business models. In: Agricultural Water Management–Making a Business Case for Smallholders, 178. International Water Management Institute (IWMI).
Ghana Cocoa Board, 2024. Increasing cocoa production in Ghana - The importance of the 4 Ps. https://cocobod.gh/news/increasing-cocoa-production-in-ghana-the-importance-of-the-4ps#:~:text=For%20instance%2C%20in%202021%20alone,employs%20over%20one%20million%20farmers.
Goldstein, M., Udry, C., 2008. The profits of power: land rights and agricultural investment in Ghana. J. Political Econ. 116 (6), 981–1022.
Habtemariam, L.T., Mgeni, C.P., Mutabazi, K.D., Sieber, S., 2019. The farm income and food security implications of adopting fertilizer micro-dosing and tied-ridge technologies under semi-arid environments in central Tanzania. J. Arid Environ. 166, 60–67.
Hall, J., Viney, R., Haas, M., Louviere, J.J., 2004. Using stated preference discrete choice modeling to evaluate health care programs. J. Bus. Res. 57, 1026–1032.
Hamidinasab, B., Javadikia, H., Hosseini-Fashami, F., Kouchaki-Penchah, H., Nabavi-Pelesaraei, A., 2023. Illuminating sustainability: a comprehensive review of the environmental life cycle and energetic impacts of solar systems on the agri-food sector. Sol. Energy 262, 111830.
Hanson, K., McPake, B., Nakamba, P., Archard, L., 2005. Preferences for hospital quality in Zambia: results from a discrete choice experiment. Health Econ. 14, 687–701.
Hensher, D.A., Rose, J.M., Greene, W.H., 2005. Applied choice analysis: a primer. Cambridge university press. ⟨https://datacommons.org/place/country/GHA?utm_medium=explore&mprop=lifeExpectancy&popt=Person&hl=en⟩.
Hole, A.R., 2007. Fitting mixed logit models by using maximum simulated likelihood. Stata J. 7 (3), 388–401.
Horrell, S., Krishnan, P., 2007. Poverty and productivity in female-headed households in Zimbabwe. J. Dev. Stud. 43 (8), 1351–1380.
Janssen, M., Hamm, U., 2014. Governmental and private certification labels for organic food: consumer attitudes and preferences in Germany. Food Policy 49, 437–448.
Jourdain, D., Lairez, J., Striffler, B., Affholder, F., 2020. Farmers' preference for cropping systems and the development of sustainable intensification: a choice experiment approach. Rev. Agric. Food Environ. Stud. 101 (4), 417–437.
Khonje, M.G., Manda, J., Mkandawire, P., Tufa, A.H., Alene, A.D., 2018. Adoption and welfare impacts of multiple agricultural technologies: evidence from eastern Zambia. Agric. Econ. 49 (5), 599–609.
Kjaer, T., Bech, M., Gyrd-Hansen, D., Hart-Hansen, K., 2006. Ordering effect and price sensitivity in discrete choice experiments: need we worry? Health Econ. 15 (11), 1217–1228.
Kotu, B.H., Oyinbo, O., Hoeschle-Zeledon, I., Nurudeen, A.R., Kizito, F., Boyubie, B., 2022. Smallholder farmers' preferences for sustainable intensification attributes in maize production: evidence from Ghana. World Dev. 152, 105789.
Kuhfeld W., 2005. *Marketing research methods in SAS*. Available from: ⟨http://support.sas.com/techsup/technote/ts722.pdf⟩.
Lancaster, K.J., 1966. A new approach to consumer theory. J. Political Econ. 74, 132–157.
Liddle, E.S., Fenner, R., 2018. Review of handpump-borehole implementation in Uganda. British Geological Survey, Nottingham, UK.
Lukawski, M.Z., Silverman, R.L., Tester, J.W., 2016. Uncertainty analysis of geothermal well drilling and completion costs. Geothermics 64, 382–391.
MacDonald, A.M., Calow, R.C., MacDonald, D.M., Darling, W.G., Dochartaigh, B.E., 2009. What impact will climate change have on rural groundwater supplies in Africa? Hydrol. Sci. J. 54 (4), 690–703. https://doi.org/10.1623/hysj.54.4.690.
Makate, C., Makate, M., Mango, N., Siziba, S., 2019. Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. J. Environ. Manag. 231, 858–868.
Martin, L., & Hurley, J. (2019). Republic of Ghana for review. December 10–12.
McFadden, D., 1974. Conditional logit analysis of qualitative choice behaviour. In: Zarembka, P.E. (Ed.), Frontiers of Econometrics. Academic Press, New York.
McFadden, D., Train, K., 2000. Mixed MNL models for discrete response. J. Appl. Econ. 15 (5), 447–470.
Mekonnen, A., Tessema, A., Ganewo, Z., Haile, A., 2021. Climate change impacts on household food security and adaptation strategies in southern Ethiopia. Food Energy Secur. 10 (1), e266.
Mensah, J.K., Ofosu, E.A., Akpoti, K., Kabo-Bah, A.T., Okyereh, S.A., Yidana, S.M., 2022. Modeling current and future groundwater demands in the White Volta River Basin of Ghana under climate change and socio-economic scenarios. J. Hydrol. Reg. Stud. 41, 101117. https://doi.org/10.1016/j.ejrh.2022.101117.
Michalscheck, M., Groot, J.C., Kotu, B., Hoeschle-Zeledon, I., Kuivanen, K., Descheemaeker, K., Tittonell, P., 2018. Model results versus farmer realities. Operation realizing diversity within and among smallholder farm systems for a nuanced impact assessment of technology packages. Agric. Syst. 162, 164–178.
Minh, T.T., Ofosu, A., 2022. Solar-based irrigation bundle profile and. scaling Ghana.
Mishra, A.K., Sudarsan, J.S., Suribabu, C.R., Murali, G., 2024. Cost-benefit analysis of implementing a solar powered water pumping system–A case study. Energy Nexus 16, 100323.
Mudhara, M., Hilderbrand, P.E., Nair, P.K.R., 2003. Potential for adoption of Sesbania sesban improved fallows in Zimbabwe: a linear programming-based case study of small-scale farmers. Agrofor. Syst. 59, 307–315.
Murage, A.W., Midega, C.A.O., Pittchar, J.O., Pickett, J.A., Khan, Z.R., 2015. Determinants of adoption of climate-smart push-pull technology for enhanced food security through integrated pest management in eastern Africa. Food Secur. 7, 709–724.
Ofori-Boateng, K., Insah, B., 2014. The impact of climate change on cocoa production in West Africa. Int. J. Clim. Change Strateg. Manag. 6 (3), 296–314.
Ofori-Boateng, K., Eregha, P.B., Baba, I., 2015. Climate conditions and cocoa yields in ECOWAS countries: fully modified OLS approach. Int. J. Green. Econ. 9 (2), 182–198.
Ortega, D.L., Waldman, K.B., Richardson, R.B., Clay, D.C., Snapp, S., 2016. Sustainable intensification and farmer preferences for crop system attributes: evidence from Malawi's central and southern regions. World Dev. 87, 139–151.
Owusu, V., 2016. The economics of small-scale private pump irrigation and agricultural productivity in Ghana. The Journal of developing areas 50 (1), 289–304.
Pörtner, H.O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R.A., Betts, R., Kerr, R.B., Biesbroek, R., Birkmann, J., 2022. Climate change *2022: Impacts, adaptation and vulnerability*. IPCC.
Revelt, D., Train, K., 2000. Customer-specific taste parameters and mixed logit: households' choice of electricity supplier. working paper, department of economics. University of California, Berkeley.
Ruto, E., Garrod, G., 2009. Investigating farmers' preferences for the design of agri-environment schemes: a choice experiment approach. J. Environ. Plan. Manag. 52 (5), 631–647.

Santeramo, F.G., Carlucci, D., De Devitiis, B., Nardone, G., Viscecchia, R., 2017. On consumption patterns in oyster markets: the role of attitudes. Mar. Policy 79 (5), 54–61.

Sarpong, D.B., Mabhaudhi, T., Minh, T. and Cofie, O., 2022. Sustainable financing ecosystem for cocoa irrigation in Ghana: a literature review. *IWMI Books, Reports*, (H051654).

Senyolo, M.P., Long, T.B., Blok, V., Omta, O., 2018. How the characteristics of innovations impact their adoption: an exploration of climate-smart agricultural innovations in South Africa. J. Clean. Prod. 172, 3825–3840. https://doi.org/10.1016/j.jclepro.2017.06.019.

Silberg, T.R., Richardson, R.B., Lopez, M.C., 2020. Maize farmer preferences for intercropping systems to reduce Striga in Malawi. Food Secur. 12 (2), 269–283.

Stuch, B., Alcamo, J., Schaldach, R., 2021. Projected climate change impacts on mean and year-to-year variability of yield of key smallholder crops in Sub-Saharan Africa. Clim. Dev. 13 (3), 268–282.

Thompson, W.J., Blaser-Hart, W.J., Krütli, P., Dawoe, E., Chavez, E., Garrett, R.D., 2022. Can sustainability certification enhance the climate resilience of smallholder farmers? The case of Ghanaian cocoa. J. Land Use Sci. 17 (1), 407–428.

Tiruneh, A., Tesfaye, T., Mwangi, W., Verkuijl, H., 2001. Gender differentials in agricultural production and decision-making among smallholders in Ada, Lume, and Gimbichu Woredas of the central highlands of Ethiopia. El Baton. International Maize and Wheat Improvement Center (CIMMYT) and Ethiopian Research Organization (EARO), Mexico.

Tonsor, G.T., Wolf, C.A., 2011. On mandatory labeling of animal welfare attributes. Food Policy 36 (3), 430–437.

Train, K., 2003. Discrete choice methods with simulation. Cambridge University Press, Cambridge.

Train, K.E., 2009. Discrete choice methods with simulation, second edition. Cambridge University Press, Cambridge.

Udry, C., 1996. Gender, agricultural production, and the theory of the household. J. Political Econ. 104 (5), 1010–1046.

Udry, C., Hoddinott, J., Alderman, H., Haddad, L., 1995. Gender differentials in farm productivity: implications for household efficiency and agricultural policy. Food Policy 20 (5), 407–423.

Waldman, K.B., Kerr, J.M., 2015. Is food and drug administration policy governing artisan cheese consistent with consumers' preferences? Food Policy 55 (5), 71–80.

Word bank Data Commons, 2021.

World Bank., 2019. Enhancing Financial Inclusion. World Bank Group, (June), 1–81. Retrieved from ⟨http://documents1.worldbank.org/curated/en/395721560318628665/pdf/Fourth-GhanaEconomic-Update-Enhancing-Financial-Inclusion-Africa-Region.pdf⟩.

Wozniak, G.D., 1993. Joint information acquisition and new technology adoption- late versus early adoption. Rev. Econ. Stat. 75 (3), 438–445.

Zuidema, P.A., Leffelaar, P.A., Gerritsma, W., Mommer, L., Anten, N.P., 2005. A physiological production model for cocoa (Theobroma cacao): model presentation, validation and application. Agric. Syst. 84 (2), 195–225.