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RESEARCH ARTICLE

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Bundling solar-based irrigation and vermicompost using a living lab approach in Ethiopia: impacts on crop yield, soil moisture and rural livelihoods

Desalegn Tegegne[a,b,c], Stefan Sieber[a,c], Goetz Uckert[c], Rediet Girma[d], Amare Haileslassie[b] and Wolde Mekuria[b]

[a]Department of Agricultural Economics, Faculty of Life Sciences, Humboldt-Universität zu Berlin, Berlin, Germany; [b]International Water Management Institute (IWMI), Addis Ababa, Ethiopia; [c]Leibniz Centre for Agricultural Landscape Research (ZALF), Sustainable Land Use in Developing Countries, Müncheberg, Germany; [d]Agricultural Engineering Department, Hawassa University, Hawassa, Ethiopia

ABSTRACT

This study in Ethiopia's Rift Valley tested two hypotheses: integrating solar-based irrigation with vermicompost would considerably increase crop yields and soil moisture retention; and smallholder farmers would perceive solar irrigation as contributing positively to livelihood diversification, household income, food security, livestock feed availability and environmental co-benefits. Participatory on-farm trials and key informant interviews were conducted to address these research questions. The trial used cabbage and pepper as test crops and employed a randomized complete block design with three treatments: Treatment 1/Control (solar-based irrigation with farmers' current practices); Treatment 2 (Treatment 1plus 4 t ha−1 of vermicompost); and Treatment 3 (Treatment 1 plus 8 t ha−1 of vermicompost). The first hypothesis was confirmed: bundling vermicompost with solar-based irrigation increased yields (pepper +78.6%, cabbage +14.3%) and improved soil moisture retention. These yield gains were economically viable, with benefit–cost ratios ranging from 0.38 to 2.46 across sites. The second hypothesis was supported: 88% of farmers adopted 2–5 new crops (75% citing improved water access), shifting toward vegetables, fruits and fodder, with reported gains in income, food security, nutrition, dry-season fodder and environmental co-benefits. Solar irrigation therefore delivers greater agronomic and livelihood benefits when integrated with vermicompost, supporting the scaling of bundled interventions.

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Organic fertilizer; crop yield; livelihood diversification; solar-based irrigation; soil moisture dynamics

1. Introduction

Human activities such as deforestation, overgrazing and unsustainable land cultivation in Sub-Saharan Africa (SSA) countries are undermining agricultural productivity (Food & Agriculture Organization of the United Nations (FAO), 2025; Mekuria et al., 2024a; Shapiro et al., 2023). Furthermore, the low adoption of agricultural technologies and sustainable systems in SSA has led to declining soil fertility and constrained efforts to achieve food security (Food & Agriculture Organization of the United Nations (FAO), 2018). This necessitates more evidence-based integrated sustainable agricultural practices to enhance the productivity of soil, crops and water (Masso et al., 2017; Wawire et al., 2021; Mekuria et al. , 2024a; Olarewaju et al., 2025) and thereby increase food security and enhance the adaptive capacity of people (Wawire et al., 2021; Olarewaju et al., 2025).

Complementing these practices, technological innovations such as solar-based irrigation are promoted in SSA countries as part of climate action programmes (Food & Agriculture Organization of the United Nations (FAO), 2018). In addition, using solar pumps for irrigation in SSA has emerged as a promising solution for smallholders, as it reduces dependency on fuel-based pumps and labour demand, and

CONTACT Desalegn Tegegne d.tegegne@cgiar.org; desalegn.tegegne.mengistu@student.hu-berlin.de Department of Agricultural Economics, Faculty of Life Sciences, Humboldt-Universität zu Berlin, Eberswalder Str. 84, 15374 Müncheberg, Berlin, 15374, Germany; Stefan Sieber Stefan.Sieber@zalf.de Department of Agricultural Economics, Faculty of Life Sciences, Humboldt-Universität zu Berlin, Eberswalder Str. 84, 15374 Müncheberg, Berlin 15374, Germany

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increases access to a more reliable water supply (IRENA, 2016; Durga et al., 2024; Liang et al., 2024). Furthermore, the emergence of solar-based irrigation as an option across SSA is attributed to its multiple benefits. Firstly, solar-based irrigation supports improvements in livelihoods by increasing crop productivity and diversifying high-value crops, such as vegetables (Birhanu et al., 2023; REEEP, 2024). Secondly, it helps achieve food and nutrition security by enabling diversified cropping systems, increasing yields and improving access to nutritious vegetables and cereals (Birhanu et al., 2023; Burney et al., 2010). Thirdly, solar-based irrigation positively contributes to household incomes by increasing harvest frequency, encouraging farmers to shift from subsistence crops to market-oriented crops and expanding cultivated areas (Sanogo et al., 2025; Yamegueu et al., 2019). Fourthly, solar-based irrigation provides environmental co-benefits by reducing greenhouse gas emissions and fuel leakage that contaminates soil and water (Guno & Agaton, 2022; Maity et al., 2024).

Studies (e.g. Song et al., 2021) reported that solar-based irrigation supports efficient water use, reducing over-irrigation and agrochemical runoff into freshwater ecosystems. In addition, Guno and Agaton (2022) indicated that reliable clean energy, in the case of solar-based irrigation, promotes greening of homestead areas, improves soil cover and reduces erosion, contributing to a healthy ecosystem. Similar trends in the use or promotion of solar-based irrigation were observed in Ethiopia (Ashine, 2025). Specifically, various governmental and non-governmental institutions have implemented solar-based irrigation over the past few years to ensure the use of shallow groundwater, water harvesting ponds and drip or overhead irrigation for multiple uses, along with capacitating farmers and development agents (Mekuria & Tegegne, 2023; Negera et al., 2025; Schmitter et al., 2016).

Despite various efforts in the country to promote solar-based irrigation and to create enabling environments, such as establishing public-private partnerships to increase access to finance and providing continuous extension support (Dejen et al., 2025; Negera et al., 2025), there remains a challenge in maximizing benefits and promoting wider adoption. Some of these challenges include the decline in soil fertility (i.e. nutrient depletion and organic matter loss), limited access to agricultural inputs, such as inorganic fertilizers, and poor soil management practices, constraining the contributions of solar-based irrigation to livelihood diversification, household income, food security and environmental co-benefits (Food & Agriculture Organization (FAO), 2023). In line with this, Falchetta et al. (2023) argued that without strong land and water resource management infrastructure and governance, widespread deployment of solar pumps may drive an unsustainable exploitation of water sources and reduce environmental co-benefits. This study further elaborates that while solar-based irrigation offers clear environmental benefits, it cannot address sustainability challenges alone. Without complementary measures, such as soil fertility management practices, integrated water governance and regulatory policies, widespread adoption risks unsustainable water extraction and diminished co-benefits. Bundling technologies and strong governance frameworks are essential to ensure long-term resource sustainability.

In response to this challenge and to support the adoption of solar-based irrigation in Ethiopia, bundling technologies that integrate renewable energy-based irrigation systems, institutional linkages and soil fertility enhancement is increasingly recognized as a climate-smart strategy for smallholder farmers, helping to improve environmental sustainability and economic resilience (Gebregergs et al., 2026; Gebremedhin et al., 2024; Hagos et al., 2017; International Water Management Institute (IWMI), 2024; Berhanu et al., 2021; Nigussie et al., 2023). Among soil fertility management practices, organic amendments play a critical role in improving nutrient availability, soil structure and water-holding capacity (Assefa & Tadesse, 2019). Vermicompost is widely adopted at the smallholder level due to its high nutrient content and positive impacts on soil moisture and crop productivity (Freyer et al., 2024). Produced by pre-composting farm wastes, inoculating them with earthworms such as Eisenia fetida, and allowing decomposition, vermicompost enhances nutrient levels, especially when diverse agricultural residues are combined (Mekuria et al., 2025). In the Ethiopian Rift Valley, the study area, vermicompost is locally prepared using animal waste, processed leaf litter and other biological materials. However, empirical evidence demonstrating the complementarity of solar-based irrigation and soil fertility management practices is lacking in Ethiopia, especially in Ethiopia's Rift Valley basins, where frequent droughts, declining soil fertility and land degradation are common (Kusse et al., 2019; Meressa and Bantie, 2024; Shahena et al., 2021; Tegegne et al., 2026).

The successful promotion of solar-based irrigation and its effective use also requires understanding farmers' opinions on solar-based irrigation (Desalegn, 2025; Sanogo et al., 2025) and ensuring collaboration among diverse stakeholders with an interest in solar-based irrigation, including solar pump providers, micro-financial institutions, local input producers (e.g. vermicompost producers) and agricultural extension systems (Korekallu Srinivasa & Mithöfer, 2024; Mekuria et al., 2024b). However, studies investigating farmers' perspectives on solar-based irrigation in the Ethiopian context, highlighting mechanisms for effective stakeholder participation and engagement, are lacking (Negera et al., 2025). Failure to consider farmers' perspectives and coordinate among stakeholders can create barriers such as high costs, maintenance uncertainties and limited access to credit or technical support (Agrawal and Jain, 2019; Durga et al., 2024).

In addition to the factors outlined above, adoption of solar water pumps among smallholder farmers is significantly influenced by socioeconomic factors such as perceived ease of use and cost, highlighting the importance of stakeholder participation (GIZ/NIRAS/Practica, 2025). Hence, without addressing these issues, even well-designed solar-based irrigation systems may be underutilized or abandoned, limiting their contribution to community resilience and environmental sustainability (Falchetta et al., 2023).

Considering the importance of bundling agricultural inputs and understanding farmers' perspectives, this study (i) investigated the integrated impacts of solar-based irrigation and vermicompost use on crop yield and soil moisture retention using field experiments in smallholder farms and (ii) explored farmers' (i.e. key informants) opinions on how solar-based irrigation contributes to livelihood diversification, household income, food security, livestock feed and environmental co-benefits. Because smallholders ultimately decide whether an innovation takes root and is scaled up, and adoption hinges on perceived benefits beyond yield gains (Danso-Abbeam et al., 2020; Kassie et al., 2017; Singha et al., 2012), the study focused on these predetermined yet farmer-validated key livelihood dimensions. This approach ensures the technology's measured agronomic impacts are linked to outcomes farmers value and provides a grounded, policy-relevant gauge of its potential for on-farm adoption and sustainable scaling.

The study hypothesized that integrating solar-based irrigation with vermicompost would significantly increase crop yield and soil moisture retention, and that smallholder farmers would perceive solar-based irrigation as contributing positively to livelihood diversification, household income, food security, livestock feed availability and environmental co-benefits. The innovative strength of this study lies in its integrated, participatory approach through field-based experimentation, coupled with qualitative insights. In contrast to the conventional researcher-driven trials, this study adopted a living lab approach, engaging farmers and other actors from design through evaluation in their own fields. This participatory model fosters knowledge co-creation by integrating local insights with scientific evidence, promotes adaptive learning through iterative feedback and strengthens ownership, key to sustaining solutions beyond the research phase. By bundling solar-based irrigation with vermicompost application, the study tackles both water and soil fertility constraints in smallholder systems; therefore, it offers climate-smart agriculture to improve productivity and resilience.

The key informant interviews add a critical socio-economic dimension to the study by capturing farmers' perceptions of the contribution of solar-based irrigation to livelihood diversification, income gains, food security, livestock feed availability and environmental co-benefits. The dual-method approach adopted in this study offers a comprehensive perspective on both the technical performance of bundled agricultural inputs and the dynamics of their adoption, thereby informing scalable interventions that align with farmers' priorities and broader sustainability objectives.

2. Materials and methods

2.1. The study area

The study was conducted in two districts, Hawassa Zuriya and Misrak Meskan, located in the Ethiopian Rift Valley Lakes Basin (Figure 1). The study districts show both similarities and differences in site characteristics (Table 1, Figure 2). For example, both sites exhibit a bimodal rainfall regime, with the short rainy season

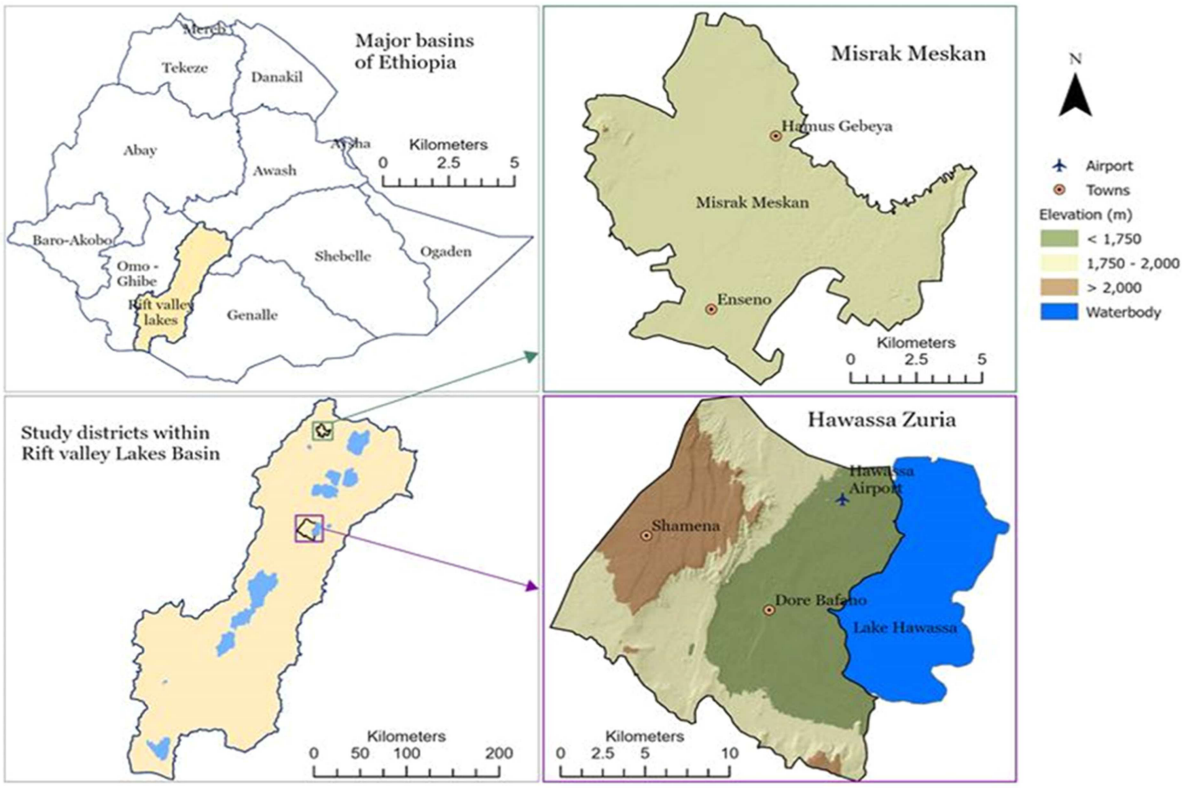


Figure 1. Location map of study districts (Source: Authors' analysis based on GIS and remote sensing data).

Table 1. Site characteristics of the two selected study sites.

Site characteristics	Hawassa Zuriya	Misrak Meskan	Sources
Altitude (m a.s.l.)	1672 - 2214	1750 - 2000	Author's analysis
Mean annual rainfall (mm)	1075	1050	CHIRPS rainfall database (1981—2025)
Mean min Temp (°C)	12	11.8	Wabela (2018)
Mean max Temp (°C)	26.7	27.4	
Slope categories	Flat (64.5%), Gentle (22.1%), Moderate steep (10%), Steep (2.8%), Very Steep (1.9%)	Flat (88.6%), Gentle (10.1%), Moderate steep (1%), Steep (0.1%), Very Steep (0.02%)	Author's analysis:
Soil type	Andosols (32.3%), Cambisols (19.4%), Fluvisols (1.9%), Leptosols (10.5%), Lovisols (29.5%), Nitisols (0.02%), Solonchaks (0.01%), Vertisols (5.81%)	Andosols (35.4%), Cambisols (6.1%), Fluvisols (0.2%), Leptosols (2.5%), Lovisols (3.3%) Planosols (2.5%), Vertisols (49.9%)	Author's analysis
Traditional agroecological zones	Moist Weyna Dega (covers 98.9% and Wet Weynadega 1.1%	Moist Weynadega (100%)	Author's analysis
Farming system	Mixed crop-livestock system	Mixed crop-livestock system	Mitiku and Amiha, 2018; Alemayehu et al., 2025; Kuta, 2025
Major crops grown	Maize, wheat, cabbage, beans, Enset and vegetables	Maize, wheat, barley, teff, beans, Enset	Abule Ebro et al., 2017; Alemayehu et al., 2025
Major Livelihood mechanisms	Agriculture, off-farm activities	Agriculture and off-farm activities	Abule Ebro et al., 2017; Alemayehu et al., 2025

Note: The traditional agroecological classifications use elevation and long-term mean annual rainfall and classify Ethiopia into 15 agroecological zones (Hurni et al., 2016). The slope classification was made based on flat (0%–5%), gentle (5%–15%), moderately steep (15%–30%), Steep (30%–45%) and very steep (>45%) (source: authors' analysis).

occurring from March to May and the main rainy season from July to September (Figure 2). Hawassa Zuriya and Misrak Meskan share a mixed crop-livestock farming system and similar agroecological zones, yet they differ in a few biophysical characteristics such as soil and topographic features (Table 1). Hawassa Zuriya is dominated by Andosols (32.2%), followed by Luvisols (29.5%), while Misrak Meskan is dominated by Vertisols (49.9%), followed by Andosols (35.4%).

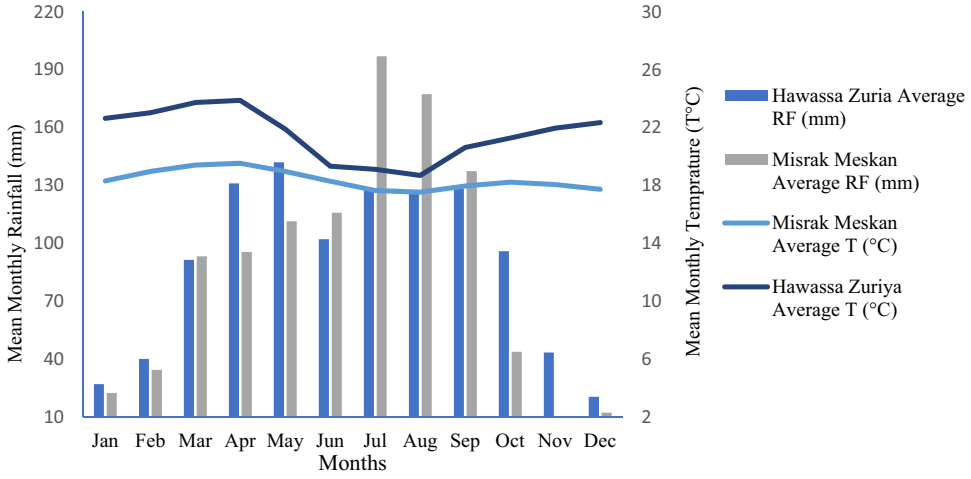


Figure 2. Mean monthly rainfall and temperature from 1981–2025, derived from the CHIRPS database (source: authors' analysis).

2.2. Research approach

2.2.1. Living lab approach and farmers' engagement

We used participatory on-farm trials to test the first hypothesis: that integrating solar-based irrigation with vermicompost would considerably increase crop yields and soil moisture retention. These trials were embedded in a Living Lab approach, which prioritized co-design of interventions, active multi-stakeholder engagement, iterative learning and continuous feedback. In practice, farmers, researchers, development workers and extension agents were involved collaboratively in refining the solar irrigation innovation under real farming conditions, rather than relying on a conventional top-down technology transfer model.

Within this Living Lab framework, the on-farm trials were co-designed to evaluate the combined effects of solar pump irrigation and vermicompost (as a soil fertility intervention) on crop yield and soil moisture dynamics. Farmers already using solar irrigation (beneficiaries) and agricultural experts from district and kebele levels actively participated in the design, planning, implementation and joint monitoring and evaluation of the trials. For instance, farmers helped select crop varieties, determine vermicompost application rates and document their existing farming practices as a basis for experimentation. The vermicompost application rates were guided by prior recommendations (e.g. Degwale et al., 2025) while accounting for local resource availability and farmers' capacities.

Irrigation was applied uniformly across all treatment plots to ensure comparability, but scheduling and operational details were coordinated with farmers to align with locally accepted practices. All participating farmers had access to a solar pump irrigation system. Furthermore, the Living Lab process involved regular field visits and multi-stakeholder discussions (farmers, researchers, extension personnel and agricultural officers), facilitating real-time identification of implementation challenges and allowing adaptations to management practices as the trials progressed.

2.2.2. Establishment of on-farm trials

The field trial was conducted in the 2025 growing season in two districts: Hawassa Zuria and Misrak Meskan, by engaging three and four farmers, respectively. We used cabbage (*Brassica oleracea*) in Hawassa Zuria and chilli pepper (*Capsicum annuum*) in Misrak Meskan as the test crops. The experimental design followed a randomized complete block design (RCBD) with three to four replications (Figure 3). In this study, each farmer plot represents a replication, and all treatments were randomly assigned within each farmer's field. The farmers involved in these trials were selected purposively using criteria such as the willingness of a farmer to engage in the on-farm trial, the availability and accessibility of the farm plots. Each farmer managed a uniform plot size of 100 m^2 (25 m (Length) × 4 m (width)), and a 1-m buffer was maintained between plots to minimize treatment interference. The treatments applied were: (i) Treatment 1 (T1): Solar-

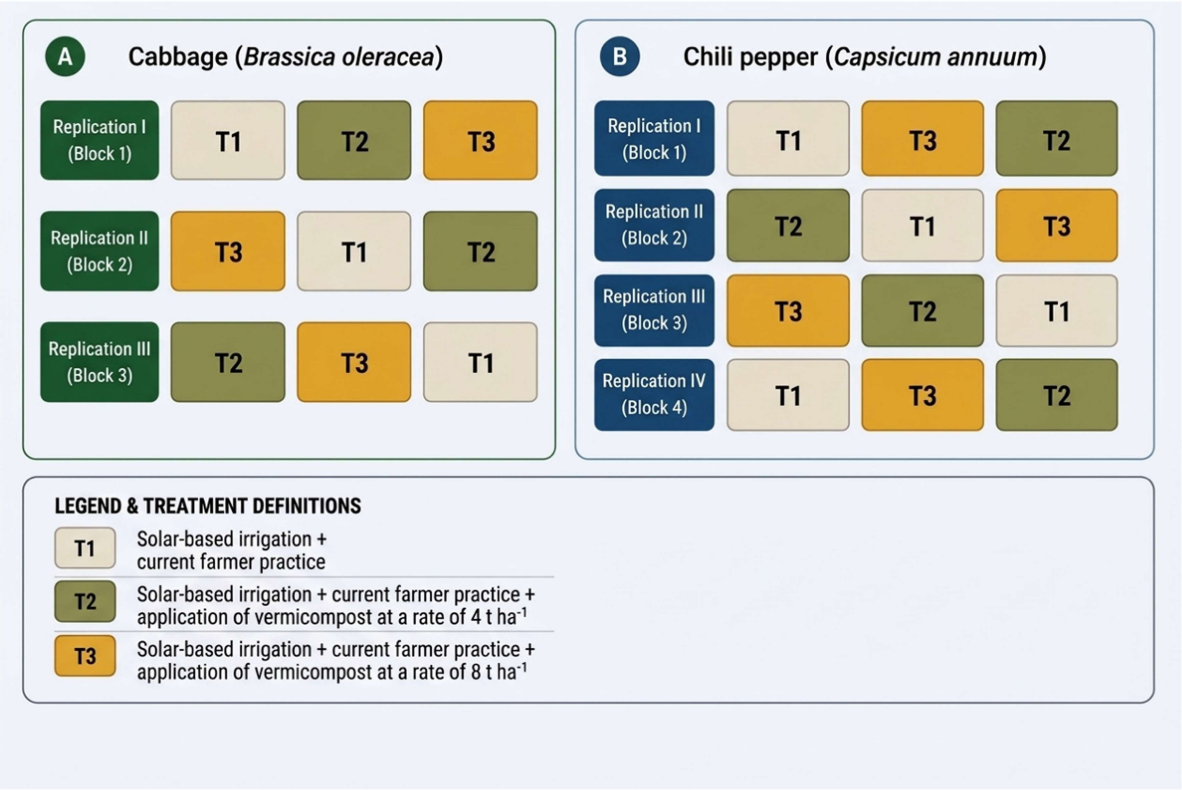


Figure 3. Schematic diagram of the experimental layout: (A) Cabbage (Brassica oleracea) and (B) Chilli pepper (Capsicum annuum).

based irrigation + current farmer practice, (ii) Treatment 2 (T2): Solar-based irrigation + current farmer practice + application of vermicompost at a rate of 4 t ha^{-1} and (iii) Treatment 3 (T3): Solar-based irrigation + current farmer practice + application of vermicompost at a rate of 8 t ha^{-1}. Because the focus of our study was to compare the bundled intervention with conventional practice, we did not include separate treatment arms representing solar- and vermicompost-only.

Current farmer practices, which are similar across all plots, refer to the application of inorganic fertilizers (diammonium phosphate (DAP) and urea) and other agronomic practices such as weeding, application of pesticides and the frequency and amount of irrigation. For plots planted with cabbage, fertilizer was applied once by incorporating both DAP and urea during the crop development stage. For chilli pepper, urea was applied during the mid-growth or flowering stage. Cabbage planting took place on the 13th of April 2025, following a two-month nursery period, whereas chilli pepper was transplanted after a 45-day nursery period on the 5th of May 2025.

In summary, all treatments were established simultaneously in each farmer's field and randomly assigned to plots, ensuring that any inherent differences among farmers affected all treatments equally. Each farmer's field served as a block, accounting for differences in soil conditions, management and plot characteristics, thereby minimizing systematic baseline differences between treatment groups.

2.2.3. Assessment of soil moisture dynamics

Following the establishment of the participatory on-farm trials, 18 soil moisture profiler probes, one per plot, were installed to monitor soil moisture dynamics during crop growth stages. The probes were inserted up to a depth of 1 m, and soil moisture was monitored at various growth stages at depths of 0–10, 10–20, 20–30, 30–40, 40–60 and 60–100 cm. Soil moisture measurements were taken using PR2/4 profiler probes (Delta-T Devices Ltd.), a widely recognized instrument for its accuracy and reliability in soil water content assessment. Readings were collected at regular intervals (every two weeks) with the portable HH2 display unit/reader, enabling efficient data collection in the field. The device's accuracy, portability and ease of use

have been well documented in previous studies (Teferi et al., 2023; Tegegne et al., 2025b). Because irrigation scheduling and water application were standardized across treatments, observed differences in soil moisture dynamics were interpreted primarily as treatment effects associated with vermicompost application rather than differences in irrigation management.

2.2.4. Assessment of farmers' opinions

We also conducted key informant interviews with 24 selected farmers to assess farmers' opinions on the benefits, costs and challenges of using solar-based irrigation. The 24 key informants were selected from farmers who adopted solar-based irrigation during the last 4 years with the support of research and development organizations, such as the International Water Management Institute (IWMI) and Farm Africa. These solar irrigation systems were not installed as part of this experimental study; participating farmers were already beneficiaries of existing solar irrigation support programmes. A mix of farmers: farmers who adopted solar-based irrigation 3–4 years ago, and those who adopted it a year ago, were included in our design to get diversified opinions. The key thematic areas covered during key informant interviews include the contribution of solar-based irrigation to (i) livelihood diversification, (ii) household income, (iii) food and nutrition security, (iv) livestock feed and (v) environmental co-benefits.

2.3. Data collection

2.3.1.l Bio-physical data collection

In each experimental plot, we monitored volumetric soil moisture content and measured economic and biological yields of test crops. Soil moisture content was monitored up to a depth of one metre, and the monitoring was synchronized with the major growth stages of each crop, namely, the initial stage, development stage, flowering or middle stage and late or harvesting stage. During each growth stage, measurements were taken twice: at the beginning and end of the growth stage. This systematic approach ensured a comprehensive understanding of soil moisture dynamics in treated and control plots, providing valuable insights into the interaction between organic amendments and soil water retention across critical crop growth stages.

Cabbage yield was measured in two distinct ways: biological yield, which included both the above-ground biomass (edible and non-edible portions combined), and economic yield, which referred only to the edible or marketable portion of the crop. To estimate the biological and economic yields of cabbage, we randomly selected three rows from each treated and control plot. The yield from each row was harvested and weighed. To estimate the economic yield of pepper, we established three randomly selected sub-plots, each with dimensions of 1 m $\times$ 1 m, in each of the treated and control plots. Then the yield from each sub-plot was harvested and weighed.

A calibrated digital weighing scale, capable of recording weights in kilograms and grams, was used to measure the harvested cabbage and pepper yields. This ensured accuracy and consistency in quantifying the yield across different treatments. The yield from three rows (cabbage) and three sub-plots (pepper) was used to calculate the mean yield per plot. The resulting averages were then extrapolated to a hectare basis to allow for comparison across treatments.

2.3.2. Socio-economic data

In the absence of baseline data, socio-economic information was collected through recall-based key informant interviews and structured checklists focusing on perceived changes before and after the adoption of solar-powered irrigation technology. These checklists captured essential information on both the benefits and the challenges of adopting solar-powered irrigation. Field observations were conducted to complement self-reported data and to validate farmers' responses. Insights and experiences gathered from farmers during field visits and interviews were subsequently discussed with researchers and extension personnel, thereby informing the interpretation of trial performance and enabling iterative feedback loops throughout the study. For example, these field observations documented more diverse crop species around homesteads, adjustments in farm management practices, expansion of irrigated fields and the introduction of livestock feed.

2.4. Data analysis

One-way analysis of variance (ANOVA) was conducted to test for significant differences in economic yield, biological yield and volumetric soil moisture among the treatments. Mean separation was performed using the least significant difference (LSD) test at the 5% significance level (95% confidence), and treatment effects were reported as percentage changes relative to the control. Yield and soil moisture data were analyzed separately for each crop, with soil moisture further stratified by crop growth stage and soil depth. This stratified approach was chosen instead of a repeated-measures model due to the participatory field design and irregular measurement intervals across farmers' fields. All statistical analyzes were performed using R software (version 4.5.1). The experiment was limited to a single growing season; therefore, multi-season repeated observations were not applicable.

Qualitative data obtained from key informant interviews were analyzed using deductive coding. The initial coding framework was formulated based on predetermined thematic areas, such as the contribution of solar-based irrigation to livelihood diversification, income generation, food security, environmental sustainability and availability of livestock feed during the dry season. Codes were noted for each relevant segment of the interview transcript after the interviews were read in their entirety. Codes were further classified based on themes by using sub-codes for some characteristics associated with each theme, such as benefit codes in connection with increased soil fertility, crop diversity, improved welfare of families and better quality of fodder. Codes were continually added inductively and, at times, deductively, as new topics emerged in the coding process; for instance, farmers sharing knowledge. Conflicting or divergent views among farmers were handled by coding these differing perspectives as distinct sub-themes or categories and comparing them across respondents, thereby explicitly capturing any minority viewpoints or deviant cases in the analysis. A codebook was created that included the final codes along with their definitions.

We used a financial analysis to compare the economic returns of yield gains due to bundling solar-based irrigation with the application of vermicompost. In this study, the costs incurred in all plots were similar except for the costs associated with the purchase and application of vermicompost. The physical outputs considered in this study were the gains or increases in the economic yields of test crops. We used local market prices for test crops to get the monetary values of the physical inputs and outputs. For the financial analysis, both physical input and output were standardized on a hectare basis. The benefit-cost ratio was used as a criterion for the financial analysis.

3. Results and discussion

3.1. Economic and biological yield of test crops

Both the economic and biological yields of cabbage were higher in treated plots than in the control plots, although the differences between treatments were not significant (Figures 4 and 5). No statistically significant differences among treatments were detected for cabbage yield, although consistent positive trends were observed across treatments (Table 2). In contrast, we detected a significant ($p < 0.05$) difference between the control and treated plots in pepper economic yield (Figure 4). Application of 8 t ha^{-1} of vermicompost increased the yields of cabbage and chilli pepper by 14.3% and 78.7%, respectively, relative to the control (T1) (Table 2). The relatively wide confidence intervals likely reflect the limited sample size, which could undermine the treatment effects. Although the cabbage response did not show a significant difference, the consistent upward trend across treatments suggests a positive effect of vermicompost application. The stronger response observed in chilli pepper could be attributed to differences in site characteristics, management and crop responses (Zhang et al., 2023).

The observed differences in yield could be attributed to the complementarity of bundled agricultural inputs and their impact on improving the availability of soil moisture and nutrient uptake. This is supported by a study in India (Verma et al., 2023), which reported that combining a vermicompost application (3 t ha^{-1}) with optimized irrigation improved grain yield, soil moisture and nutrient uptake. Other studies conducted elsewhere in the world (Kumar et al., 2022; Li et al., 2024) also demonstrated that bundling complementary agricultural inputs helps to increase crop yield. The positive contribution of bundled agricultural inputs to increasing agricultural productivity is attributed to their positive effect on soil fertility, nutrient uptake and water-use efficiency (Zhang et al., 2020). Maximizing the

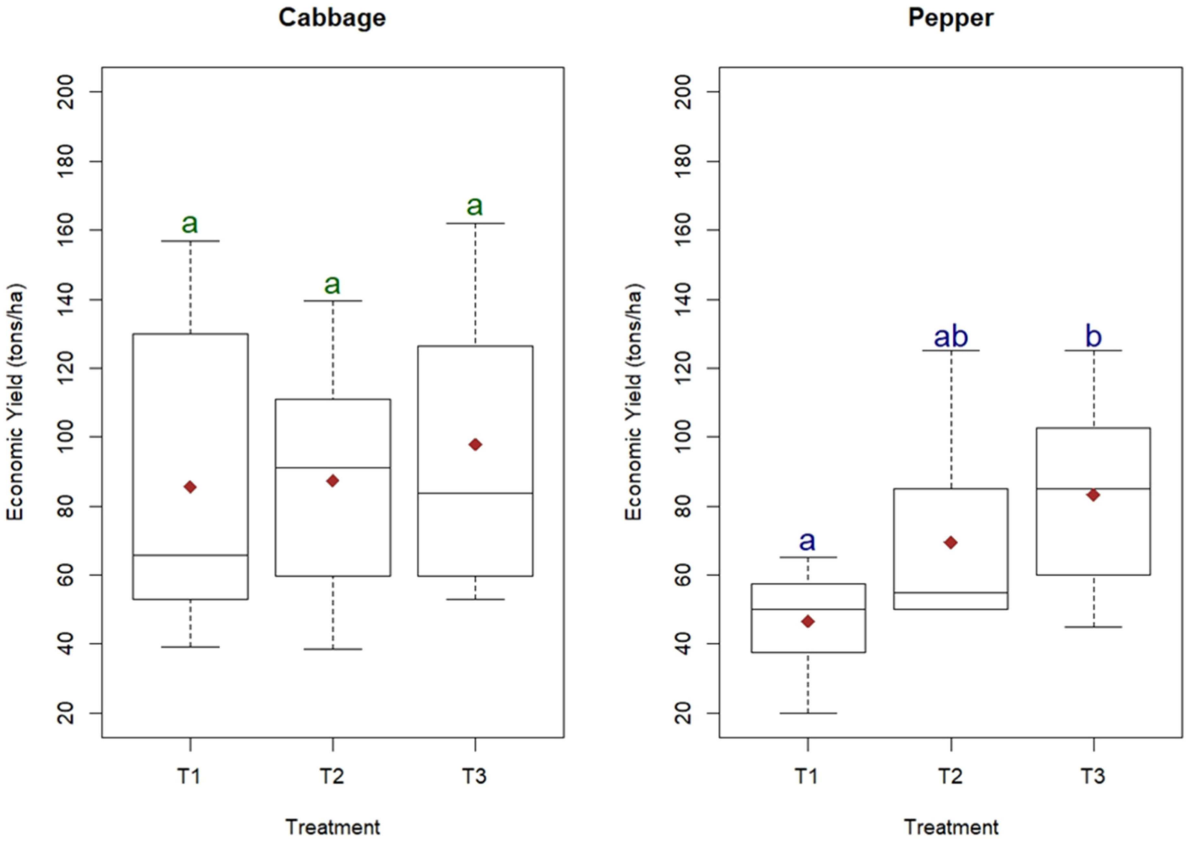


Figure 4. Economic yield of cabbage and pepper in the treated and control plots. T1 - solar-based irrigation with farmers' current practices; (ii) T2-solar-based irrigation plus farmers' practices and 4 t ha^{-1} of vermicompost; and (iii) T3-solar-based irrigation plus farmers' practices and 8 t ha^{-1} of vermicompost. Different letters among treatments showed significant differences at $p < 0.05$.

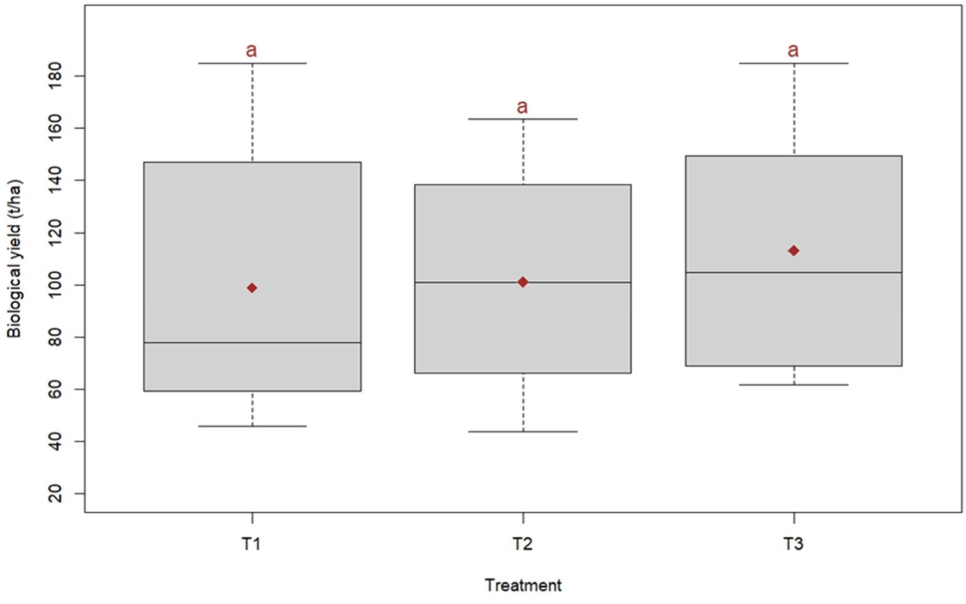


Figure 5. The biological yield of cabbage in control and treated plots. T1—solar-based irrigation with farmers' current practices; (ii) T2-solar-based irrigation plus farmers' practices and 4 t ha^{-1} of vermicompost; and (iii) T3-solar-based irrigation plus farmers' practices and 8 t ha^{-1} of vermicompost. See other details in Figure 4.

Table 2. Yield performance of cabbage and pepper under different treatments (mean ± 95% CI).

Crop	Treatment	Sample size	Yield type	Average yield (t ha^{-1})	95% CI (Economic yield)	% change vs T1
Cabbage	T1	3	Biological yield	98.9	[−52.6, 250.4]	—
Cabbage	T2	3	Biological yield	101.0	[−18.7, 220.7]	2.18%
Cabbage	T3	3	Biological yield	113.1	[−9.9, 236.1]	14.36%
Cabbage	T1	3	Economic yield	85.60	[−44.7, 215.9]	—
Cabbage	T2	3	Economic yield	87.36	[−12.6, 187.4]	2.05%
Cabbage	T3	3	Economic yield	97.82	[−11.1, 206.7]	14.27%
Pepper	T1	4	Economic yield	46.7	[23.1,70.3]	—
Pepper	T2	4	Economic yield	69.6	[36.3,103]	49.11%
Pepper	T3	4	Economic yield	83.3	[43.7, 122.9]	78.57%

benefits of solar-based irrigation through bundling with complementary agricultural inputs could be a viable option to increase adoption and wider use of solar-based irrigation by smallholder farmers. This, in turn, could help to improve the long-term sustainability and profitability of solar-based irrigation with considerable environmental co-benefits.

3.2. Financial gains due to bundling solar-based irrigation with vermicompost

Table 3 summarizes the results of the financial analysis of bundling solar-based irrigation with the application of different levels of vermicompost. Treatment 3, which received 8 t ha^{-1} of vermicompost, incurred the highest cost (the purchase and application of vermicompost) (ETB 112,000) but generated substantial gains, ETB 137,500 from cabbage and ETB 220,000 from pepper. In contrast, Treatment 2 (4 t ha^{-1}) had a lower cost (ETB 56,000) and produced ETB 21,067 from cabbage and ETB 146,627 from pepper. The individual crop-based BCR values indicate that pepper production is more profitable under both treatments (2.46 for Treatment 2 and 1.96 for Treatment 3), while cabbage shows marginal returns at lower application rates and relatively higher returns compared to lower application rates. This indicates that profit maximization does not necessarily coincide with yield maximization under increasing input levels. Overall, the findings suggest that bundling solar-based irrigation with the application of vermicompost could be an economically viable option and help to increase households' income and support the adoption and wider use of solar-based irrigation. Although the results demonstrate strong economic returns under solar-based irrigation combined with vermicompost, scalability depends on access to credit, subsidy schemes or cooperative financing mechanisms, as upfront capital costs for solar irrigation systems remain high for most smallholder farmers (Otoo et al., 2018).

The economic potential of bundling vermicompost with irrigation technologies is demonstrated by comparable evidence from other countries in the world. Vermicompost use was perceived to increase yields, improve fertilizer-use efficiency and improve net economic returns for farmers growing pepper in

Table 3. Additional physical inputs due to bundling solar-based irrigation with vermicompost application, and associated gains and economic viability.

Additional physical inputs	Treatment 1	Treatment 2	Treatment 3
Vermicompost (t ha^{-1})	0.0	4	8
Labour cost (man-days per hectare)	0.0	20	40
Monetary costs of the additional inputs			
Vermicompost (ETB ha^{-1})	0.0	50,000	100,000
Labour (ETB ha^{-1})	0.0	6000	12,000
Total additional cost (ETB ha^{-1})	0.0	56,000	112,000
Additional gains of physical outputs			
Cabbage yield (t ha^{-1}) (Yield in treated plots minus yield in control plots)	0.0	1.756	12.219
Pepper yield (t ha^{-1})	0.0	4.583	7.333
Monetary values of outputs			
Cabbage (ETB kg^{-1})	0.0	12	12
Pepper (ETB kg^{-1})	0.0	30	30
Total additional benefits or gains due to the change or increase in yield			
Cabbage (ETB ha^{-1})	0.0	21,066.7	137,500
Pepper (ETB ha^{-1})	0.0	146,626.7	220,000
Benefit-cost ratio (BCR)			
Cabbage		0.38	1.31
Pepper		2.46	1.96

Note: Benefit-Cost Ratios (BCR) were calculated separately for cabbage and pepper using crop-specific yield gains and market prices, while treatment costs were estimated on a per-hectare basis for each crop.

Southwest China under continuous cropping conditions (Zhang et al., 2023). Similarly, Boyacı et al. (2025) in Poland found that regulated watering using vermicompost increased pepper productivity and improved water-use efficiency, increasing farm profitability.

The results indicate that while higher vermicompost application (8 t ha^{-1}) generates a substantially larger physical yield increase for both cabbage and pepper, the economic return per unit of investment does not rise proportionally. In fact, the benefit–cost ratio (BCR) is higher at the lower application rate (4 t ha^{-1}), particularly for pepper, suggesting that the economic threshold, the point at which additional input no longer yields proportionally higher economic gains, differs from the point of maximum physical yield. For example, in a pepper crop trial study where vermicompost was applied, yield increased by 28%–68.8% and net returns also increased despite higher input costs; however, the maximum economic efficiency (BCR) was recorded for moderate rates of vermicompost application rather than the highest rate (Zhang et al., 2023); similarly another study, in a black gramme trial, gross yield increased but net returns decreased beyond an application rate of about 4.5 t ha^{-1} of vermicompost, suggesting that economic returns would decrease as rates increased (Joshi et al., 2023). These findings suggest that economic optimization of input use is more important than yield maximization alone, particularly under resource-constrained smallholder conditions. This divergence highlights that maximizing yield is not the same as maximizing profit. Since these findings are based on indicative results from a limited assessment, they underscore the need for more detailed studies to establish economically optimal vermicompost application rates that balance both physical productivity and financial returns.

3.3. Availability of soil moisture in treated and control plots

The results showed that the volumetric soil moisture content was higher in the treated plots than in the untreated plots (Table 4). The treatment effects were detected at all stages of crop development. The results were consistent at both sites, suggesting that vermicompost can lead to positive changes in soil moisture across different soil conditions and management practices. The changes in volumetric soil moisture content in the Hawassa Zuriya district, where cabbage was used as a test crop, were greater at effective root depths in most cases (Table 4). At Misrak Meskan Woreda, where chilli peppers were used as a test crop, the effect of vermicompost on conserving soil moisture was also pronounced during the critical growth stage, and the effects of the treatment were higher in the top 20 cm (Table 4).

Significant differences ($p < 0.05$) between treatments in volumetric soil moisture content were observed at 20–30, 30–40 and 40–60 cm depths in the latter growth stages compared to the initial and development stages (Table 4). This suggests that over time, vermicompost applied at planting becomes more thoroughly integrated with the soil, facilitating a gradual release of essential nutrients and an increasingly strong binding of soil particles; together, these cumulative effects progressively improve soil structure and moisture retention, effects that become especially pronounced during the later stages of crop growth (Ceritoğlu et al., 2018; Manyuchi et al., 2013; Oyege & Balaji Bhaskar, 2023). Adequate soil moisture during the flowering stage is critical for yield potential, and practices that enhance soil moisture contribute to sustainable crop production (Singh et al., 2025). Previous studies confirm that vermicompost improves soil structure, aeration and water retention, supporting better plant growth and flowering (Castellini et al., 2024; Kifle et al., 2025; Obeng et al., 2024; Rivier et al., 2022; Steffen et al., 2019; Tegegne et al., 2025a; Wang et al., 2017). Our findings and the findings of previous studies support that integrating vermicompost with solar-based irrigation could strengthen crop resilience and long-term farm sustainability, ensuring sustainable small-scale irrigation systems (Blouin et al., 2019; Manzoor et al., 2024). These findings position vermicompost as a climate-smart and sustainable strategy for improving soil health and crop productivity.

3.4. Contribution of solar-based irrigation to rural livelihood

The analysis of how solar-based irrigation is associated with the diversification of people's livelihoods showed an increase in crop diversity, harvest frequency, size of irrigated land and the quantity of market-oriented crops following its use (Figure 6). Most (88%) of respondents (21 out of 24) reported adding two to five new crops after implementing solar-based irrigation. These included vegetables, such as cabbage, carrot, pepper and onion, perennial fruit trees (mango, avocado, banana, papaya and apple), and fodder

Table 4. The mean (±SE) volumetric soil moisture content (V%) at different stages of crop growth in treated and control plots.

			Volumetric soil moisture content (%)	
Crop stage (S)	Soil depth (cm)	Treatment	Cabbage	Pepper
S1	0_10	T1	29.4 ± 2.7[a]	17.2 ± 2.5[a]
S1	0_10	T2	32.9 ± 2.3[a]	20.7 ± 4.3[a]
S1	0_10	T3	34.1 ± 0.4[a]	21.8 ± 3.1[a]
S1	10_20	T1	35.1 ± 0.5[a]	21.1 ± 2.2[a]
S1	10_20	T2	38.6 ± 0.6[a]	25.5 ± 2.2[a]
S1	10_20	T3	40.8 ± 4.6[a]	23.7 ± 3.4[a]
S1	20_30	T1	37.5 ± 1.3[a]	22.5 ± 1[a]
S1	20_30	T2	39 ± 0.9[a]	24.6 ± 0.4[a]
S1	20_30	T3	42.9 ± 2.1[a]	22 ± 1.5[a]
S1	30_40	T1	28.2 ± 1.8[a]	18.1 ± 1.6[a]
S1	30_40	T2	30.7 ± 3.6[a]	21.1 ± 1[a]
S1	30_40	T3	38 ± 4.5[a]	22.3 ± 1.4[a]
S1	40_60	T1	26.5 ± 3[a]	22.7 ± 3.1[a]
S1	40_60	T2	31.3 ± 1.1[a]	31.3 ± 1.1[a]
S1	40_60	T3	32.4 ± 0.6[a]	28.1 ± 2.3[a]
S1	60_100	T1	40.4 ± 7.1[a]	29.2 ± 4.7[a]
S1	60_100	T2	49.9 ± 8.5[a]	34.7 ± 3.2[a]
S1	60_100	T3	48.2 ± 4[a]	32 ± 3.7[a]
S2	0_10	T1	28.1 ± 6[a]	11.1 ± 1.8[a]
S2	0_10	T2	30.1 ± 4.5[a]	19.9 ± 3.8[a]
S2	0_10	T3	31.6 ± 2.9[a]	19.8 ± 2.5[a]
S2	10_20	T1	29.7 ± 4.3[a]	18 ± 2[a]
S2	10_20	T2	35.2 ± 2.4[a]	24.1 ± 0.6[a]
S2	10_20	T3	35.6 ± 0.9[a]	25.6 ± 3.2[a]
S2	20_30	T1	35.5 ± 3.1[a]	19.9 ± 3.1[b]
S2	20_30	T2	39.7 ± 3.3[a]	28.3 ± 0.6[a]
S2	20_30	T3	42.9 ± 2.5[a]	27.1 ± 1[ab]
S2	30_40	T1	33.5 ± 2[a]	17.5 ± 1.8[b]
S2	30_40	T2	39.5 ± 3.6[a]	27.8 ± 0.4[a]
S2	30_40	T3	45.6 ± 2.6[a]	27.2 ± 1.6[a]
S2	40_60	T1	33.9 ± 1.3[a]	26 ± 1.5[b]
S2	40_60	T2	39.1 ± 1.5[a]	31.5 ± 0.2[a]
S2	40_60	T3	39.1 ± 1.9[a]	32.2 ± 1.1[a]
S2	60_100	T1	51.4 ± 3[a]	28.5 ± 3.5[a]
S2	60_100	T2	57.1 ± 2.3[a]	32.1 ± 2.6[a]
S2	60_100	T3	54.7 ± 1.9[a]	36.5 ± 2.8[a]
S3	0_10	T1	21.9 ± 3.5[a]	12.3 ± 2.7[a]
S3	0_10	T2	30 ± 7.8[a]	20.4 ± 2.1[a]
S3	0_10	T3	29.2 ± 2.8[a]	19 ± 1.5[a]
S3	10_20	T1	28.7 ± 7.2[a]	20.7 ± 2.3[a]
S3	10_20	T2	38.7 ± 5.2[a]	25.3 ± 1.9[a]
S3	10_20	T3	35.7 ± 2.6[a]	25.7 ± 2.2[a]
S3	20_30	T1	35.7 ± 2.6[a]	21.6 ± 2.6[a]
S3	20_30	T2	39.3 ± 3.7[a]	26 ± 2[a]
S3	20_30	T3	39.3 ± 8[a]	24.6 ± 2.8[a]
S3	30_40	T1	39.1 ± 5.5[a]	21.4 ± 3.9[a]
S3	30_40	T2	40.7 ± 5.2[a]	27 ± 1.9[a]
S3	30_40	T3	50.7 ± 9[a]	25.7 ± 2[a]
S3	40_60	T1	36.9 ± 4[a]	27.4 ± 1.8[a]
S3	40_60	T2	39 ± 4.1[a]	31.4 ± 3.7[a]
S3	40_60	T3	40.3 ± 1.2[a]	32.6 ± 2.4[a]
S3	60_100	T1	49.7 ± 10.2[a]	30 ± 3.2[a]
S3	60_100	T2	56.9 ± 10.5[a]	35.3 ± 2.1[a]
S3	60_100	T3	62.6 ± 10.6[a]	38.5 ± 2.6[a]
S4	0_10	T1	33.2 ± 3.6[a]	21 ± 0[b]
S4	0_10	T2	36 ± 4.2[a]	30.1 ± 1[a]
S4	0_10	T3	36.3 ± 2.9[a]	28.3 ± 0.3[a]
S4	10_20	T1	31 ± 0.5[b]	19.7 ± 2.4[b]
S4	10_20	T2	33.3 ± 0.9[ab]	31.7 ± 0.9[a]
S4	10_20	T3	38.2 ± 2.1[a]	28.3 ± 1.8[a]
S4	20_30	T1	30 ± 2.1[b]	24 ± 2.1[b]
S4	20_30	T2	35.9 ± 3.5[ab]	30.9 ± 2.1[ab]
S4	20_30	T3	40.7 ± 1.2[a]	33.1 ± 0.5[a]
S4	30_40	T1	27.7 ± 3.3[a]	23.8 ± 0.4[a]
S4	30_40	T2	32 ± 4.2[a]	25.7 ± 3.9[a]
S4	30_40	T3	35.3 ± 4.7[a]	30.7 ± 1.8[a]
S4	40_60	T1	29.6 ± 4.9[a]	26.4 ± 4[a]
S4	40_60	T2	36 ± 4.7[a]	32.4 ± 0.4[a]
S4	40_60	T3	37 ± 4.5[a]	35.7 ± 1.5[a]
S4	60_100	T1	30.6 ± 5.4[a]	30 ± 1.5[a]
S4	60_100	T2	34.3 ± 3.5[a]	38.3 ± 4.2[a]
S4	60_100	T3	44.3 ± 3.3[a]	38.3 ± 0.3[a]

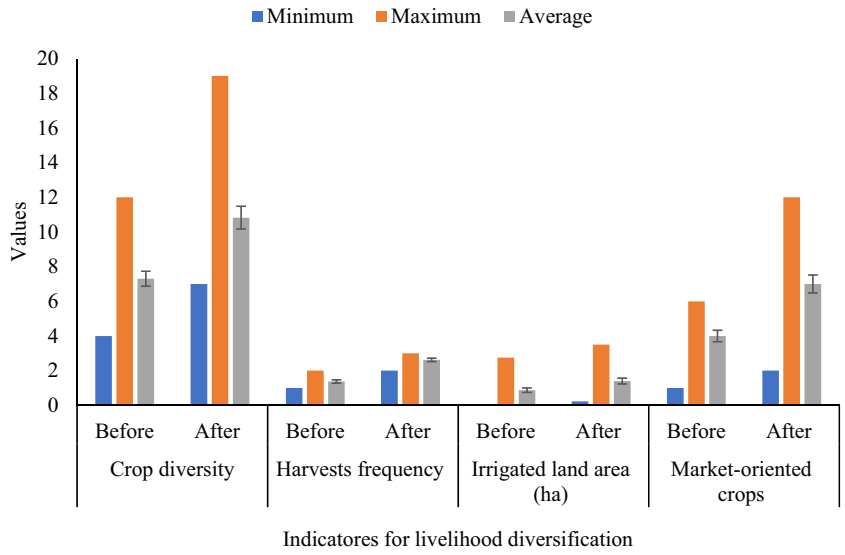


Figure 6. Changes in livelihood indicators following the implementation of solar-based irrigation.

crops (Desho grass and elephant grass), reflecting a shift toward higher-value, market-oriented crops. According to 75% of the respondents, this observed shift in cropping systems is attributed to the improved access and availability of water through solar-based irrigation. Key informants echoed this view, which aligns with Chaudhari et al. (2025), who reported that solar-based irrigation systems provide smallholder farmers with a reliable water source, potentially enhancing crop production and farm resilience. Similarly, other studies (e.g. Minh & Ofosu, 2022) noted that the use of solar-based irrigation encourages the cultivation of market-oriented crops and greater crop diversification in smallholder farming systems.

The results indicate that respondents perceived solar-based irrigation to improve aspects of their livelihoods by enabling more diverse cropping, expanding irrigated land and increasing harvest frequency. Farmers have shifted from primarily growing cereals and staples to cultivating a wider range of vegetables, fruits and fodder crops, consistent with a move toward higher-value and market-oriented production. Respondents indicated that increased water availability through solar-based systems encouraged long-term investments in perennial fruit trees, whereas the inclusion of fodder crops has supported livestock production. Overall, these associations imply that solar-based irrigation can contribute to more resilient, productive and income-generating farming systems than traditional rainfed practices. This interpretation is in line with Yang et al. (2024), who noted that improving water access and use efficiency via solar-based irrigation may foster greater farm resilience and productivity.

Most (79%) of the respondents witnessed an increase in harvest frequency following the implementation of solar-based irrigation. Aggregated recall data from 24 key informants indicated that the number of harvests per year was reported to rise from a mean of one before solar-based irrigation to a mean of three after irrigation (Figure 6). Similar perceptions have been reported in Ethiopia (Wana & Dukamo, 2025) and across Sub-Saharan Africa (Falchetta et al., 2023), where small-scale irrigation was reported to increase the annual harvest frequency among smallholder farmers. Respondents in our study attributed these increases in harvest frequency primarily to improved access to and availability of water after adopting solar-based irrigation.

Following the implementation of solar-based irrigation, respondents reported that the total area of land under irrigated agriculture increased from 0.9 to 1.5 hectares, which suggests improved water availability for irrigation. Similar patterns were noted in Ethiopia and Mali, where the expansion of irrigated farmlands was made possible by solar irrigation (Birhanu et al., 2023; Wana & Dukamo, 2025). Likewise, the number of market-oriented crops grown by respondents grew from three to seven, reflecting a greater emphasis on cash crops following the use of solar-based irrigation. This shift is consistent with studies showing that improved irrigation encourages adoption of market-oriented crops among smallholders in sub-Saharan Africa (Falchetta et al., 2023; Kanda et al., 2026). Notably, however, the adoption of solar-based irrigation did

not appear to lead to livelihood diversification beyond the agricultural sector in our case. This outcome aligns with observations from other smallholder studies, where irrigation improvements mainly enhanced on-farm agricultural productivity but had a limited impact on non-farm income diversification (Wana & Dukamo, 2025).

Respondents noted that increased water availability, access and reliability with solar-based irrigation influenced their farm management decisions. Specifically, they felt that this improvement in water supply reduced production risk, allowed multiple cropping seasons, improved planting decisions and facilitated the inclusion of high-value market-oriented crops. In line with this, most (83%) of the respondents indicated that they are now more willing to take risks and try new practices on their farms. Additionally, market participation was perceived to have increased, with respondents reporting expanding their range of saleable crops from an average of 2–5 products before to 5–12 products after adopting solar-based irrigation. These newly sold products include vegetables, fruits and high-value crops such as avocado, mango, chilli pepper and cabbage, which have emerged as common market-oriented crops following the introduction of solar-based irrigation systems.

3.5. Contribution of solar-based irrigation to household income

Implementing solar-based irrigation was associated with increases in farmers' incomes and economic opportunities, according to respondents' self-reported recall data. Approximately 96% (23 out of 24) of the respondents experienced total annual income growth ranging from slight increases (from 154,000 to 171,000 ETB, + 11%) to over fourfold (from 24,200 to 101,200 ETB, + 318%) (Figure 7). Only one respondent (4%) showed no net increase owing to higher input costs offsetting irrigation benefits. Although the study did not undertake a formal comparison of these financial gains with the upfront investment costs of solar irrigation, respondents generally perceived that the reported income improvements would allow recovery of the initial costs within a relatively short payback period, typically not exceeding five years.

Moreover, based on key informants' recall, irrigated crops were the primary source of income for 21 respondents (88%). Before the introduction of solar-based irrigation, key informants indicated that more than 70% of the income was earned from rainfed crops and livestock. Following the introduction of solar-based irrigation, the share of income from irrigated crops reportedly rose to 50%–70% of the total household income. Most of the respondents (83%, 20 out of 24) said they diversified their crop-based

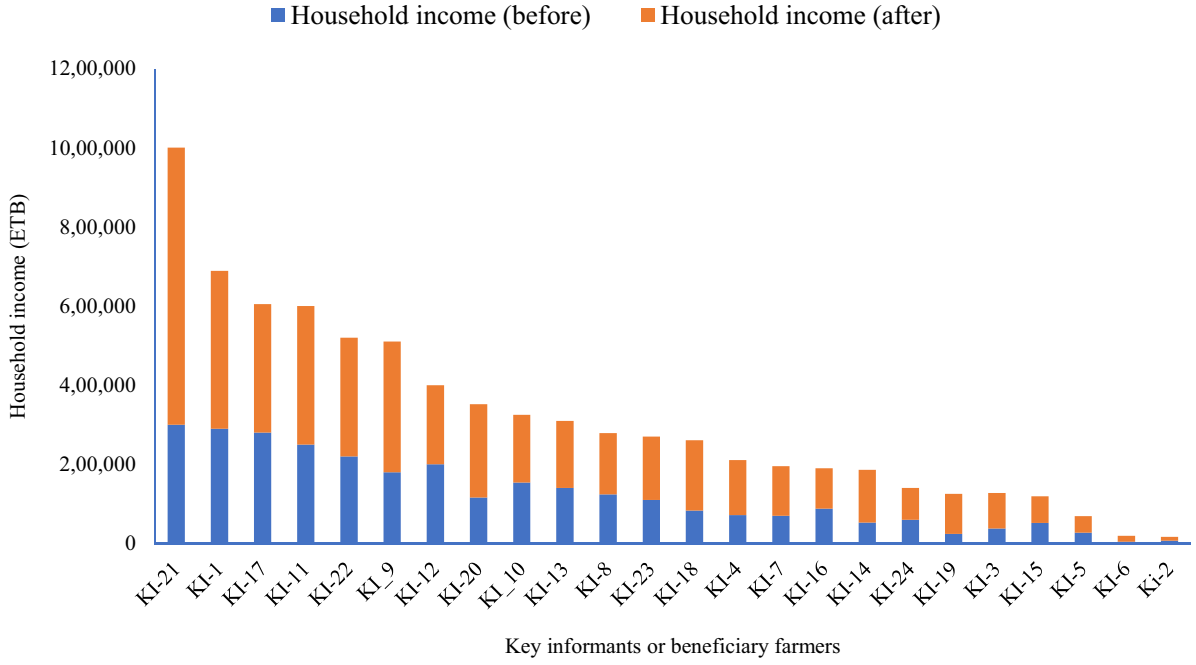


Figure 7. Household annual income before and after solar-based irrigation.

income after adopting solar-based irrigation, which they attributed to improved water access and availability. In contrast, livestock income remained stable, contributing around 10%–30% to the household income.

The results suggest that many households experienced a longer period of income generation following the introduction of solar-based irrigation. In total, 75% of the respondents reported earning an income year-round (10–12 months). Respondents largely attributed this improvement to the ability to harvest multiple times per year with irrigation, particularly for high-value vegetables and fruits, such as cabbage, avocado, carrot, chilli pepper and khat. Some respondents (25%) still generated income for a few months, but even in these cases, respondents reported higher earnings, which they linked to the expansion of high-value irrigated crops. Similar results were reported by Assefa et al. (2020), indicating that solar-based irrigation increases yields, permits year-round cultivation and increases the income of smallholder farmers. The perceived increase in household income following the introduction of solar-based irrigation was also attributed by respondents to reduced fuel and labour costs, which they felt improved profit margins. For example, the majority (87.5%) of respondents stated decreased spending on diesel, while 79% specifically mentioned reduced labour costs and time. However, one respondent (4%) observed a slight increase in costs due to a greater need for fertilizers, seeds and labour for expanded vegetable production. This is consistent with research from Ethiopia by Negera et al. (2025), who found that by removing costly diesel pumps and maximizing water use efficiency, solar-powered irrigation systems were perceived to reduce production costs for farmers. Similarly, Gebregziabher et al. (2019) in Ethiopia and Birhanu et al. (2023) in Mali reported that the use of solar-based irrigation resulted in considerable reductions in ongoing fuel costs, which increased net farm revenues.

Furthermore, key informants' accounts indicated that the increase in household income following solar-based irrigation was closely related to improved markets in nearby towns. Specifically, the results indicated that approximately 83% of respondents reported accessing new or expanded markets, including larger towns (e.g. Hawassa and Butajira). In some cases, farmers said that wholesalers began purchasing produce directly from their farms, which reportedly reduced transaction costs and increased their bargaining power. Liang et al. (2024) highlights that the adoption of solar irrigation systems has facilitated stronger integration of smallholder farmers into local value chains. Complementing this, Sanogo et al. (2025) and Birhanu et al. (2023) provide evidence from Burkina Faso showing that solar-powered irrigation not only enhanced production but also enabled farmers to access regional markets, where they could secure more competitive prices for their produce. This expanded market access was particularly beneficial for perishable crops such as vegetables and fruits, allowing farmers to sell at higher prices and thereby strengthen their participation in local value chains. Nevertheless, the benefits were not uniformly distributed; a subset of respondents, approximately 17% (four individuals), remained confined to local markets, suggesting that some barriers to broader market integration persisted despite these technological advancements.

The respondents further described that their household income was utilized for multiple purposes, ranging from fulfilling their immediate needs to achieving long-term goals (Figure 8). Spending on day-to-day consumables was the most reported use of income, whereas less than 50% of respondents mentioned that they saved or invested in asset-building activities. Household consumption mainly referred to spending on food, clothing, phones and other daily needs. Expenditure on agricultural investments is related to expenditure on agricultural inputs such as fertilizers, seeds and agrochemicals. Social costs included contributions to community associations like Edir (a traditional community-based mutual support association in Ethiopia), as well as holidays and taxes. Saving or asset building was related to depositing money in the bank and making major purchases, such as large-capacity solar pumps, housing construction and livestock. Our findings align with previous research showing that solar-based irrigation not only increases farm income but also stimulates investment in agricultural inputs, and facilitates the accumulation of household assets, including solar pumps, housing improvements and livestock (Assefa et al., 2020; Goel, 2022; Guno & Agaton, 2022).

These results derived from the key informants' experience imply that while solar-based irrigation was perceived to contribute to higher household income, the way this income is utilized shows a balance between meeting immediate consumption needs and pursuing long-term investments. Most households prioritized spending on food, clothing and other daily necessities, reflecting the importance of income in addressing basic livelihood requirements. However, fewer than half of the respondents allocated income

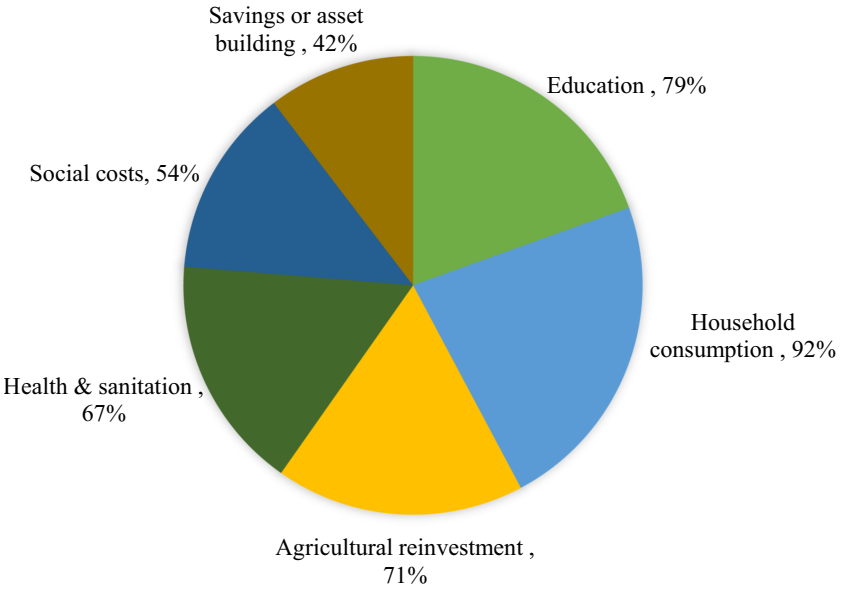


Figure 8. Income utilization categories by percentage of respondents.

toward savings or asset building, suggesting limited capacity or preference for long-term wealth accumulation. Expenditures on agricultural inputs highlight reinvestment in production, whereas spending on social costs reflects the role of cultural and communal obligations in shaping household financial decisions. Overall, these findings suggest that solar-based irrigation has been associated with improved household income and more diversified expenditure patterns, although investment in assets and savings remains relatively underutilized compared to immediate consumption.

3.6. Food and nutrition security

Table 5 summarizes the respondents' food and nutrition security trends as perceived following the adoption of solar-based irrigation. The majority (88%) of respondents reported experiencing improvements in food quantity, availability and self-sufficiency. According to their recollections, the percentage of food sourced from their own farms increased from 50% before the adoption of solar-based irrigation, rising to 75%–100% after irrigation. Respondents also pointed to increased crop diversity around their homesteads, particularly vegetables (cabbage, carrot, onion) and fruits (avocado, mango, papaya), as a key factor in improving their self-sufficiency in terms of nutritious food.

Table 5. Changes in food security indicators before and after solar irrigation.

Indicator	Before solar irrigation	After solar irrigation
Food quantity and self-sufficiency	Limited production; 50% self-produced food	Improved; 87.5% (21/24) improved self-sufficiency (75%–100% self-produced).
Meal frequency	Mostly 2–3 meals/day	The majority (71%) were stable at 3 meals/day; 25% (6/24) increased from 2 to 3 meals; 1 case reached 4/day.
Dietary diversity	Diet dominated by cereals; low fruit/vegetable intake; irregular dairy/meat intake	83% (20/24) improved dietary diversity; increased fruit and vegetable intake (daily/near-daily in many cases); dairy improved for 50%; meat, egg, & legumes still limited (average 2–3 days/week).
Respondent's food expenditure	Ranges between 100–9900 ETB/month	50% (12/24) reduced expenditure (by 30%–60%) due to higher self-production, 42% (10/24) increased expenditure, linked to diet diversification & income growth, while 8% (2/24) had no major change.
Consumption of specific food groups	Cereals (daily); vegetables (1–3 days/week); fruits (very limited 1–2 days/week); dairy (low); meat/eggs/legumes (rare)	Cereals daily (100%); vegetables frequent (3–7 days/week, 83%); fruits 3–7 days/week (66% daily/near-daily); dairy improved (3–7 days, 50%); meat/eggs/legumes: improved but still limited (2–3 days/week).
Child nutrition	Limited fruit/vegetable; diet dominated by cereals; moderate diversity	Dietary diversity improved: more fruit, vegetables, dairy; children eating more nutritious foods (92% (22/24).

Approximately 50% of respondents reported reducing their monthly/weekly expenditure by 30%–60%, which they attributed to increased self-production. For example, one respondent said their spending dropped from 9900 to 6300 ETB/month, and another from 8400 to 3000 ETB/month, after adopting solar irrigation. However, 38% of respondents reported an increase in expenditures, which was linked to higher income and diet diversification, while 8% reported little or no change.

In over 90% of the respondents' households, child nutrition was reported to have improved, which respondents attributed to increased availability of fruits, vegetables and dairy that they felt enhanced diet quality and provided more nutritious meals. A few cases mentioned only slight improvements, with fruit intake still being limited.

The analysis of the food consumption score (FCS) indicated notable variation in dietary diversity and food security status among the 24 respondents. Most respondents (75%) fell within the acceptable FCS (score > 35), indicating a relatively frequent consumption of cereals, legumes, vegetables, fruits, animal-source foods and dairy. For example, 12.5% (3/24) of the respondents with high FCS (score > 63) consumed multiple food groups, with higher contributions from protein-rich foods such as meat, legumes and dairy. The results imply that while most households have an acceptable food consumption score, reflecting a relatively diverse and frequent intake of various food groups, there are still notable disparities in dietary quality. A small proportion of respondents demonstrated high dietary diversity with greater access to protein-rich foods, indicating better food security and nutrition. However, one-quarter of households remain in the borderline category, relying heavily on cereals with limited consumption of nutrient-dense foods, suggesting ongoing vulnerability to poor dietary quality and potential nutritional deficiencies. Overall, solar-based irrigation appears to enhance food diversity and security, but some households continue to face constraints in accessing a balanced diet, which is consistent with the findings of studies conducted in Burkina Faso, Ethiopia and Mali (Birhanu et al., 2023; Negera et al., 2025; Sanogo et al., 2025).

3.7. Livestock feed production and resilience

Respondents indicated that the implementation of solar-based irrigation improved livestock feed production, seasonal feed availability and livestock resilience (Table 6). They attributed this perceived improvement in livestock feed production to cultivating fast-growing and high-biomass species, such as green fodder (elephant grass and desho grass), supplemented with maize stover, teff straw and other crop residues. Approximately 17% (4/24) of the respondents indicated no change in fodder production, as they prioritized food crops, while one respondent (4%) had not yet implemented fodder production but had plans.

Regarding the use of irrigated land for forage, 15 respondents (63%) allocated part of their irrigated land or smaller plots along field borders to fodder production. Another six respondents (25%) did not allocate irrigated land for fodder, although some grew fodder along field borders or intercropped it with other crops. Approximately 12.5% (3/24) had not yet used irrigation for fodder but expressed intentions to do so in the future. This indicates that although feed production is not always the primary goal for every household, respondents have used solar irrigation to integrate forage into their cropping systems.

In terms of seasonal feed availability, 19 respondents (79%) reported improved feed availability during the dry season, which they felt reduced seasonal vulnerability and helped ensure year-round livestock feed supplies. Previously, before adopting solar irrigation, dry-season feed was scarce, forcing respondents to rely on limited amounts of crop residues or hay. Respondents perceived that the increased availability of feed during the dry season improved their livestock's resilience by bridging seasonal feed gaps, improving

Table 6. Changes in livestock feed production before and after solar irrigation.

Indicator	Before solar irrigation	After solar irrigation
Fodder/feed quantity and quality	Limited; crop residues, seasonal hay	Green fodder (Elephant and Desho grass), maize stover, other crop residues
Irrigated land used for fodder	None or minimal	Plots (0.125–0.3 ha) or field borders
Seasonal feed availability (dry season)	Scarce, unreliable	Reliable year-round; dry-season availability improved
Impact on livestock productivity	Baseline: feed shortage	Respondents claimed improved milk, growth, fattening and reduced feed costs
Preferred forage species	Limited options	Elephant grass, Desho grass, maize/teff residues

feed quality and increasing livestock productivity. In line with this, due to more reliable and higher-quality livestock feed, 75% of respondents (18 out of 24) reported improvements in milk production, animal growth, fattening and reduced feed costs. This finding aligns with Hussein et al. (2024), who observed that irrigated fodder plots using water-lifting technologies like solar pumps achieved superior forage yields in Ethiopia. Similarly, Schmitter et al. (2016) noted that solar pump-based irrigation helped smallholders secure livestock feed during dry seasons when it is typically scarce.

3.8. Employment and rural labour dynamics

The results in Table 7 suggest that the adoption of solar-based irrigation was perceived to enhance labour efficiency rather than consistently generating additional rural employment, particularly at the household scale. For example, 50% (12/24) of the respondents depended on their family members for farm operations both before and after solar irrigation, indicating that family labour remains the main source of agricultural labour. Approximately 42% (10/24) of respondents reported employing 2–5 additional workers on a temporary labour basis, which they attributed to irrigation-enabled crop intensification, particularly for high-value and labour-intensive crops such as vegetables (e.g. pepper and carrot).

New rural job opportunities created directly by solar-based irrigation were reported to be limited at the homestead level. For instance, 13 respondents (54%) indicated that solar-based irrigation had not yet generated significant off-farm employment. However, some respondents described indirect job opportunities emerging through the expansion of irrigated crops, farm processing and seedling production. Meanwhile, 46% (11/24) of the respondents reported no new rural occupations other than family labour, suggesting that small-scale, homestead-based irrigation has little effect on the formation of a larger labour market. These findings are supported by research done in Pakistan, demonstrating that solar pump irrigation systems increased farm income and productivity; however, jobs were primarily generated in the system's maintenance and operation rather than through a range of off-farm agricultural labour (Raza et al., 2022; Tamoor et al., 2021).

Approximately 38% (9/24) of respondents noted increased female participation in agricultural tasks after adopting solar irrigation. They explained that this change occurred because the technology reduces the physical burden of watering crops and thereby enables broader engagement by women. In contrast, 33% (8/24) of the respondents observed no change in women's participation, while 8% (2/24) indicated male-dominated labour. Supporting evidence from Nepal and Burkina Faso also shows that solar irrigation systems can reduce women's workload and enhance their participation in smallholder agriculture, particularly in market gardening and household-level irrigation (Shrestha et al., 2023; Ouedraogo et al., 2025).

3.9. Environmental benefits and on-farm biodiversity

The findings suggest that the adoption of solar-based irrigation was perceived to generate multiple environmental co-benefits alongside its agricultural impacts. A large majority of respondents (96%) reported planting more high-value fruit trees, such as avocado, mango, papaya, banana and coffee, around their homesteads. Respondents indicated that the main goals of these agroforestry efforts were to reduce soil erosion, regulate microclimates, increase soil fertility and provide shade. Such tree-based and biodiversity-rich practices under increased irrigation are consistent with more general research demonstrating that increased water availability promotes the adoption of agroforestry and increases ecosystem services (Falchetta et al., 2023).

Table 7. Employment opportunity and rural labour dynamics after the adoption of solar irrigation.

Indicator	Observed trend	% of respondents
Labourers employed (family vs. hired)	Family labour is sufficient and remains primary; no additional workers needed	50%
	Increased labour demand due to irrigation expansion/intensification	42%
New rural job opportunities	Limited direct job creation: indirect/temporary jobs created (farm expansion, seedling preparation, processing)	54%
	No new jobs created beyond family labour	46%
Gender and labour participation	Female participation increased/household labour became more inclusive	38%
	Male-dominated labour	8%
	No change in gender participation	33%

In addition, more than half of the respondents (58%) observed an increase in bees, birds and other insects, which they believed was due to the year-round availability of flowering crops and greenery, suggesting a positive effect on pollinators. However, a quarter of the respondents (25%) reported little or no change and 12.5% noted that pollinator benefits were constrained by pesticide and herbicide use, highlighting this as a key limitation.

Biodiversity-supportive practices were also widely mentioned, with 83% of respondents reporting intercropping, planting hedgerows and desho grass, shade provision and diversification of vegetation around their homesteads. These practices enhance both spatial and functional diversity, although they remain concentrated at the homestead scale rather than extending to broader landscapes. Simultaneously, respondents indicated that efforts to conserve or reintroduce indigenous species have been relatively weak. While half of the respondents observed improved survival of Enset (*Ensete ventricosum*), banana (*Musa spp*), avocado (*Persea americana*), mango (*Mangifera indica*) and some grasses, only 12.5% mentioned the recovery or preservation of native grasses, shrubs or medicinal plants such as *Kebericho* (*Echinops kebericho*) and *Chirakot*. These responses indicate that biodiversity gains are largely oriented toward economically valuable species rather than native or culturally important ones. This pattern mirrors findings in studies of smallholder irrigation adoption, where improved water access enhances vegetation diversity but often focuses on profitable species and less on native biodiversity (Wamalwa et al., 2024).

Environmental changes were also widely observed, with 92% of respondents noting the visible greening of homesteads, reduced soil erosion and improved soil moisture, even during the dry season. Many respondents highlighted additional benefits, including enhanced aesthetics, shade provision and the creation of socially valuable spaces for recreation, cultural ceremonies and community gatherings. A smaller proportion (12.5%) emphasized contributions to microclimate regulation and climate resilience. Overall, these results suggest that solar-based irrigation is perceived not only boosts agricultural productivity but also to contribute to broader environmental improvements, including support for biodiversity, ecosystem services and social well-being, although such benefits remain largely limited to the homestead scale rather than the wider landscape. These observations align with modeling studies that demonstrate the substantial potential of solar pump-based irrigation systems to enhance environmental resilience; however, their wider impact at the landscape level depends on effective governance, integrated water resource management and coordinated land-use planning. (Falchetta et al., 2023).

While solar energy irrigation technology offers several advantages, some general studies, e.g. Closas and Rap (2017), have noted that it could lead to increased groundwater extraction if regulation expansion is unregulated. In this study, respondents did not report any noticeable increase in water extraction, likely because of the small scale of application and cooperative water use among the participating farmers. However, this finding should be understood in the context of the sustainable development debate surrounding solar irrigation technology. To ensure that solar irrigation remains sustainable in the long run, there is a need for water governance measures, including groundwater monitoring and efficient on-farm water management, moving forward.

4. Conclusion and recommendations

4.1. Conclusion

This study, conducted in the Ethiopian Rift Valley basin, combined on-farm field experiments with farmers' and key informants' reported experiences and recollections rather than measured baseline data. The evidence indicates that pairing a solar pump-based irrigation system with vermicompost application as a soil fertility management practice can help maximize the perceived benefits of solar-based irrigation and encourage adoption. On-farm trials produced positive agronomic results, while farmers associated the bundled practice with improved crop yields and soil moisture. Taken together, these observations suggest that integrating multiple climate-smart practices rather than promoting a single technology in isolation may be important for maximizing benefits and encouraging broader uptake of innovations.

Farmers viewed solar-based irrigation very positively. They reported diversifying into high-value crops, irrigating larger areas and harvesting more frequently, and they linked these changes to higher productivity

and better livelihoods. Many farmers also reported shifting from subsistence cereals to higher-value crops like vegetables and fruits, a change they believed enhanced market participation, reduced production risks and provided steadier income for both daily needs and long-term investments. Additional perceived gains, including improved food and nutrition security, increased dry-season livestock feed and environmental co-benefits, reinforced the attractiveness of solar-based irrigation from the farmers' perspective and point a strong basis for scaling and wider adoption.

From a practical standpoint, these findings support promoting solar-powered irrigation together with integrated soil fertility management, particularly vermicompost, as a bundled entry point for climate-smart intensification in similar agroecological settings. Because the results rest partly on farmer perceptions and on trials that did not isolate individual treatment effects, the case for the bundle should be advanced through phased scaling that pairs technology deployment with monitoring and complementary support services—rather than through stand-alone technology promotion.

These conclusions should be interpreted cautiously. The absence of separate solar-only and vermicompost-only treatments limited the attribution of individual effects, while the lack of detailed soil measurements constrained the explanation of biophysical mechanisms. The economic analysis was limited to plot-level costs rather than system-level returns. Far from undermining the findings, these limitations highlight priorities for future research: more granular soil monitoring, experimental designs isolating individual and combined effects, and broader economic assessments. Addressing these gaps will strengthen the evidence base for climate-smart interventions combining renewable energy–based irrigation with sustainable soil fertility management.

4.2. Recommendations

Building on the findings and on issues raised by participants, the following practical, stakeholder-oriented actions are recommended.

For development programmes and extension systems

- Promote solar-powered irrigation and vermicompost as a bundled package rather than as stand-alone technologies, and deliver farmer training on their combined use, agronomic management and integration into existing cropping systems.
- Support reliable access to quality organic inputs, including materials and know-how for on-farm vermicompost production, so that the bundle can be sustained beyond initial project support.
- Strengthen market linkages by supporting cooperatives, improving rural transport and expanding storage infrastructure to reduce post-harvest losses in the higher-value crops enabled by irrigation.
- Integrate nutrition-sensitive interventions and diversified, climate-smart farming components into solar irrigation programmes so that productivity gains translate into measurable food and nutrition benefits at the household level.

For policymakers and development partners

- Expand affordable financing mechanisms—such as targeted credit lines, smart subsidies or asset-financing schemes—that make solar irrigation systems and complementary inputs (including vermicompost) accessible to resource-poor farmers.
- Ensure that the expansion of solar-powered irrigation is accompanied by sustainable water management practices to protect groundwater and surface water resources as irrigated area increases.
- Adopt inclusive approaches that secure equitable participation of women and other resource-constrained farmers in access to irrigation technologies, training, finance and markets, consistent with participants' concerns about inclusion.

For future researchers

- Design experiments that separately test solar-only, vermicompost-only and combined treatments to attribute individual and interaction effects and to quantify the added value of bundling.

- Incorporate granular soil monitoring -covering fertility, moisture dynamics and biological indicators—to better explain the biophysical mechanisms underlying the yield and soil moisture responses reported here.
- Extend economic analyzes beyond plot-level costs to system-level returns, including labour, water use, capital and investment costs, to inform scaling decisions and policy design.

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Author contributions

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ORCID

Desalegn Tegegne http://orcid.org/0000-0002-0288-2364
Stefan Sieber http://orcid.org/0000-0002-4849-7277
Goetz Uckert http://orcid.org/0000-0002-4359-5871
Wolde Mekuria http://orcid.org/0000-0001-5252-4795

Data availability statement

The data supporting the results presented in this study can be obtained from the corresponding author on request. The data are not publicly available to protect the personal privacy of the respondents.

Ethical statement

This research received ethical approval from the International Water Management Institute (IWMI) with ethical approval number #2025_07. Verbal informed consent was obtained from all key informants before data collection.

References

Abule Ebro, A. E., Girma Abebe, G. A., & Engida Oda, E. O. (2017). Livestock feed resources in Southern Ethiopia: The case of meskan district. *Livestock Research for Rural Development*, *29*(11), 214.

Agrawal, S., & Jain, A. (2019). Sustainable deployment of solar irrigation pumps: Key determinants and strategies. *Wiley Interdisciplinary Reviews: Energy and Environment*, *8*(2), e325. https://doi.org/10.1002/wene.325

Alemayehu, H., Haile, W., & Kiflu, A. (2025). Characterization and classification of soils at jara gelalicha and aruma areas, sidama region, Southern Ethiopia. *Frontiers in Environmental Science*, *13*, 1569469. https://doi.org/10.3389/fenvs.2025.1569469

Ashine, E. T. (2025). Solar-based irrigation system application as an option for energy source for irrigation water management in Ethiopia: A review. *International Journal of Energy and Power Engineering*, *14*(1), 23–28. https://doi.org/10.11648/j.ijepe.20251401.12

Assefa, S., & Tadesse, S. (2019). The principal role of organic fertilizer on soil properties and agricultural productivity: A review. *Agric. Res. Technol. Open Access J*, *22*(2), 1–5. https://doi.org/10.19080/ARTOAJ.2019.22.556192

Assefa, T. T., Adametie, T. F., Yimam, A. Y., Belay, S. A., Degu, Y. M., Hailemeskel, S. T., Tilahun, S. A., Reyes, M. R., & Prasad, P. V. (2020). Evaluating irrigation and farming systems with solar MajiPump in Ethiopia. *Agronomy*, *11*(1), 17. https://doi.org/10.3390/agronomy11010017

Berhanu, Y., Angassa, A., & Aune, J. B. (2021). A system analysis to assess the effect of low-cost agricultural technologies on productivity, income, and GHG emissions in mixed farming systems in Southern Ethiopia. *Agricultural Systems*, *187*, 102988. https://doi.org/10.1016/j.agsy.2020.102988

Birhanu, B. Z., Sanogo, K., Traore, S. S., Thai, M., & Kizito, F. (2023). Solar-based irrigation systems as a game changer to improve agricultural practices in sub-saharan Africa: A case study from Mali. *Frontiers in Sustainable Food Systems*, *7*, 1085335. https://doi.org/10.3389/fsufs.2023.1085335

Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., Creamer, R., Dendooven, L., Fliessbach, A., Geissen, V., Hale, L., Impey, C., de Jong-Hagelstein, S., Kuhlmann, A., Mäder, P., Pulleman, M., Quénéhervé, P., Rusek, J., Singh, J., … Brun, J. J. (2019). Soil invertebrates and ecosystem services. *Soil Biology and Biochemistry*, *135*, 1–13.

Boyacı, S., Atilgan, A., Rolbiecki, R., & Kocięcka, J. (2025). The effect of irrigation and vermicompost applications on the growth and yield of greenhouse pepper plants. *Water*, *17*(22), 3219. https://doi.org/10.3390/w17223219

Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-powered drip irrigation enhances food security in the Sudano–Sahel. *Proceedings of the National Academy of Sciences*, *107*(5), 1848–1853. https://doi.org/10.1073/pnas.0909678107

Castellini, M., Bondì, C., Giglio, L., & Iovino, M. (2024). Impact of vermicompost addition on water availability of differently textured soils. *Heliyon*, *10*(15), e35699. https://doi.org/10.1016/j.heliyon.2024.e35699

Ceritoğlu, M., Şahin, S., & Erman, M. (2018). Effects of vermicompost on plant growth and soil structure. *Selcuk Journal of Agriculture and Food Sciences*, *32*(3), 607–615. https://doi.org/10.15316/SJAFS.2018.143

Closas, A., & Rap, E. (2017). Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy*, *104*, 33–37. https://doi.org/10.1016/j.enpol.2017.01.035

Danso-Abbeam, G., Dagunga, G., & Ehiakpor, D. S. (2020). Rural non-farm income diversification: Implications on smallholder farmers' welfare and agricultural technology adoption in Ghana. *Heliyon*, *6*(11), e05393. https://doi.org/10.1016/j.heliyon.2020.e05393

Degwale, A., Kebede, G., Woldeselassie, A., & Laekemariam, F. (2025). Combined application of vermicompost and mineral K fertilizer improves root yield of sweet potato [Ipomoea batatas (L.) Lam] in Southern Ethiopia. *Heliyon*, *11*(3), e42250. https://doi.org/10.1016/j.heliyon.2025.e42250

Dejen, Z. A., Negera, M., Tegegne, D., Mekuria, W., Feysa, G. L., & Haileslassie, A. (2025). Inclusive innovation bundling and scaling pathways for smallholders' solar irrigation in Ethiopia. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Scaling for Impact Program.

Desalegn, T. (2025). Opportunities to improve water productivity in farmer-led irrigation: A case study of Ethiopia, *Enhancing Water and Food Security Through Improved Agricultural Water Productivity: New Knowledge, Innovations and Applications* (pp. 341–360). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-96-1848-4_15

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 Reviews*, *51*, 101294. https://doi.org/10.1016/j.esr.2024.101294

Falchetta, G., Semeria, F., Tuninetti, M., Giordano, V., Pachauri, S., & Byers, E. (2023). Solar irrigation in sub-saharan Africa: Economic feasibility and development potential. *Environmental Research Letters*, *18*(9), 094044. https://doi.org/10.1088/1748-9326/acefe5

Food and Agriculture Organization (FAO). (2023). Soil organic matter management for climate-smart agriculture in AfricaRome

Food and Agriculture Organization of the United Nations (FAO). (2025). State of Food and Agriculture: Tackling land degradation - summary and findings (SOFA 2025)

Food and Agriculture Organization of the United Nations (FAO). (2018). Climate-Smart Agriculture Case Studies 2018: Successful approaches from different regionsRome

Freyer, B., Ellssel, P., Nyakanda, F., & Saussure, S. (2024). *Exploring the off-farm production, marketing and use of organic and biofertilisers in Africa: A scoping study*. Report to the European Commission. DeSIRA-LIFT European Union This work is licensed under a Creative Commons Attribution 4.0 International License DeSIRA-LIFT would be grateful to receive a copy of or a link to the text in which this publication is cited. i Table of contents, 1, p.5.

Gebregergs, T., Gebre, G. G., Mohammed, M. J., Tegegne, D., & Sieber, S. (2026). Effect of integrated use of organic and inorganic fertilizer on wheat productivity in tigray, Ethiopia. *Compost Science & Utilization*, *33*(3), 1–13. https://doi.org/10.1080/1065657X.2026.2715548

Gebregziabher, G., Haileslassie, A., Biazin, B., Schmitter, P. S., Chali, A., Otoo, M., Lefore, N., Barron, J., Tegegne, D., & Dubale, T. (2019). Solar-powered water pumping can boost smallholder income: A business model based on action research from LIVES, *Livestock and Irrigation Value Chains for Ethiopian Smallholders and Africa RISING. Lessons from Action Research Projects, December 2016* (pp. 8–9). Addis Ababa, Ethiopia.

Gebremedhin, G., Weldegebriel, Z., & Birhanu, A. (2024). Effects of vermicompost on soil fertility and crop yield under irrigated conditions in Ethiopia. *Journal of Soil Science and Environmental Management*, *15*(2), 45–57.

GIZ/NIRAS/Practica. (2025). Solar irrigation market analysis in Ethiopia(Report).
Goel, S. (2022). Implementing solar irrigation sustainably: A guidebook for state policymakers on maximizing the social and environmental benefits from solar pump schemes. International Institute for Sustainable Development (IISD).
Guno, C. S., & Agaton, C. B. (2022). Socio-economic and environmental analyses of solar irrigation systems for sustainable agricultural production. *Sustainability*, *14*(11), 6834. https://doi.org/10.3390/su14116834
Hagos, F., Gebrekirstos, A., Tamene, L. D., Schmitter, P. S., Tegegne, D., Haileslassie, A., Barron, J., Lefore, N., & Mupangwa, W. (2017). Innovation adoption for scaling: Africa RISING science, innovations and technologies with scaling potential from the Ethiopian Highlands. *International Livestock Research Institute (ILRI) and International Water Management Institute (IWMI)*.
Hurni, H., Berhe, W. A., Chadhokar, P., Daniel, D., Gete, Z., Grunder, M., & Kassaye, G. (2016). Soil and water conservation in Ethiopia: Guidelines for development agents, p. 134). Bern, Switzerland: Centre for Development and Environment (CDE), University of Bern, with Bern Open Publishing (BOP).
Hussein, M. A., Riga, F. T., Derseh, M. B., Assefa, T. T., Worqlul, A. W., Haileslassie, A., Adie, A., Jones, C. S., & Tilahun, S. A. (2024). Application of irrigation management and water-lifting technologies to enhance fodder productivity in smallholder farming communities: A case study in robit bata, Ethiopia. *Agronomy*, *14*(5), 1064. https://doi.org/10.3390/agronomy14051064
International Water Management Institute (IWMI). (2024). *Solar irrigation for agricultural resilience (SoLAR) project*. IWMI.
IRENA. (2016). Solar pumping for irrigation: Improving livelihoods and sustainability.
Joshi, D., Yadav, L. R., Ratore, B. S., Srivastava, H., Verma, R. S., Gurjar, B. S., Yadav, M., Sharma, C., & Karol, A. (2023). Enhancing nutrient uptake and economics of black gram through vermicompost and vermiwash application. *International Journal of Environment and Climate Change*, *13*(9), 3186–3193. https://doi.org/10.9734/ijecc/2023/v13i92563
Kanda, E., Dirwai, T. L., Tegegne, D., Choruma, D. J., & Haileslassie, A. (2026). Agricultural water management in maize-based systems: Challenges, opportunities, and sustainable solutions in Kenya, Malawi, Zambia, and Zimbabwe, *Agricultural Water Management in Africa*. 87–129. https://doi.org/10.1016/B978-0-443-21584-1.00010-7
Kassie, G. W., Kim, S., & JrFellizar, F. P. (2017). Determinant factors of livelihood diversification: Evidence from Ethiopia. *Cogent Social Sciences*, *3*(1), 1369490. https://doi.org/10.1080/23311886.2017.1369490
Kifle, T., Deboch, A., & Nigussie, W. (2025). Participatory demonstration of irrigation scheduling under solar pump irrigation for sweet potato (Ipomoea batatas L.) production in dijo woreda, halaba zone, Ethiopia. *Asian Journal of Research and Review in Agriculture*, *7*(1), 143–148. https://doi.org/10.56557/ajrra/2025/v7i1162
Korekallu Srinivasa, A., & Mithöfer, D. (2024). Unpacking stakeholder perceptions on challenges for increasing adoption of solar-powered irrigation systems in India: AQ methodology study. *Q Open*, *4*(2), qoae020. https://doi.org/10.1093/qopen/qoae020
Kumar, R., Sharma, S. N., & Singh, B. (2022). Long-term fertilization strategies for improving productivity, profitability and water-use efficiency of soybean–wheat cropping systems. *The Journal of Agricultural Science*, *160*(3), 369–381.
Kusse, T., Balemi, T., & Abera, T. (2019). Effect of integrated application of poultry manure and chemical NP fertilizers on growth, yield and yield components of highland maize variety on vertisol at ambo university on station, Ethiopia. *International Journal of Sustainable Agricultural Research*, *6*(4), 183–197. https://doi.org/10.18488/journal.70.2019.64.183.197
Kuta, A. A. (2025). Effect of land use types and soil depth on selected soil physicochemical properties in sidama regional state, Southern Ethiopia. *Asian Journal of Research in Agriculture and Forestry*, *11*(4), 60–67. https://doi.org/10.9734/ajraf/2025/v11i4444
Li, Y., Feng, X., Huai, Y., Hassan, M. U., Cui, Z., & Ning, P. (2024). Enhancing crop productivity and resilience by promoting soil organic carbon and moisture in wheat and maize rotation. *Agriculture, Ecosystems & Environment*, *368*, 109021. https://doi.org/10.1016/j.agee.2024.109021
Liang, Z., Shorter, A. L., & Winter, A. G. (2024). Quantifying the energetic cost tradeoffs of photovoltaic pumping systems for sub-saharan African smallholder farms. *Irrigation Science*, *42*(1), 149–161. https://doi.org/10.1007/s00271-023-00872-9
Maity, R., Sudhakar, K., & Razak, A. A. (2024). Agri-solar water pumping design, energy, and environmental analysis: A comprehensive study in tropical humid climate. *Heliyon*, *10*(21), e39604. https://doi.org/10.1016/j.heliyon.2024.e39604
Manyuchi, M., Chitambwe, T., Phiri, A., Muredzi, P., & Kanhukamwe, Q. (2013). Effect of vermicompost, vermiwash and application time on soil physicochemical properties. *International Journal of Chemical and Environmental Engineering*, *4*(4).
Manzoor, A., Naveed, M. S., Ali, R. M. A., Naseer, M. A., Ul-Hussan, M., Saqib, M., Hussain, S., & Farooq, M. (2024). Vermicompost: A potential organic fertilizer for sustainable vegetable cultivation. *Scientia Horticulturae*, *336*, 113443. https://doi.org/10.1016/j.scienta.2024.113443
Masso, C., Nziguheba, G., Mutegi, J., Galy-Lacaux, C., Wendt, J., Butterbach-Bahl, K., Wairegi, L., & Datta, A. (2017). Soil fertility management in sub-saharan Africa, *Sustainable Agriculture Reviews* (Vol. *25*, pp. 205–231). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-58679-3_7
Mekuria, W., & Tegegne, D. (2023). Water harvesting.

Mekuria, W., Dessalegn, M., Ebrahim, G. Y., Tegegne, D., Haile, A. T., & Ruckstuhl, S. (2024a). Stakeholder analysis to guide co-production of nature-based solutions to address livelihood vulnerability: the case of Dolo Ado and Bokolmayo districts, Somali Regional State, Ethiopia. *International Water Management Institute (IWMI)*, p. 36.

Mekuria, W., Phimister, E., Yakob, G., Tegegne, D., Moges, A., Tesfaye, Y., Melaku, D., Gerber, C., Hallett, P. D., & Smith, J. U. (2024b). Gully rehabilitation in Southern Ethiopia–value and impacts for farmers. *SOIL*, *10*(2), 637–654. https://doi.org/10.5194/soil-10-637-2024

Mekuria, W., Gebreab, Y. T., Teshale, T., Feyisa, G. L., Kamanda, J., & Haileslassie, A. (2025). Feasibility of vermicompost production and business models for sustainable agriculture in the rift valley system of Ethiopia, p. (45). Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Scaling for Impact Program.

Meressa, A. M., & Bantie, L. (2024). The impacts of climate change on peasants' crop production in major crop-producing zones in Ethiopia. *Discover Sustainability*, *5*(1), 443. https://doi.org/10.1007/s43621-024-00628-1

Minh, T. T., & Ofosu, A. (2022). Solar-based irrigation bundle profile and, *scaling in Ghana*. IWMI.

Mitiku, B., & Amiha, N. (2018). Evaluation of multifunctional fodder bank trees and shrubs in meskan woreda enseno usma kebele. *Journal of Natural Sciences Research*, *8*(13), 43–47).

Negera, M., Dejen, Z. A., Melaku, D., Tegegne, D., Adamseged, M. E., & Haileslassie, A. (2025). Agricultural productivity of solar pump and water harvesting irrigation technologies and their impacts on smallholder farmers' income and food security: Evidence from Ethiopia. *Sustainability*, *17*(4), 1486. https://doi.org/10.3390/su17041486

Nigussie, A., Alemayehu, E., & Tadesse, A. (2023). Integrating vermicompost and irrigation for improved soil health and yield in Ethiopian highlands. *Agricultural Water Management*, *286*, 108361.

Obeng, F. K., Teye, F., & Boadi, E. (2024). Integrating biochar with solar drip irrigation technology for smallholder vegetable farming in south-eastern Ghana yields profitable returns. *Asian Journal of Agricultural Extension, Economics & Sociology*, *42*(8), 1–14.

Olarewaju, O. O., Fawole, O. A., Baiyegunhi, L. J., & Mabhaudhi, T. (2025). Integrating sustainable agricultural practices to enhance climate resilience and food security in sub-saharan Africa: A multidisciplinary perspective. *Sustainability*, *17*(14), 6259. https://doi.org/10.3390/su17146259

Otoo, M., Lefore, N., Schmitter, P., Barron, J., & Gebregziabher, G. (2018). Business model scenarios and suitability: Smallholder solar pump-based irrigation in Ethiopia. Agricultural water Management–Making a business case for smallholders (*Vol. 172*International Water Management Institute (IWMI).

Ouedraogo, K. R., Tete, K. H., Soro, Y. M., & Darga, A. (2025). Solar water pumping systems for a sustainable development of the market gardening sector in Burkina Faso. *Discover Sustainability*, *6*(1), 969. https://doi.org/10.1007/s43621-025-01636-5

Oyege, I., & Balaji Bhaskar, M. S. (2023). Effects of vermicompost on soil and plant health and promoting sustainable agriculture. *Soil Systems*, *7*(4), 101. https://doi.org/10.3390/soilsystems7040101

Raza, F., Tamoor, M., Miran, S., Arif, W., Kiren, T., Amjad, W., Hussain, M. I., & Lee, G. H. (2022). The socio-economic impact of using photovoltaic (PV) energy for high-efficiency irrigation systems: A case study. *Energies*, *15*(3), 1198. https://doi.org/10.3390/en15031198

REEEP. (2024). SOARING: Solar irrigation fact sheetRenewable Energy and Energy Efficiency Partnership

Rivier, P.-A., Jamniczky, D., Nemes, A., Barna, G., Uzinger, N., Rékási, M., & Farkas, C. (2022). Short-term effects of compost amendments to soil-on-soil structure, hydraulic properties, and water regime. *Journal of Hydrology and Hydromechanics*, *70*(1), 74–88. https://doi.org/10.2478/johh-2022-0004

Sanogo, M., Yonaba, R., Keïta, A., Lawane, A., Barbier, B., Aminatou, A. M. G., Bazié, I., & Ouarmé, S. (2025). Adoption of solar-powered pumps in agriculture: Insights from smallholders in Burkina Faso. *Discover Agriculture*, *3*(1), 53. https://doi.org/10.1007/s44279-025-00205-8

Schmitter, P. S., Tegegne, D., Adie, A., Baudron, F., Blümmel, M., Lefore, N., & Barron, J. (2016). Evaluation of suitable water lifting and on-farm water management technologies for the irrigation of vegetables and fodder in Lemo district, Ethiopia. *International Water Management Institute (IWMI) and International Livestock Research Institute (ILRI)*. Africa RISING Program.

Shahena, S., Rajan, M., Chandran, V., & Mathew, L. (2021). Conventional methods of fertilizer release, *Controlled release fertilizers for sustainable agriculture* (pp. 1–24). Academic Press. https://doi.org/10.1016/B978-0-12-819555-0.00001-7

Shapiro, A., Annunzio, R., Desclée, B., Jungers, Q., Kondjo, H. K., Iyanga, J. M., Gangyo, F. I., Nana, T., Obame, C. V., Milandou, C., & Rambaud, P. (2023). Small-scale agriculture continues to drive deforestation and degradation in fragmented forests in the Congo basin (2015–2020). *Land Use Policy*, *134*, 106922. https://doi.org/10.1016/j.landusepol.2023.106922

Shrestha, P., Sharma, R., & Karki, T. (2023). Technology for whom? Solar irrigation pumps, women, and smallholders in Nepal. *Frontiers in Sustainable Food Systems*, *7*, 1143546. https://doi.org/10.3389/fsufs.2023.1143546

Singh, R., Sharma, P., & Kumar, A. (2025). Improving the physical quality of coarse-textured soils by organic amendments: Effects of compost, vermicompost, and biochar on water retention. *Applied Sciences*, *15*(6), 3392. https://doi.org/10.3390/app15063392

Singha, A. K., Baruah, M. J., Bordoloi, R., Dutta, P., & Saikia, U. S. (2012). Analysis on influencing factors of technology adoption of different land based enterprises of farmers under diversified farming system. *Journal of Agricultural Science*, *4*(2), 139. https://doi.org/10.5539/jas.v4n2p139

Song, J., Wu, Z., Wang, J., Zhang, K., Wang, K., Liu, K., Duan, L., & Hou, H. (2021). Application of highly concentrated sunlight transmission and daylighting indoors via plastic optical fibers with comprehensive cooling approaches. *Renewable Energy*, *180*, 1391–1404. https://doi.org/10.1016/j.renene.2021.08.112

Steffen, G. P. K., Maldaner, J., de Morais, R. M., Saldanha, C. W., Missio, E. L., Steffen, R. B., & Osorio Filho, B. D. (2019). The vermicompost anticipates flowering and increases tomato productivity. *Agrociencia Uruguay*, *23*(1), e54–e54. https://doi.org/10.31285/AGRO.23.1.7

Tamoor, M., ZakaUllah, P., Mobeen, M., & Zaka, M. A. (2021). Solar-powered automated irrigation system in rural area and their socio-economic and environmental impact. *International Journal of Sustainable Energy and Environmental Research*, *10*(1), 17–28. https://doi.org/10.18488/journal.13.2021.101.17.28

Teferi, E., O'Donnell, G., Kassawmar, T., Mersha, B. D., & Ayele, G. T. (2023). Enhanced soil moisture retrieval through integrating satellite data with pedotransfer functions in a complex landscape of Ethiopia. *Water*, *15*(19), 3396. https://doi.org/10.3390/w15193396

Tegegne, D., Damtie, M. T., & Shumye, A. (2025a). Assessment of irrigation performance trends using selected comparative indicators over consecutive periods: A case study of the koga irrigation scheme in the amhara region, Ethiopia. *Irrigation and Drainage*, *74*(2), 809–819. https://doi.org/10.1002/ird.3021

Tegegne, D., Schmitter, P., Worqlul, A. W., & Lefore, N. (2025b). Estimating crop coefficients for vegetable production and agricultural water management under climate change in sub-humid tropics. *Frontiers in Water*, *7*, 1355154. https://doi.org/10.3389/frwa.2025.1355154

Tegegne, D., Sieber, S., Uckert, G., Girma, R., Moges, A., & Mekuria, W. (2026). Using local knowledge and scientific assessment for inclusive land restoration in halaba, central Ethiopia. *Discover Sustainability*, *7*(1), 943. https://doi.org/10.1007/s43621-026-03681-0

Verma, H. P., Sharma, O. P., Shivran, A. C., Yadav, L. R., Yadav, R. K., Yadav, M. R., Meena, S. N., Jatav, H. S., Lal, M. K., Rajput, V. D., & Minkina, T. (2023). Effect of irrigation schedule and organic fertilizer on wheat yield, nutrient uptake, and soil moisture in northwest India. *Sustainability*, *15*(13), 10204. https://doi.org/10.3390/su151310204

Wamalwa, F., Maqelepo, L., Williams, N., & Falchetta, G. (2024). Solar irrigation potential in sub-saharan Africa: A crop-specific techno-economic analysis. *Environmental Research: Food Systems*, *1*, 025001.

Wana, T. G., & Dukamo, T. A. (2025). Trends and sustainability of small-scale irrigation in Southern Ethiopia: Exploring constraints and adoption dynamics. *BMC Agriculture*, *1*(1), 1–15. https://doi.org/10.1186/s44399-025-00013-x

Wang, X. X., Zhao, F., Zhang, G., Zhang, Y., & Yang, L. (2017). Vermicompost improves tomato yield and quality, and the biochemical properties of soils with different tomato planting history in a greenhouse study. *Frontiers in plant science*, *8*, 1978. https://doi.org/10.3389/fpls.2017.01978

Wawire, A. W., Csorba, Á., Tóth, J. A., Michéli, E., Szalai, M., Mutuma, E., & Kovács, E. (2021). Soil fertility management among smallholder farmers in Mount Kenya East region. Heliyon, *7*(3), e06488. https://doi.org/10.1016/j.heliyon.2021.e06488

Yamegueu, D., Alokore, Y., & Corso, G. (2019). Potential of microfinanced solar water pumping systems for irrigation in rural areas of Burkina Faso. *Energy, Sustainability and Society*, *9*(1), 8. https://doi.org/10.1186/s13705-019-0190-7

Yang, K., Hu, J., Ren, Y., Zhang, Z., Tang, M., Shang, Z., Zhen, Q., & Zheng, J. (2024). Enhancement of soil organic carbon, water use efficiency, and maize yield (Zea mays L.) in sandy soil through organic amendment (Grass peat) incorporation. Ag. *ronomy*, *14*(2), 353. https://doi.org/10.3390/agronomy14020353

Zhang, M., Liu, Y., Wei, Q., Liu, L., Gu, X., Gou, J., & Wang, M. (2023). Ameliorative effects of vermicompost application on yield, fertilizer utilization, and economic benefits of continuous cropping pepper in karst areas of southwest China. *Agronomy*, *13*(6), 1591. https://doi.org/10.3390/agronomy13061591

Zhang, Z., Dong, X., Wang, S., & Pu, X. (2020). Benefits of organic manure combined with biochar amendments to cotton root growth and yield under continuous cropping systems, xinjiang, China. *Scientific Reports*, *10*, 4718. https://doi.org/10.1038/s41598-020-61118-8