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Agricultural Productivity of Solar Pump and Water Harvesting Irrigation Technologies and Their Impacts on Smallholder Farmers' Income and Food Security: Evidence from Ethiopia

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Abstract: Irrigation plays a crucial role in enhancing food production, increasing land productivity, and improving the livelihoods of smallholder farmers in Sub-Saharan Africa (SSA). Solar pumps and water harvesting ponds have emerged as promising technologies for sustainable agriculture for smallholders in SSA and beyond. The socio-economic impacts of these systems are less studied in the existing literature. This study examined the agricultural productivity of solar pump and water harvesting irrigation technologies and their impacts on income and food security among smallholder farmers in the Central Rift Valley, Lake Hawassa, and Upper Awash sub-basin areas in Ethiopia. Data were collected from 161 farming households that were selected randomly from woredas where solar pump and water harvesting pond irrigation systems had been implemented. The sample size was determined using the power calculation method. Bio-physical observation and measurements were also conducted at field levels. The benefit–cost ratio (BCR) and net water value (NWV) from the use of solar pump and water harvesting pond irrigations were analyzed to assess the viability of these systems. The household food consumption score (HFCS) and household dietary diversity score (HDDS) were calculated to measure food security, while the revenue from crop production was used to measure crop income. An endogenous switching regression model was applied to address the endogeneity nature of the adoption of the irrigation technologies. The counterfactual analysis, specifically the Average Treatment Effect on the Treated (ATT), was used to evaluate the impacts of the irrigation technologies on income and food security. Results indicate that the ATT of crop income, HFCS, and HDDS are positive and statistically significant, illustrating the role of these irrigation systems in enhancing smallholder farmers' welfare. Moreover, smallholder farmers' solar pump irrigation systems were found to be economically viable for few crops, with a BCR greater than 1.0 and an NWV ranging from 0.21 to 1.53 USD/m^3. It was also found that bundling agricultural technologies with solar pump irrigation systems leads to enhanced agricultural outputs and welfare. The sustainable adoption and scale-up of these irrigation systems demand addressing technical and financial constraints, as well as input and output market challenges.

Keywords: sustainable agriculture; crop income; food security; water productivity; net water value; benefit–cost ratio; technology bundle

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1. Introduction

Irrigation development is a major contributor to national and household food security, improved rural livelihoods, and social well-being. For SSA, small-scale irrigation holds large potential to ensure food and nutrition security and income generation [1]. Ethiopia's estimate of irrigation potential varies, with an economic irrigation potential of about 5.7 million ha in all scales [2,3]. However, recent unpublished studies suggest that the irrigation potential could be as high as 11 million ha with the adoption of different water management technologies. The development of irrigation in Ethiopia is currently at only about 15% of its potential, of which the largest proportion is from small-scale irrigation schemes. Small-scale irrigation in the Ethiopian context is a scheme with an irrigated area of less than 200 ha, typically managed by individual farmers or small communities. Small-scale irrigation plays a pivotal role in improving livelihoods, food security, and employment opportunities [4,5]. The government is widely engaged in expanding smallholder irrigation because these can be implemented with limited technical knowledge and large financial investments. Moreover, smallholder household irrigation practices can be implemented in a disintegrated manner, and their management avoids complex situations that are encountered in communal irrigation schemes.

Solar pumps are generally referred to as relatively less affordable for smallholder farmers in Africa due to higher investment costs, while having low operation and maintenance costs, thus being more reliable [6,7]. Solar pumps are environmentally friendly (carbon-free) alternatives to diesel pumps for lifting water to use for irrigation. In low- and medium-head water pumping sites, solar PV water pumps are particularly used for irrigation [8]. Household-level small standalone solar pumps have been accepted over the past decade in developing nations, including African nations, for lifting water for use in smallholder irrigation, particularly from shallow groundwater and surface water sources [9,10]. Several studies indicate that there is yet more potential to expand solar-powered irrigated agriculture in Africa, thereby improving livelihoods and food security for smallholder farmers [11–13].

Although solar pump irrigation systems can greatly benefit smallholders, the level of the benefit can depend on the type of crops grown, water application systems, the size of the irrigated land, markets, and input costs [1], as well as the technology bundles applied. Diesel engine pumps are being widely used in Ethiopia by smallholders, particularly for the production of cash crops (vegetables and fruits). While these are often feasible for growing cash crops, the operation and maintenance costs are higher and they are not environmentally friendly as they contribute to greenhouse gas emissions, mainly carbon dioxide. In addition, the use of diesel pumps by smallholder farmers is constrained by the shortage of fuel, adulteration, and the lack of spare parts [14]. In regions like SSA, where the cost of diesel fuel is high or where reliable access to the electricity grid is lacking, solar pump irrigation for smallholders can provide a relatively flexible and climate-friendly alternative energy source [15]. As a result, as per [1], solar technologies are becoming a viable option for both large- and small-scale farmers. The few studies that assessed the economics of solar irrigation pumps for countries in SSA found positive results [1]. Some of these studies include [16] for Benin; [17,18] for Zimbabwe; and [19,20] for Ethiopia.

In Ethiopia, a large potential exists to expand solar PV-powered small-scale irrigation, estimated at about 3,835,000 ha [21]. Over the last decade, efforts have been made to expand the adoption of solar pumps in Ethiopia. International Water Management Institute (IWMI) and its partners through different projects have promoted solar pumps along with water management practices, for example, in the Central Rift Valley basin. Solar-based irrigation is also piloted and promoted by other actors, including the Agricultural Transformation Institute (ATI), the Ministry of Irrigation and Lowlands (MILL), NGOs such as Farm Africa, and regional state offices. However, critical assessments of the impacts and user perspective are largely lacking. It is therefore of interest to understand the impacts of the interventions from the targeted farmer's viewpoints.

Water is often one of the major limiting factors of production for smallholder farmers in Ethiopia. Due to very scatted and disintegrated nature of smallholder farms in Ethiopia, access to larger and formal irrigation infrastructures is often limited [22–24]. However, although a comprehensive national-level study is not available, the country has considerable shallow groundwater potential, suitable for irrigation in smallholder agriculture. Ref. [25] reported that shallow groundwater has a promising potential to support small-scale irrigated agriculture. Despite the efforts to expand smallholder solar pump irrigation systems, studies on water productivity and net water values under these systems are lacking. Research suggests that solar-powered and water harvesting irrigation systems can enhance agricultural productivity and farm income [16,26]. However, previous studies have not extensively examined the impact of solar-powered irrigation on the welfare of smallholder farmers in Ethiopia, and there is limited empirical research on how water harvesting irrigation affects the welfare of smallholder farmers in the country [27,28].

This paper, therefore, aims to conduct a study on smallholder solar pump and water harvesting irrigation systems by collecting data from target farmers to assess their water productivity and their impacts on household welfare. The specific objectives are (i) to evaluate the socio-economic impacts of solar pumps and water harvesting ponds among smallholder farmers; (ii) to assess water productivity and net water values for irrigated crops using solar pumps and water harvesting ponds; (iii) to identify agricultural technology bundles utilized by smallholder farmers and their impacts on water productivity and household welfare indicators; and (iv) to pinpoint challenges associated with solar-powered and water harvesting irrigation technologies for smallholder farmers and put forward possible interventions for enhanced adoption and productivity.

This study contributes to the existing studies and policy practices in a number of ways. In the first place, it shows how the solar-powered and water harvesting irrigation technologies can transform small-scale farming by increasing agricultural productivity and enhancing rural well-being. It provides evidence on which crops and under what finance schemes these irrigation systems are viable using various metrics, which was absent from previous studies. It also highlights that the solar-powered irrigation is a climate-friendly alternative and helps farmers become more climate-adaptable. Secondly, the study would give the public at large an opportunity to learn about solar pump and water harvesting irrigation systems, which are new technologies in Ethiopia. Thirdly, the study pinpoints challenges that prevent smallholder farmers from adopting solar-powered and water harvesting irrigation technologies and suggests possible interventions to address these challenges. This is useful for planning the next steps for research and investment that can support the wider adoption of these technologies by smallholder farmers. Fourthly, the evidence generated under this study would help develop partnership-based business models involving solar pump suppliers, users, policymakers, and financial institutions to ensure the financial sustainability of the scaling efforts. Lastly, the study provides evidence that assists the agricultural policymakers in designing effective strategies that scale up the adoption of solar-powered and water harvesting irrigation by smallholder farmers in the country.

2. Materials and Methods

2.1. Study Area Description

The study area comprises seven woredas (districts), which are Ada'a, Adami Tulu Jido Kombolcha, Debub Sodo, Misrak Meskan, Alicho Woriro, Sankura and Hawassa Zuria.

The area lies in the Central Rift Valley (CRV) and Lake Hawassa sub-basins, which are both parts of the Rift Valley Lakes Basin, and in the Upper Awash sub-basin in Ethiopia. The majority of the area, however, lies in the Central Rift Valley (CRV) sub-basin. CRV is located approximately between 38°15′ E and 39°20′ E, and 7°10′ N and 8°30′ N, and its elevation ranges from approximately 1600 m above mean sea level (amsl) to over 3000 m [29]. Its climate is tropical, wet, and dry, with the annual rainfall ranging from about 650 mm to 1250 mm and average temperatures of 19 °C in the valley to about 14 °C in the highlands. The area is situated in parts of three political administrative regions: Oromia, Central Ethiopia, and Sidama. The population of the CRV sub-basin is over 7 million and covers approximately 1.5 million hectares of land, comprising four lake systems: Ziway, Abiyata, Langano, and Shalla. The region is particularly well known for the production of horticultural crops, as well as cereal production [30]. Livestock farming is also a major economic activity. The CRV is an area experiencing expanding irrigation development and pressures on the water resources (on fresh lakes and shallow groundwater) [31]. Figure 1 shows the location of the study area.

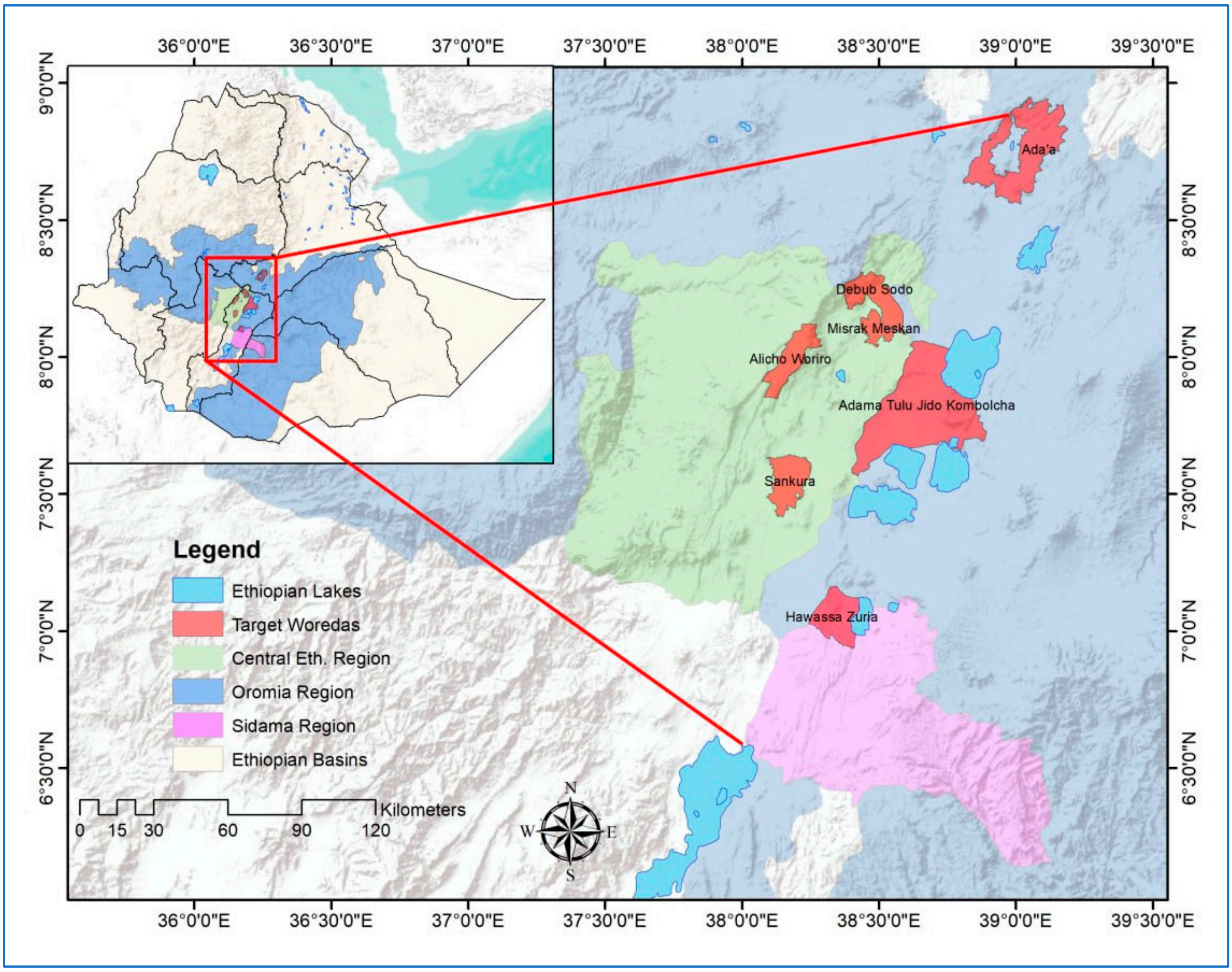


Figure 1. Location of the study area and six target woredas (districts).

2.2. Sampling and Data Collection

The study collected data from 161 farming households that were randomly selected from woredas where solar pump and water harvesting pond irrigation systems were implemented by different organizations and farmers themselves. The sample size was calculated using the power calculation method, commonly used in impact analysis (Figure 2). It was determined based on a significance level of 5%, a power of 80%, and a minimum detectable effect (effect size) taken from previous similar study. According to [32], solar-powered irrigation systems contribute to increased food security by enhancing the technical efficiency of wheat production by about 11%, which was used as the effect size in this study. The sample size determination also took into account the percentage of food-secure households in the CRV, which is approximately 40% [33,34]. The determined sample size is small, which signifies the fact that the solar pump irrigation is still in the pilot stage in Ethiopia and that there are a limited number of farmers using water harvesting ponds for irrigation.

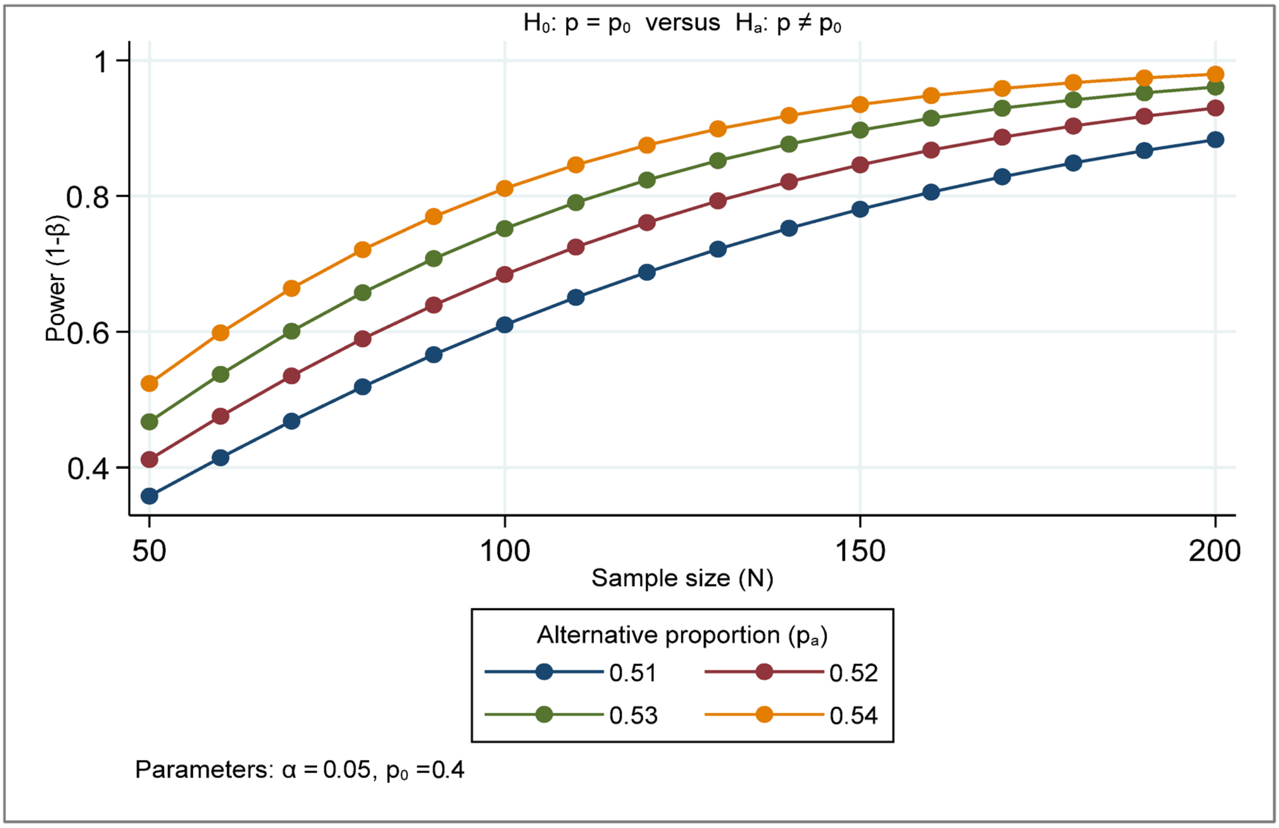


Figure 2. Sample size determination using the power calculation analysis.

Once the total sample size was established, it was shared between irrigation beneficiary and non-beneficiary groups. In particular, 77 households were chosen from the group of irrigation beneficiaries, and the remaining 84 households were selected from the non-beneficiary group. Out of the beneficiary group, 57 households were solar pump irrigation users, while 20 households are water harvesting irrigation users. The sample irrigation beneficiaries (users) were chosen using the lottery method. However, the randomly chosen household was replaced from the remaining beneficiary households if his solar pump was not working at the time of the survey. On the other hand, non-users of solar-powered irrigation were randomly selected using a systematic random sampling technique based on a sampling frame obtained from agricultural development agents. In Ethiopia, development agents (DAs) are trained professionals who work closely with farmers to provide a variety of agricultural extension services aimed at increasing agricultural outputs and improving farming practices.

Both quantitative and qualitative primary data were collected through a household survey, focus group discussion (FGD), and key informant interview (KII). The household survey was conducted using a structured questionnaire designed in computer-assisted personal interviews (CAPIs). The data collected through the questionnaire covered important variables, such as basic household socio-economic characteristics, agricultural input usage, and production using solar pump irrigation, water harvesting pond irrigation, and rain-fed agricultural production. It also addressed food security, water usage practices in solar pump and water harvesting pond irrigations, and challenges related to solar pump and water harvesting irrigation methods. A team of experts reviewed the questionnaire and provided feedback. Finally, it was validated by conducting pilot testing with a small number of farmers. This helped identify potential issues, such as ambiguous questions and response biases, allowing for corrections before the full-scale implementation of the survey instrument. In order to mitigate non-response bias during data collection, several effective measures were taken. The questionnaire was administered among the selected smallholder farmers through structured interview by the trained enumerators. The respondents were also offered incentives to motivate their participation in the survey. In addition, the quality of data was checked during data collection by conducting descriptive analyses on key variables, and the enumerators received feedback.

Community-level information was also collected, with a particular focus on the opportunities and challenges related to solar-powered and water harvesting pond irrigation through FGDs and KIIs. One KII and one FGD were conducted in each woreda. Key informants for the study included agricultural development agents, woreda agricultural experts, knowledgeable elders, and religious leaders. The participants of the FGD are smallholder farmers, including both users and non-users of solar-powered and water harvesting-based irrigation. For crop water requirements, climate data (including rainfall, wind speed, temperature, sunshine hours, and relative humidity) from nearby meteorological stations were obtained from the Ethiopian Meteorological Institute (EMI).

2.3. Variables of the Study

The variables of interest in this study include social, economic, and environmental. Specifically, these include the adoption of solar pump and water harvesting pond-based irrigation, welfare indicators such as crop income and food security, water productivity, net water value, benefit–cost ratio, and water supply adequacy.

Crop income refers to the earnings obtained by a farming household in a year from agricultural production using solar pump irrigation, water harvesting pond irrigation, and rain-fed agriculture.

Food security: The food security of farming households is measured using the household food consumption score (HFCS) and household dietary diversity score (HDDS). Both the HFCS and HDDS are less susceptible to measurement errors when compared to other indicators of food security because the data for these indicators are obtained by recalling a shorter period of time [35,36]. We asked respondents to answer a brief questionnaire about the frequency of their household's consumption of eight food groups over the past seven days. Then, the HFCS was calculated based on the frequency of food consumed during the last seven days and the relative importance of food groups consumed [35,37], as expressed in Equation (1). The results range from 0 to 112; the maximum value implies that each of the food groups was consumed every day over the last 7 days.

$$\mathrm{HFCS_i} = \sum_{j=1}^{m} w_j f_{ji} \quad (1)$$

where $\mathrm{HFCS_i}$ is the food consumption score of i^{th} household; $j = 1, 2, \ldots$ m is the number of food groups consumed by the household; w_j is the weight assigned to each food group; and f_{ji} is the frequency of different food group consumed by household i over the last 7 days.

The HFCS is widely used to evaluate food security in populations, particularly providing evidence on which household groups need interventions. A higher HFCS is an indicator of improved nutritional outcomes and reflects households' greater financial capacity to purchase nutritious foods [38]. Therefore, the HFCS is used to assess the effectiveness of targeted nutritional interventions and programs and guide policies that aim to increase the affordability and accessibility of nutritious foods, particularly among the food-unsecure groups within a population.

The HDDS indicates the number of different food groups consumed during the past 24 h. It is constructed based on 12 food groups and if they have been consumed within the previous 24 h, assigning equal weight to each group [37]. The food groups are cereals (A), roots and tubers (B), vegetables (C), fruits (D), meat (E), eggs (F), fish (G), pulses (H), milk (I), oil (J), sugar (K), and miscellaneous (L). Each food group is assigned a score of 1 if consumed in the previous 24 h or 0 if not consumed during the last 24 h. The HDDS is calculated as indicated in Equation (2).

$$\mathrm{HDDS_i} = \mathrm{A} + \mathrm{B} + \mathrm{C} + \mathrm{D} + \mathrm{E} + \mathrm{F} + \mathrm{G} + \mathrm{H} + \mathrm{I} + \mathrm{J} + \mathrm{K} + \mathrm{L} \quad (2)$$

The HDDS ranges from 0 to 12, with a higher score indicating a more diverse diet. A higher HDDS implies improved household food access and nutritional adequacy. Its implications extend beyond household dietary habits to broader policies focused on food security, nutrition, and socio-economic development. Like the HFCS, it can be used as a household food access metric and it can determine the level of food security, especially in regions where food shortages are common. It also provides evidence on households with lower dietary diversity. This helps policymakers in devising targeted initiatives, including increasing the availability and accessibility of a variety of foods and creating nutrition awareness in such households. Improved household socio-economic status significantly increases the HDDS, indicating that policies that promote economic development by improving educational attainment, creating employment opportunities, and distributing income fairly can also improve the dietary diversity of households [39].

Adoption of irrigation technology: The adoption of solar pumps and the adoption of water harvesting pond-based irrigation are treated as binary variables. Adoption takes a value of 1 if the farming household adopts irrigation and 0 if the household does not adopt any type of irrigation.

Water productivity (yield in kg m^{-3}): As water availability for smallholder farmers becomes scarce, achieving more crop yields per drop of water is a key agricultural sustainability indicator. It is an indicator for comparing yields of the same crops among different production systems and farmers. In this study, it is used to depict differences in the productivity of crops under different financing schemes of solar pumps, namely government-supported, NGO-supported, and self-purchased, as well as among irrigated and rainfed production systems. It is defined as follows:

$$\mathrm{WP} = \frac{\mathrm{Yield}}{\mathrm{VW_d}} \quad (3)$$

where WP is water productivity (kg m^{-3}), Yield is the amount of crop harvest per season/annum (kg), and VW_d is the total amount of water delivered to the field in a season/annually (m^3).

Data on the yield of each crop were collected from the sample households. The volume of water delivered was calculated using parameters such as the duration of a single irrigation event and the frequency of irrigation per week, which were collected from the sample households, along with the flow rate of the pumps measured in the field. Equation (4) was used to compute the seasonal volume of irrigation water delivered.

$$VW_d = Q * t * f * Nw * \frac{3600}{1000} \quad (4)$$

where VW_d is the seasonal volume of irrigation water delivered (m^3), Q is the measured flow rate of the pump (L/s), t is the duration of a single irrigation event (hours), f is irrigation frequency per week, and Nw is the number of weeks per crop season. This indicator can be very useful to compare and benchmark WP values from other regions and to advice improvement.

Net water value (NWV): Water delivers an economic value to users in different sectors; for agriculture, NWV is suitable for the analysis and comparison of the net values delivered from water among different crops and households. With apparent water scarcity challenges and excelling climate variability and change, the economic value that water provides is becoming highly competitive among sectors. The value of agricultural water is, however, perceived to be very low compared to other competitive uses [40]. The net value of water refers to the net economic value derived from the use of water for crop production. This essentially is obtained by deducting all the costs from the benefits derived from the use of a unit volume of water. It is expressed as in Equation (5) below:

$$NWV = \frac{TB - TC}{VW_d} \quad (5)$$

where TB is the total benefit from harvest per season (in USD), TC is the total costs of production per season (in USD), and VW_d is the total volume of water delivered to the field in a season (m^3). Total benefits were determined from crop yield data and farm gate crop prices obtained from the sample households for each crop. The volumes of water used were calculated from field water delivery details such as flow rates, duration, and the frequency of water application using Equation (4).

Benefit–cost ratio (BCR): This is another variable used for comparing the profitability of different irrigated crops, production systems, and technologies among smallholder farmers and crops. The BCR is defined as the ratio of total benefits to total costs of irrigation practices. It is used both for comparison among different irrigated crops, as well as for different financing schemes and technologies associated with irrigation using solar pumps and water harvesting ponds. For this study, data on benefits were collected for one year, and hence one year of data was considered. While this could be a drawback, it provides a reasonable estimate of annual benefits over the useful period of the technologies. Similarly, variable production costs for one year were considered and assumed to adequately represent the annual costs over the useful period. The benefits are from the harvests and were determined from the data collected from the households as well as farm gate prices of crops, while the costs consist of all input and other production costs (collected from households). The BCR is computed as in Equation (6):

$$BCR = \frac{TAB}{TAC} \quad (6)$$

where TAB is the total annual benefits (is USD) and TAC is the total annual costs (in USD).

Adequacy of the irrigation water supply: This is an indicator of how adequately irrigation water demands are met by seasonal water supplies. As water is a major production factor, it conveys a key message concerning future interventions related to the water supplies needed to match demands. It is expressed as in Equation (7):

$$Adequacy = \frac{VW_d}{VW_r} \quad (7)$$

where VW_d is the volume of water delivered to the field in a season (m^3) for a particular crop, determined using Equation (4), and VW_r is the volume of seasonal irrigation water demand for a particular crop (m^3). While the VW_d was determined from parameters of field water supply, VW_r was determined using CROPWAT software version 8.0 [41,42] for each crop using crop and climate data.

2.4. Econometric Model

The adoption of irrigation technology is not exogenously determined, as farmers are not randomly assigned to either solar pump or water harvesting pond irrigation systems. Farmers may self-select to use the irrigation system or be included in an irrigation program by government or non-government organizations (NGOs), which can result in selection bias.

We used the endogenous switching regression (ESR) model to address the problem of endogeneity caused by selection bias [43–45]. The ESR approach is selected over the other quasi-experimental models as it addresses the endogeneity of irrigation technology adoption by considering both observed and unobserved sources of bias [46]. The ESR involves three steps. The first step involves formulating a probit model to analyze factors influencing the adoption of solar pumps and water harvesting irrigations. A farmer adopts irrigation technology to maximize benefits, which is expressed as the increased income earned from crop cultivation and improved food security.

If y_i^* represents the latent variable that represents the expected crop income or food security by adopting irrigation technology, it can be expressed as in Equation (8), which is the probit model.

$$y_i^* = \mathbf{x}_i'\beta + \varepsilon_i \tag{8}$$

$$y_i = \begin{cases} 1 \text{ if } y_i^* > 0 \\ 0 \text{ Otherwise} \end{cases}$$

where $\mathbf{x}_i'$ is a vector of exogenous factors, including the instrumental variable, and β is a vector of parameters to be estimated.

In this study, we used altitude as an instrumental variable because it is believed to meet the exclusion restriction, meaning it directly affects the adoption of irrigation technology while its effect on crop income and food security is mediated through the adoption of irrigation. Altitude has a strong correlation with the adoption of solar-powered irrigation and water harvesting systems. The uptake of solar-powered irrigation is higher in lowland areas where underground water is abundant, while water harvesting pond irrigation is predominantly adopted in highland areas where rainfall can be easily collected and water loss due to evaporation is minimal. In addition, altitude is an exogenous variable to the smallholder farmers as it is not influenced by their decision-making behavior.

The second step involves formulating a model that illustrates the relationship between an outcome variable (crop income and food security in this study) and a set of exogenous variables included in the probit model, excluding the instrumental variable.

$$w_i = z_i\theta + u_i \tag{9}$$

where w_i is the crop income or food security, z_i stands for a vector of exogenous regressors, θ is a vector of parameters to be estimated, and u_i is the error term with a mean of zero and constant variance.

In applying the ESR model, it is crucial to test for the existence of selection bias, which is considered a primary source of endogeneity. Therefore, we derived selection correction terms (inverse Mill's ratios) from the probit model specified in Equation 8 and included it as an additional regressor in the outcome equations [47,48]. The inverse Mill's ratio is computed as shown in Equation (10).

$$\hat{\lambda}_i = \begin{cases} \frac{\phi(x_i'\beta)}{\Phi(x_i'\beta)} \text{ if } y_i = 1 \\ -\frac{\phi(x_i'\beta)}{1-\Phi(x_j'\beta)} \text{ if } y_i = 0 \end{cases} \quad (10)$$

where λ_i refers to the inverse Mill's ratio, ϕ is the normal probability density function, and Φ is the normal cumulative distribution function. Finally, the outcome equation indicated in Equation (9) above is re-expressed in Equation (11).

$$w_i = z_i\theta + \rho\hat{\lambda}_i + \tau_i \quad (11)$$

where τ_i is the error term with a mean of zero and constant variance.

In the third step, we assessed the impacts of solar irrigation and/or water harvesting pond irrigation on the crop income and food security of farming households using the average treatment on the treated (ATT) [44,49,50]. ATT is the difference between the actual and counterfactual statuses of adopters of irrigation technology, as shown in Equation (12).

$$ATT = E(w_{1i}|z_i, y_i = 1) - E(w_{0i}|z_i, y_i = 1) = z_i(\theta_1 - \theta_0) + \hat{\lambda}_{1i}(\rho_1 - \rho_0) \quad (12)$$

where $E(w_{1i}|z_i, y_i = 1)$ is the actual status of irrigation technology adopters and $E(w_{0i}|z_i, y_i = 1)$ is the counterfactual status of adopters for not adopting irrigation technology.

3. Results and Discussion

In this section, an overview of key variables is provided through descriptive statistics. Then, agricultural productivity, net water values, benefit–cost ratio, and the adequacy of water supplies will be presented for different crops, financing schemes, and agricultural technologies under solar pump and water harvesting irrigation systems. Next, the comparisons of different clusters based on different socio-economic indicators of sample households will be presented. Factors affecting the adoption of irrigation technologies and their effect on the welfare of households will also be analyzed using the econometric method.

3.1. Descriptive Statistics

Table 1 presents a descriptive summary of the key variables used in this study. For the gender composition of the sampled households, 86% of them are male, while only 14% are female, indicating the predominance of male-headed households in our sample. The average age of the sampled households is approximately 45 years, and on average, the household head completed fifth grade. The average household size of the farming households in the study area is almost seven members. Out of these, about five members can supply their labor services to generate income for the household. The average dependency ratio is approximately 0.81, indicating that the number of working-age household members exceeds the number of non-working (dependent) household members.

The sampled households hold an average land size of approximately 1.18 hectares; of which about 0.31 hectares of land can be irrigated and about 0.85 hectares cannot be irrigated. The average areas of land irrigated with a solar-powered and water harvesting pond system are 0.17 and 0.20 hectares, respectively, which is less than one-fourth of a hectare. Even though the farmers have relatively extensive experience in crop farming, averaging about 27 years, their experience in irrigation agriculture is only about 5 years on average. The average annual income derived from agricultural production with the use of irrigation (including solar-powered systems and water harvesting ponds) and rain-fed agriculture is USD 1214.09. The average HFCS and HDDS of the sampled households are 59.53 and 7.27, respectively, exceeding the standard average values. This indicates that the food security status of the sampled farming households is relatively good.

Table 1. Descriptive statistics of key variables.

Variables	Mean	Std. Dev.	Min	Max
Gender (dummy)	0.86	0.34	0	1
Age (in years)	45.18	11.13	22	76
Years of schooling (in years)	5.05	4.00	0	17
Household size (in number)	6.84	2.29	2	15
Family labor (in number)	4.82	2.26	1	15
Total land (in hectare)	1.18	0.87	0.125	6
Irrigable land (in hectare)	0.31	0.47	0	3
Land irrigated with solar pump (in hectare)	0.17	0.14	0.00	0.63
Land irrigated with water harvesting pond (in hectare)	0.20	0.16	0.06	0.75
Non-irrigable land (in hectare)	0.85	0.68	0	5
Experience of crop farming (in years)	27.23	10.99	5	57
Experience of irrigation (in years)	4.91	6.84	0	33
Household crop income (in USD)	1214.09	1774.27	0	9164.12
HFCS (ranges from 0 to 112)	59.53	18.58	21.5	112
HDDS (ranges from 0 to 12)	7.27	1.59	4	11

3.2. Productivity, Net Water Value, Benefit–Cost, and Adequacy of Water for Solar Pump Irrigation Systems

3.2.1. Source of Irrigation Water and Extent of Irrigated Crops Using Solar Pumps

The sources of water for irrigation in the area are shallow hand-dug groundwater wells with depths ranging from 12 to 18 m (Figure 3). The wells were dug by the human labor of the farming households. Water is pumped from the wells using solar-powered pumps with typical flow rates varying between 0.2 and 1.0 L per second. To effectively utilize the solar energy, farmers usually irrigate during 9:30 a.m. to 3:30 p.m., and some farmers have storage tanks to irrigate some crops during the off-pump hours.

(**a**) (**b**)

Figure 3. (**a**) Typical shallow hand-dug well as a water source, (**b**) solar panel and elevated tank for water storage.

The area proportion of solar pump-irrigated crops in the area is shown in Figure 4. The total irrigated area of households considered for this study is 22.3 ha. The largest irrigated area is occupied by collard (19%), followed by avocado (18%), while onion, green pepper, and cabbage show 14% coverage (Figure 4). Collard is a main vegetable crop in the area for household consumption as well as for markets, while avocado has recently been widely grown due to its economic value for the farmers (both in local markets as well as for export).

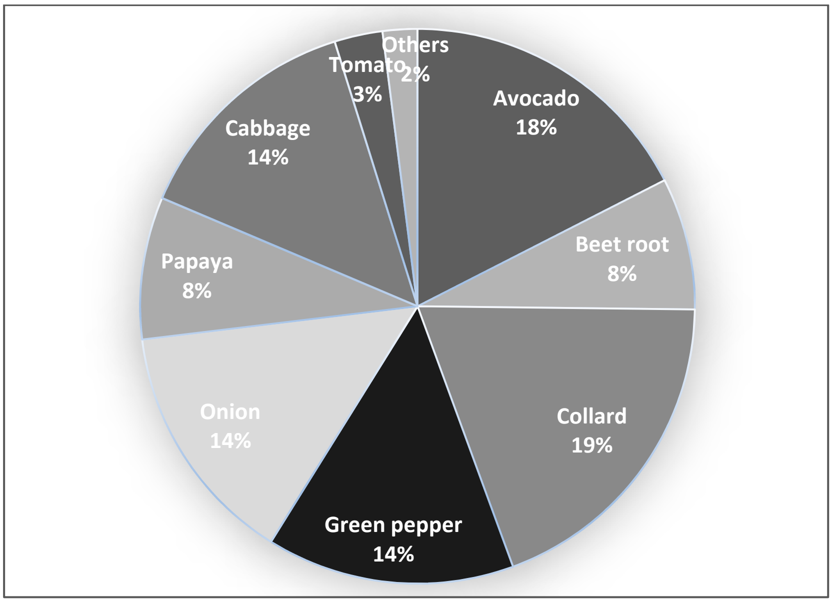


Figure 4. Area proportion of crops irrigated by solar pumps in the study area.

3.2.2. Water and Land Productivity

Higher values of water productivity (WP) for a particular crop may be attributed to the more efficient and productive use of water (more crop per drop). Yield is a function of several factors, including water, fertilizer inputs, farming practices, crop varieties, etc. However, WP values can still give an idea on what needs to be performed if it is low and what has improved in the case of satisfactory values. Table 2 presents WP values for ten irrigated crops under solar pumps. For most of the crops, the WP values are competitive compared to results from different parts of the world. For instance, the WP of irrigated avocado production in Mexico was reported to be 1.34 kg/m^3 [51], which is good compared with 1.26 kg/m^3 for this study. Water supply to most of the crops indicated that adequacy is less than 1.0, depicting deficit irrigation practices that could have contributed to higher water productivity. Particularly, the average WP values for tomatoes under this study were found to be significantly high (13.24 kg/m^3) compared to the results of WP of the crop under different field conditions. Wide ranges of WP values for tomatoes were reported in different parts of the world under deficit and normal irrigation practices, reaching as high as 74 kg/m^3 under intermediate deficit water applications, while very low values as low as 2 kg/m^3 were also reported at the field level [52–56].

While land productivity (LP) is also a result of various factors, higher values may often be attributed to better irrigation water management and the adequacy of the supply. The values of LP for irrigated crops are shown in Table 2. The LP for tomato (17.3 ton/ha) has been compared to yield levels in Ethiopia by studies like [57,58], while the productivity is lower compared to yields in several other parts of the world. For avocado, the LP is fairly competitive (10.4 ton/ha); but still, there is room for improvement, as per the results reported, for example, by [59,60].

Table 2. Water and land productivity of crops for solar pump irrigation systems in the study area.

Crop	LP (in kg/ha)	WP (in kg/m^3)
Avocado	10,421	1.26
Beet Root	5690	0.72
Carrot	4375	0.31
Collard	9014	0.01
Green Pepper	3378	0.38
Onion	9214	2.34
Papaya	8758	0.75
Lettuce	1224	0.07
Cabbage	10,123	1.46
Tomato	17,333	13.24

Except for the LP values for the avocado and tomato crops, which are in line with the ranges of research results, the values for other crops are much lower, with high yield gaps and, thus, room for improvement. While the reasons could be partly accountable to the misuse of water (inadequate management and shortage), there are several other required improvements in technology and inputs to fill the yield gaps and thus enhance the LP, as well as the WP.

3.2.3. Net Value of Irrigation Water

The net value of water is a measure of the monetary value that is derived from a unit volume of water used for irrigation. The net value in USD was calculated as the difference between the total benefits and total costs for a particular crop per unit volume of irrigation water applied. The costs include all costs for acquiring the land, input costs, and labor. The benefits are from the market value of the agricultural produce. The net water values per irrigated crop for crops with positive net water values are shown in Table 3. A very useful result from this analysis is that from the ten irrigated crops, only five of them, namely avocado, green pepper, onion, cabbage, and tomato, have net positive benefits, thus positive net water values. This means that it is only these five crops that are worth feasibly cultivating with irrigation using solar pumps, while the other five crops derive negative net water values, meaning that they are not feasible for irrigated production under the current production systems. The reasons are to do with sub-optimal inputs, low productivity, and market challenges for these crops. Substantial improvements are needed to enable these crops to attain higher yields and thus positive net water values. A key finding of this study depicts that solar irrigation systems need to be provided with other agricultural technology bundles (such as seeds, fertilizers, as well as improved agronomic practices) if the systems are to be successful.

Table 3. Crops with positive net water vales in the study area under household solar pump irrigation.

Crop	Gross Water Value, USD/m^3	Net Water Value, USD/m^3
Avocado	0.65	0.21
Green Pepper	0.99	0.21
Onion	1.04	0.28
Cabbage	1.08	0.22
Tomato	4.02	1.53

Of the five economically viable crops, tomato has the highest net water value of 1.53 USD/m^3, while all the other four crops have lower water values of similar magnitude. Avocado, green pepper, and cabbage have similar net water values, while their gross water values varied, depicting different levels of production costs. Onion has a higher net water value following tomato; so, the two crops constitute the most valuable crops for production using solar pump irrigation. Net water values of irrigated crops are widely based on production systems and market conditions. Global average net water values of crops ranged between USD 0.05 and 0.25 per m^3 [61]. The NWV of crops in Table 3 exhibit net water values in or very close to this range, which compares well to the values of water reported. Several other studies, on the other hand, reported much higher values of water (ranging 0.23–1.75 USD/m^3) around the world under similar conditions, such as [62] in Mexico; [63] in Colombia; [64] in Ethiopia; and [65] in Iran. This reveals that the net water values of the current study are much lower and need efforts to improve. Tomato is an exception, mainly due to good market demands and prices as well as higher productivity due to better production systems adopted by farmers. Tomato is grown by a small number of farmers but with good agronomic practices and, hence, good yields.

Net values of water for solar pumps were also evaluated by the three financing schemes: NGO-supported, government-supported, and private purchase for aggregates of all crops (see Table 4). Solar pumps supported by the NGO and private purchases exhibit positive net water values, while those supported by the government have an overall negative net water value. The households who were supported by Farm Africa (NGO) practice more effective production systems, as there are better follow-ups and support services provided. On the other hand, those supported by the government (Agricultural Transformation Institute), particularly those in Ada'a, have not reached their full production scale for crops, such as avocado, and do not use the solar pumps effectively. This is, therefore, an attribute contributing to lower benefits and thus negative net water values. Households who purchased the solar pumps by their own means also experienced limitations in technology adoption and thus have lower production, resulting in negative net water values.

Table 4. Net value of water by financing scheme for solar pump irrigation.

Financing Scheme	Average Net Annual Benefit per Household (in USD)	Average Annual Water Volume Delivered per Household (in m^3)	Overall Average Net Water Value (in USD/m^3)
NGO-supported	513.18	2237.4	0.23
Government-supported	−58.61	3181.7	−0.02
Private purchase	146.93	2260.6	0.06

3.2.4. Benefit–Cost Analysis by Crops and Financing Scheme

Benefit–cost analysis is a well-established approach for assessing the financial viability of investments in irrigation development. In this study, the benefit–cost ratio (BCR) was used to assess the viability of irrigated crop production by solar pumps for two cases: (i) per each crop and (ii) per financing scheme for solar pumps. For financial viability, the benefits must be greater than the costs (positive BCR) for a particular crop or multiple crops for project viability. From the analysis based on crops (across all households), only five crops, namely avocado, green pepper, onion, cabbage, and tomato, have BCRs greater than 1.0 (ranging 1.91 to 2.99) (Table 5), which implies that these crops are economically viable for irrigated production under the current production systems using solar pumps and that farmers have the incentive to do it. In general, for these five crops, the BCRs are superior to several studies of conventional small-scale irrigation investments in several areas [66,67]. On the other hand, all the other crops have a BCR of 1.0 or less, which shows that they are not viable for irrigated production. Of all the crops with a BCR greater than 1.0, tomato is the most economically viable crop for irrigation using solar pumps (BCR = 2.99), followed by onion and cabbage. The underlying factors for the economic non-viability of irrigation with solar pumps for some crops could be multiple. However, the main ones are (1) market conditions (lower market values as well as limited access to well-established market centers); (2) crop diseases and high input costs; and (3) the optimal use of inputs and agronomic practices by smallholders and thus lower productivity. As the adoption of solar pumps expand in Ethiopia and other SSA countries, the results from the BCR analysis provides useful information for decision-making in crop selection, as well as designing interventions.

Table 5. Benefit–costs ratio for irrigated crops using solar pumps at the study area.

Crop	BCR
Avocado	2.45
Beet Root	0.45
Carrot	0.45
Collard	0.77
Green Pepper	1.91
Onion	2.77
Papaya	1.02
Lettuce	0.21
Cabbage	2.53
Tomato	2.99

Note: Only five crops, namely avocado, green pepper, onion, cabbage, and tomato, are financially viable for irrigation with household solar pumps.

Benefit–cost analysis was also performed by aggregating the benefits and costs associated with each crop per financing scheme (Figure 5). The farmers who were supported by the NGO generally exhibited the largest BCR, 2.34, followed by that of private purchase with BCR, 1.28. Overall, irrigated crop production under the two financial schemes (NGO support and private purchase) is found to be financially viable under the existing production systems. On the other hand, on average, government-supported farmers (BCR of 0.85) were found to be financially non-feasible under the existing production. The reasons for solar pump irrigation practices under government support having a BCR less than 1.0 could be multiple, including lower/immature yield and production scale for orchard crops, less effective utilization of the solar power for irrigation, limitations in technology and support services, etc.

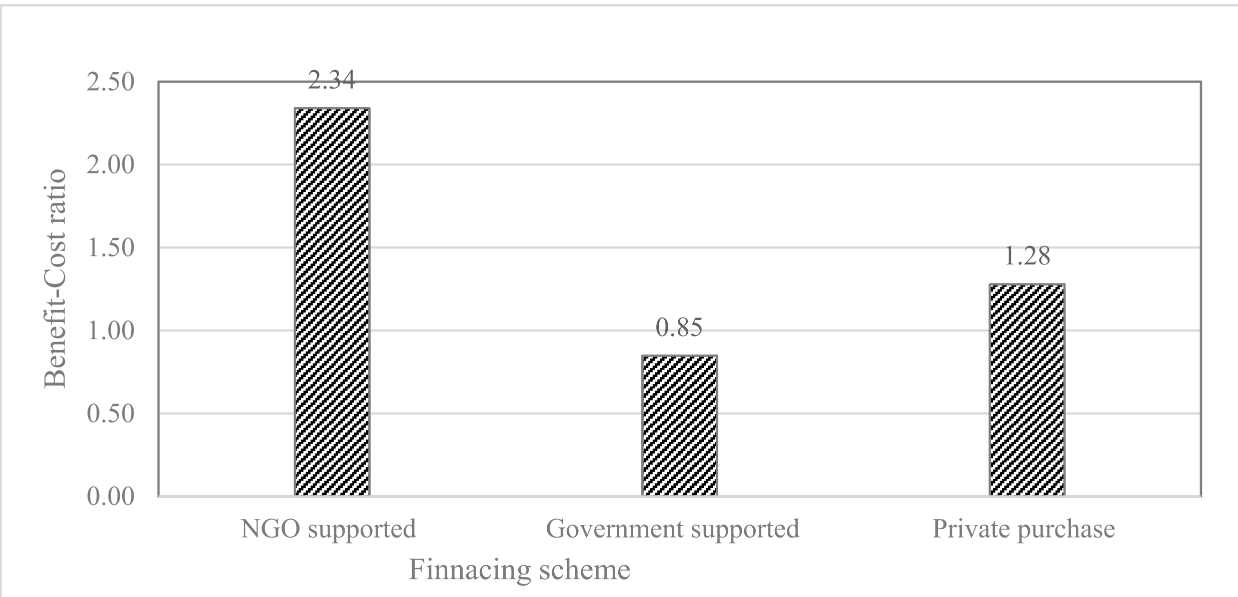


Figure 5. BCR for solar pumped irrigation by financing scheme.

3.2.5. Benefit–Cost and Net Water Value per Technology Bundles

Agricultural technologies, in addition to water, play a decisive role in increasing yields and benefits. In this study, efforts were made to evaluate the impacts of the adoption of different technologies on land productivity, net water value, and the BCR. Seven technologies were considered, i.e., intercropping (C), row planting (P), crop rotation (R), improved seed/seedlings (I), chemical fertilizer (F), organic fertilizer (O), and agrochemicals (A). Eight technology bundles were identified, as shown in Figure 6, to evaluate and compare their impacts on productivity and economic returns. The analysis was performed for all farmers adopting the technology bundles across all the financing schemes. Farmers have different levels of adoption of technologies. It was observed that farmers use at least two technologies and a maximum of six. In general, on average, farmers that use at least four technologies attained relatively better values of the BCR. Results also indicate that the higher the number of technologies adopted, the better the outputs on both the BCR and net water value (NWV). Notably, farmers adopting the technology combinations PRIFA and PRIFOA attained higher values on both indicators (Figure 6). Improved seed (I) is one of the most important examples that need to be supplied with solar pump systems. Farmers in Ethiopia have not yet gone so far in the use of organic fertilizers, thus a combined use of chemical (F) and organic (O) fertilizers has resulted in better outputs. Row planting (P) is also an important farming practice for better outputs, which most farmers are adopting already. The key technologies that demonstrate significant impacts and need to be bundled with solar pump irrigation systems are improved seed, chemical fertilizers, organic fertilizers, row plating, agrochemicals, and crop rotation.

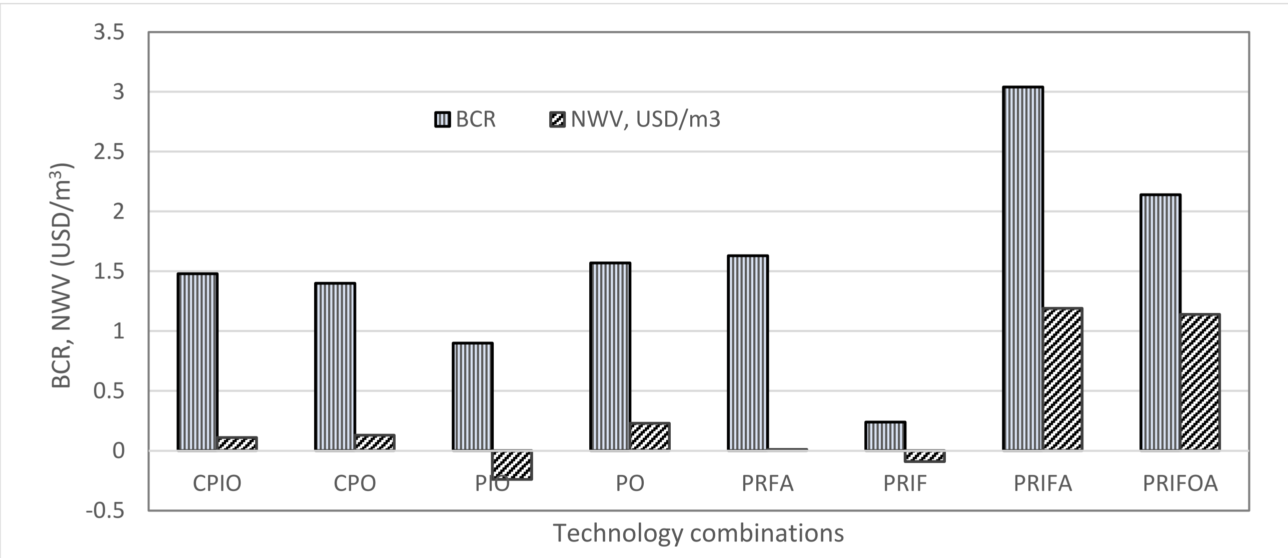
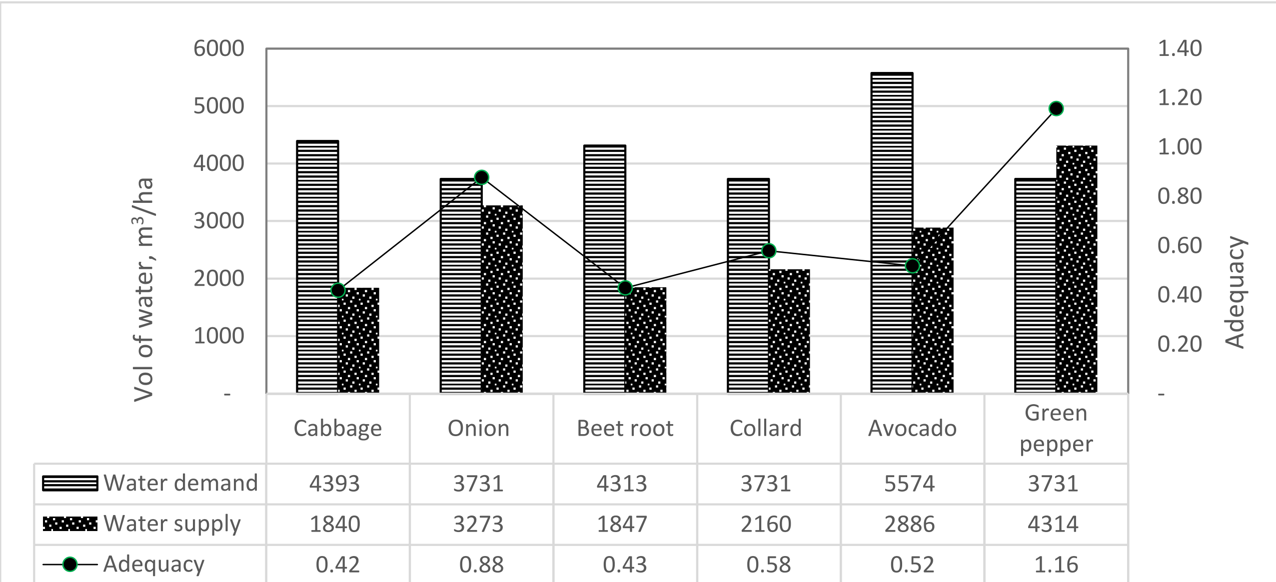


Figure 6. Agricultural technology bundles and their impacts on BCR and net water value. Note: C = intercropping, P = row planting, R = crop rotation, I = improved seed/seedlings, F = chemical fertilizer, O = organic fertilizer, and A = agrochemicals.

3.2.6. Adequacy of Water Supplies

Adequacy is an important indicator of field water delivery performance [68–70]. For six crops that are widely and commonly irrigated by the majority of the farmers, for all three financial schemes, the seasonal irrigation water demands and volume of applied water were determined per ha of land. Irrigation water demands were determined by applying an irrigation efficiency of 80%, which suffices for smallholder solar pump irrigation systems where water is applied in proximity to the pumping site. It is observed that the adequacy of water supplies is all less than 1.0., except for green pepper, showing that crop production takes place under deficit irrigation (Figure 7). For several crops, only about half of the water demands were supplied; hence, achieving higher yields is possible for these crops if water supplies are improved. The reason for reduced water supplies may not be necessarily due to water shortages but a lack of knowledge on the right amount of water. This also implies that appropriate extension services need to be provided as part of solar pump irrigation technology bundles. On the other hand, as the landholding sizes and area under each crop are very small, farmers have limited opportunity to increase their yields from land expansion through deficit irrigation practices. Thus, ideally, full irrigation is required for maximum benefits and deficit irrigation is not advised under the existing conditions.



	Cabbage	Onion	Beet root	Collard	Avocado	Green pepper
Water demand	4393	3731	4313	3731	5574	3731
Water supply	1840	3273	1847	2160	2886	4314
Adequacy	0.42	0.88	0.43	0.58	0.52	1.16

Figure 7. Overall adequacy of irrigation water by irrigated crops.

The adequacy of water supply by financing schemes can also give an idea on the differences in the field irrigation practices under the three schemes. NGO-supported farmers have the lowest overall adequacy, while the government-supported ones have the highest adequacy (Figure 8). This may be attributed to ill advice that had been given to NGO-supported farmers to save water, which resulted in significant deficits. This implies that NGO-supported farmers have a special large potential to increase yields, hence benefiting from increasing water supplies to match demands. Government-supported farmers can also increase their yields and benefits by supplying more water, but have a smaller opportunity of closing yield gaps only through water supplies; thus, other technologies and inputs are also equally important.

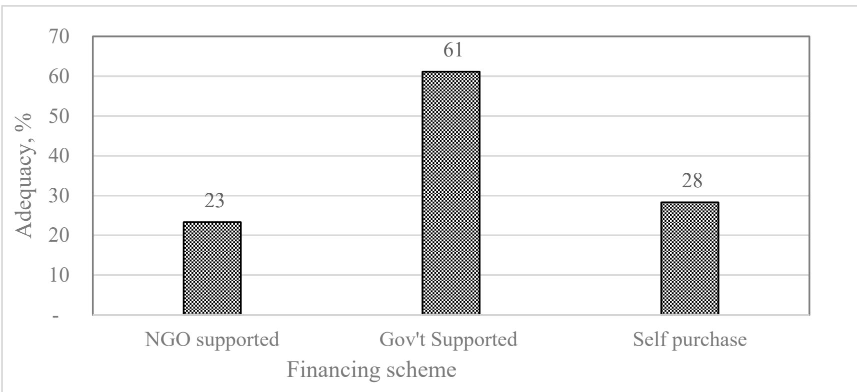


Figure 8. Overall adequacy of irrigation water supply under solar pumps by financing scheme.

3.3. Productivity, Adequacy, and Economic Indicators of Irrigation Using Water Harvesting Ponds

There are two kinds of water harvesting ponds being used for irrigation—small-sized lined ponds (sizes ranging 75 to 185 m^3) and large-sized unlined ponds (sizes ranging from 278 to 5786 m^3) (Figure 9). As the water is harvested during the rainy season and is ideally used for irrigation during the dry season, storage volume is one of the key determinants of sustainable irrigation and productivity using water harvesting ponds. However, due to insufficient storage volumes, water storage ponds are often used as supplementary sources of irrigation.

(**a**) (**b**)

Figure 9. Typical water harvesting ponds: (**a**) large and unlined, (**b**) small and lined.

3.3.1. Adequacy and Productivity of Irrigation Water Supplies from Ponds

Household water harvesting ponds often meet a fraction of the total water demands of the crops grown and used to supplement rainfall [71–73]. In this study, it is found that for all crops, the total water requirement of the crops met by irrigation from the ponds is less than 23%, while the demands met by rainfall range from 77% to 93% under a 100% supply of the water demands of crops (see Table 6). On average, the adequacy of water supplies from the ponds are only 0.14 (14%), while the other 86% is from rainfall. In cases of much less rainfall, production would take place under deficit irrigation. The size could have been increased to increase irrigated areas as well as to grow crops fully with irrigation from the ponds. So, only part of the total seasonal water demand is met by irrigation from the ponds. Therefore, net irrigation water productivity is only a fraction of the gross water productivity (rainfall plus irrigation) and is assumed to be in a proportional manner to the fraction of total water demands met by irrigation from the ponds. Net WP values are given in Table 6.

Table 6. Adequacy and net water productivity for irrigation from water harvesting ponds.

Crops	Seasonal Water Delivery from Ponds, m^3/ha	Total Seasonal Irrigation Demand, m^3/ha	Adequacy	Net WP of Irrigation Water, kg/m^3
Beet root	673.9	2985	0.23	0.66
Collard	214.9	2985	0.07	0.39
Carrot	488.1	2985	0.16	2.04
Onion	481.4	2985	0.16	1.51
Potato	386.9	3800	0.10	0.63
Cabbage	370.3	3514.0	0.11	0.40
Total	2615.4	19,254.0	0.14	

3.3.2. Net Water Value (NWV)

The values of water for water harvesting ponds were calculated for the amount of irrigation water supplied from the ponds. Four of the six main crops grown using water harvesting ponds have negative net water values. Small-scale water harvesting ponds were reported to be feasible solutions to enhance the production of smallholder farmers through supplemental irrigation around the world [74,75], but the success depends on several factors. For the current study, the four crops (collard, potato, cabbage, and beetroot) are not financially viable under the existing production systems using water harvesting ponds. This is of course true considering the development costs of the ponds, as well. The total production costs for these crops are greater than the total benefits, for which the causes are associated with (i) low yields due to the limited use of technologies, (ii) inadequacy of stored water, (iii) poor farming practices, (iv) poor markets, and (iv) economies of scale (small land sizes which are not profitable enough to provide technological bundles). The two financially viable crops for production are onion and carrot, with net water values of USD 0.28/m^3 and USD 0.09/m^3, respectively.

3.3.3. Benefit–Cost Analysis

Households with large ponds have the opportunity to cultivate irrigated crops over a larger area, thus attaining larger yields/benefits. Therefore, the BCR for larger ponds is higher than that of small ponds (see Table 7). However, the overall BCR for both small and large ponds under the existing production systems is less than 1.0 (financially not viable) considering the construction costs of the ponds. Due to seepage losses, even the volume of water from large ponds is insufficient to substantially increase yields and benefits, and input uses are sub-optimal. However, there is potential to enhance the feasibility of water harvesting ponds. A study by [76] reveals that the feasibility of water harvesting ponds can be enhanced by an appropriate sizing of ponds, improving inputs, farm practices, markets, etc. The higher BCR for larger size ponds clearly demonstrates that these are more beneficial regardless of higher excavation costs. So, for sustainable benefits, efforts need to be made to expand the implantation of larger sized ponds by providing required supports to farmers.

Table 7. BCR of water harvesting ponds by size.

Pond Type	Total Costs, USD	Total Benefits, USD	BCR
Small	21,682.77	12,202.26	0.67
Large	25,711.20	18,862.00	0.95

The BCR was also determined for different technology combinations being used by households practicing irrigation from water harvesting ponds. Table 8 indicates that a higher BCR is associated with a larger number of technology combinations used by farmers, notably PRIFA, PRIFO, and PRIFOA.

Table 8. BCR for water harvesting ponds for different technology bundles.

Technology Bundle	TC (in USD)	TB (in USD)	BCR
PRF	305.17	285.71	0.94
PRIF	379.18	206.39	0.54
PRIFA	437.45	360.12	0.82
PRIFO	390.56	427.18	1.09
PRIFOA	524.11	636.88	1.22
PRIO	448.33	160.71	0.36
PRO	625.10	184.15	0.29

Note: P = row planting, R = crop rotation, I = improved seed/seedlings, F = chemical fertilizer, O = organic fertilizer, and A = agrochemicals.

3.4. Factors Influencing the Adoption of Solar Pump and Water Harvesting Pond-Based Irrigation

Agricultural technology, including irrigation technology, is influenced by socio-economic, institutional, and environmental factors [77,78]. In this study, the probit model was used, where the adoption of solar irrigation and water harvesting pond irrigation are treated as dependent variables to identify significant factors influencing the adoption. The results of the probit regressions are presented in Table 9. Following the important empirical literature [79,80], ten explanatory variables were used in the probit regression to determine their effect on farmers' adoption of the two types of irrigation in the study areas. As shown in Table 9, the Wald test rejected the null hypothesis that all regression coefficients are simultaneously equal to zero, implying that the model is a good fit. A multicollinearity test was conducted using the Variance Inflation Factor (VIF), which is less than 10 for each regressor. The regression results show that the gender, age, and education level of the household head, family labor, irrigable land size, irrigation farming experience, altitude, and regional dummies have significant effects on the adoption of irrigation technology. The age and education level of the household head, irrigable land size, irrigation farming experience, and regional dummies positively influence the adoption of solar pump irrigation, while the gender of the household head and altitude have negative effects. On the other hand, the adoption of water harvesting pond irrigation is positively influenced by family labor, irrigable land size, irrigation experience, and altitude and is negatively affected by the age of the household head.

Table 9. Factors influencing the adoption of solar pump and water harvesting irrigation technologies.

Variables	Solar Pump Irrigation Adoption	Water Harvesting Pond Irrigation	Adoption of Both Irrigation Type
Gender	−0.887 ** (0.409)	1.054 (0.804)	−0.427 (0.331)
Age of household head	0.029* (0.016)	−0.081 ** (0.032)	−0.002 (0.013)
Years of schooling	0.131 *** (0.041)	−0.090 (0.057)	0.061 * (0.034)
Dependency ratio	−0.216 (0.174)	−0.060 (0.300)	−0.304 * (0.171)
Family labor	−0.021 (0.080)	0.318 ** (0.128)	0.112 (0.069)
Irrigable land size	1.539 ** (0.680)	1.848 ** (0.885)	2.789 *** (1.066)
Irrigation experience	0.159 ** (0.068)	0.221 ** (0.092)	0.202 ** (0.087)
Oromia dummy	2.500 *** (0.914)	–	3.227 ** (1.312)
Central Ethiopia dummy	2.752 *** (0.940)	–	3.238 ** (1.317)
Altitude	−0.006 *** (0.001)	0.001 ** (0.000)	0.000 (0.000)
Constant	5.331 *** (2.503)	−2.967 * (1.677)	−3.904 ** (1.561)
Pseudo R^2	0.55	0.66	0.59
Wald Chi^2	43.53	33.11	29.29
Prob > Chi^2	0.000	0.000	0.001

Values in brackets represent robust standard errors. ***, **, and * represent significance levels at 1%, 5%, and 10%, respectively.

The gender of the household head has a negative influence on the adoption of solar irrigation, indicating that male-headed households are less likely to adopt solar-powered irrigation. This is due to the government and NGO favoring women in accessing solar irrigation because of the significant burdens and challenges that women face, especially in developing countries [81].

Age plays a key role in influencing farmers' decisions to adopt agricultural technologies, either positively or negatively [50]. Likewise, in this study, we found that the age of the household head has a positive influence on the adoption of solar pump irrigation but has a negative effect on the adoption of water harvesting pond irrigation. The positive relationship can result from the fact that older households have more crop farming experience, have accrued more assets, and developed wider social networks [50,82]. This enables older farmers to have a higher likelihood of adopting solar pump irrigation than younger farmers. On the other hand, the negative relationship between age and irrigation technology adoption can be explained by the fact that as farmers grow older, they become more reluctant to adopt new technologies due to being more risk-averse and lacking the physical ability to carry out farm operations with short planning horizons [83–85].

The education level of the household has a positive impact on the adoption of solar-powered irrigation, but is found to be insignificant in water harvesting pond irrigation. The positive sign indicates the importance of education in embracing solar-powered irrigation. Educated farmers are more likely to be equipped with the necessary skills and knowledge, increasing their chances of adopting new agricultural technologies, such as solar irrigation. Refs. [79,86] also reported similar findings from their respective studies.

In Ethiopia, most farmers do not hire labor or pay wages for agricultural activities. Instead, they rely on family labor, which also plays a crucial role in influencing the adoption of agricultural technology. Family labor is found to be insignificant in the adoption of solar pump irrigation, as this type of irrigation does not require extensive human effort. This finding supports a study by [80] that documents the insignificant effect of family labor on solar pump irrigation. On the contrary, water harvesting pond irrigation requires physical human effort, and, hence, its adoption is significantly and positively influenced by family labor, as indicated by this study. This result corroborates the findings of [87], indicating that having more labor within a household would increase the likelihood of effective farm management. Likewise, ref. [85] explained that households with more family members involved in labor are more likely to adopt water harvesting irrigation because of the labor-intensive activities involved in constructing the ponds, using the water for irrigation, and cultivating crops.

Land is a crucial resource in agricultural production, and numerous studies have indicated that land size significantly influences farmers' decisions regarding the adoption of agricultural technologies [79,82,86]. Table 9 shows that as the size of irrigable land increases, farmers are more likely to adopt both solar and water harvesting pond irrigation, which is consistent with the findings of the study by [86].

The other important factor positively influencing the adoption of both irrigation technologies in this study is farmers' experience in crop farming. This implies that the more experience farmers have in crop farming, the more likely they are to adopt irrigation technology to gain higher benefits associated with crop cultivation. Greater experience in crop farming enables farmers to accumulate more capital, empowering them to explore the benefits associated with adopting irrigation technology. This, in turn, enhances the adoption of irrigation technology. This study reached the same conclusion, which aligns with the finding reported by [85].

The geographical location and administrative regions, as indicated by altitude and regional dummies, also influence the adoption of irrigation technology. The adoption of solar irrigation is negatively affected by altitude, while the adoption of water harvesting pond irrigation is positively influenced by altitude. In other words, an increase in altitude promotes the adoption of water harvesting irrigation and decreases the adoption of solar pump irrigation. This makes sense, as most solar pump users are located in lowland areas where there is relatively more availability of underground water, while water harvesting users are located in highland areas where the depletion of water resources is low. Farmers in the Oromia and Central Ethiopia regions are more likely to adopt solar irrigation compared to farmers in the Sidama region.

3.5. Welfare Impacts of Solar Pump and Water Harvesting Pond Irrigation

Mean difference tests and counterfactual analysis are applied to evaluate how irrigation technologies (such as solar and water harvesting ponds) affect the welfare of smallholder farmers in the study area. Table 10 presents a comparison of household crop and food security indicators between adopters and non-adopters of the irrigation technologies. As shown in the table, users of irrigation, whether through solar-powered or water harvesting ponds, exhibit a higher crop income, HFC, and HDDS, with statistically significant differences. This suggests that the adoption of irrigation technology enhances the income and food security of farmers in the study area. Farmers can increase their earnings from farming activities by utilizing solar pumps for irrigation [88]. Ref. [28] also found that using irrigation through water harvesting ponds can increase farmers' income, resulting in higher earnings compared to income generated from rainfed agriculture.

Table 10. Crop income and food security of adopters and non-adopters of irrigation technologies.

Irrigation Technology	Welfare Indicators	Mean		Mean Difference
		Non-Adopters	Adopters	
Solar irrigation	Crop income (in USD)	613.65	2115.70	−1502.06 ***
	HFCS	52.26	65.67	−13.41 ***
	HDDS	6.67	8	−1.33 ***
Water harvesting pond irrigation	Crop income (in USD)	613.65	1166.37	−552.72 **
	HFCS	52.26	72.58	−20.32 ***
	HDDS	6.67	7.7	−1.033 ***
Solar and water harvesting pond irrigation	Crop income (in USD)	613.65	1869.12	−1255.48 ***
	HFCS	52.26	67.46	−15.21 ***
	HDDS	6.67	7.92	−1.26 ***

Note: Non-adopters are those cultivating crops using only rain-fed agriculture. HFCS and HDDS represent household food consumption score and household dietary diversity score, respectively. *** and ** are significance levels at 1% and 5% respectively.

The financing options for solar-based irrigation affect smallholder farmers' crop income, food security, and overall well-being. Farmers in the study area acquired solar-powered irrigation through one of three finance schemes: self-purchase, government support, and NGO support. By clustering the solar-powered irrigation based on these finance schemes, it is important to analyze the impacts of solar-powered irrigation on crop income and food security for farmers. Table 11 demonstrates that farmers who receive support from NGOs and the government earn more crop income compared to those who invest in solar panels using their own money. However, when it comes to food security measures, farmers who receive support from NGOs or purchase their own panels are in a more favorable position than those who are assisted by the government.

Table 11. Crop income and food security by finance schemes of solar pump irrigation.

Finance Scheme for Solar Panels	Mean of Welfare Indicators		
	Crop Income (in USD)	HFCS	HDDS
Self-purchase	1319.53	63.93	7.8
Government support	1942.97	58.71	7.47
NGO support	2710.87	71.44	8.48

The farmers who received assistance from NGOs have much higher crop earnings and food security compared to those in the other two schemes. This is because the farmers who obtained solar panels through NGOs also obtained free essential agricultural inputs like improved seeds, fertilizers, and other inputs. As a result, they use a combination of more technologies. As seen in Table 12, farmers who receive assistance from NGOs use a minimum of four agricultural technologies, while those who purchase their solar panels or are supported by the government may use two technologies. From the table, it is also evident that approximately 67% of farmers who adopted a bundle of seven agricultural technologies are supported by an NGO, while about 67% of farmers who adopted a bundle of two agricultural technologies purchased solar panels with their own funds. This suggests that smallholder farmers can enhance their crop income and food security by adopting a combination of multiple agricultural technologies. The limited use of agricultural technologies by self-purchase and government-supported farmers has to do with two issues: (i) cost of technologies—at least some of the technologies are associated with costs which farmers have to make decisions about—and (ii) a lack of dedicated support on technology bundles, as even dedicated capable farmers have knowledge barriers for the use of some of the technologies.

Table 12. Adoption rate of agricultural technology bundle by solar panel finance schemes.

Agricultural Technology Bundles	Number of Technologies in the Bundle	Rate of Adoption		
		Self-Purchase	Government Support	NGO Support
CPRIFOA	7	16.67	16.67	66.67
CPRIOA, CPRFOA, PRIFOA	6	18.75	31.25	50
PRIFA, PRIFO, PRIOA, PRFOA, CPRFA	5	29.41	29.41	41.18
PRIO, PROA, CPIO, PRFA, PRIF, CPOA, CPRI	4	10	40	50
PFO, PIO, PRA, PRF, CPF	3	60	40	-
PO, CO	2	66.67	33.33	-

Note: C = intercropping, P = row planting, R = crop rotation, I = improved seed/seedlings, F = chemical fertilizer, O = organic fertilizer, and A = agrochemicals.

Agricultural technologies such as intercropping, row planting, crop rotation, improved seeds, chemical and organic fertilizers, and agrochemicals are essential for irrigating crops using solar-powered pumps and water harvesting ponds. Farmers use different combinations of these technologies for solar-powered and water harvesting pond irrigation. As demonstrated in Table 13, the agricultural technology bundles with more technologies tend to be associated with a higher crop income and HFCS for both solar pump and water harvesting pond irrigations. This suggests that the adoption of a combination of a range of agricultural technologies, along with solar pumps and water harvesting pond irrigation systems, is necessary to enhance the welfare of smallholder farmers in the study area.

Table 14 presents the estimates of the treatment effects, particularly the ATT of irrigation technologies, on household crop income and food security indicators. The ATT of the welfare indicators, including crop income and the HDDS for solar-powered irrigation, is positive and statistically significant. However, the ATT of the HFCS is statistically insignificant. This implies that adopters of solar irrigation would have had lower crop income and lower dietary diversity scores if they had not adopted solar-powered irrigation. The impact on household income is greater than the impact on the HDDS. Household crop income increased by 104.41%, while the HDDS increased by 5.82% due to the adoption of solar pump irrigation. Therefore, the adoption of solar-based irrigation enhances the income earned from crop production and the dietary diversity of farming households in the study areas. Similar results were demonstrated by [1,88], indicating that the adoption of solar pump irrigation leads to increased production and income from irrigated crops among smallholder farmers in Ethiopia. Ref. [89] also found that solar-powered irrigation is a promising intervention that can enhance farm income and food security for farmers in India.

Table 13. Technology bundles adoption and their impacts on household welfare.

Technology Bundle	SP	WHP	Crop Income (in USD)		HFCS		HDDS	
			SP	WHP	SP	WHP	SP	WHP
CPRIFOA	✓		4124.93	-	78.58	-	8.83	-
PRIFOA	✓	✓	2749.97	847.03	66.68	86.33	8.29	8.33
CPRIFO		✓	-	767.40	-	68.5	-	7.5
PRIFO	✓	✓	2270.36	1504.68	75.33	69.35	9.33	7.6
PRIOA	✓	✓	1343.10	177.23	71	71	9.33	7
PRIFA	✓		829.25	-	77.71	-	8.43	-
PRFOA	✓		1123.33		60.67	-	7	-
PRFO		✓	-	531.69	-	72.5	-	8
PRIO	✓		2481.50	-	50.67	-	7.33	-
CPIO	✓		2130.28	-	68.5	-	8	-
PRA	✓	✓	205.76	354.46	34	51	6	7

Note: C = intercropping, P = row planting, R = crop rotation, I = improved seed/seedlings, F = chemical fertilizer, O = organic fertilizer, and A = agrochemicals, SP = Solar pump irrigation, WHP = water harvesting pond irrigation, HFCS = household food consumption score, and HDDS = household dietary diversity score. The symbol ✓ indicates the technology bundle was applied by farmers in SP and/or WHP irrigation system.

Table 14. Treatment effects of solar pump irrigation on household welfare.

Type of Irrigation System	Welfare Indicators	Adopting (1)	Non-Adopting (2)	ATT = (1)–(2)
Solar pump irrigation	Crop income (in USD)	2115.70 (147.19)	1035.03 (33.60)	1080.67 *** (150.98)
	HFCS	65.67 (1.21)	66.08 (1.01)	−0.41 (1.57)
	HDDS	8 (0.09)	7.56 (0.08)	0.44 *** (0.12)
Water harvesting pond irrigation	Crop income (in USD)	1166.37 (164.28)	229.56 (66.88)	936.80 *** (177.38)
	HFCS	72.58 (2.51)	46.84 (3.12)	25.74 *** (4.01)
	HDDS	7.7 (0.164)	7.09 (0.159)	0.61 ** (0.228)
Solar pump and water harvesting irrigation	Crop income (in USD)	1869.12 (112.66)	524.08 (40.65)	1345.04 *** (119.76)
	HFCS	67.46 (0.90)	64.80 (1.50)	2.66 (1.75)
	HDDS	7.92 (0.05)	7.71 (0.10)	0.21 ** (0.11)

*** and ** are significance levels at 1% and 5% respectively. Values in brackets represent robust standard errors.

Moreover, Table 14 reveals that the ATT of the household crop income is positive and statistically significant for water harvesting irrigation, implying that the adoption of water harvesting pond irrigation enhances the income earned from crop production in the study areas. Refs. [28,85] also found that the adoption of water harvesting irrigation increases household farm income. The water harvesting irrigation not only boosts crop revenue but also improves household food security in the study area, as indicated by the positive and statistically significant ATT for the HFCS and HDDS. A positive ATT indicates that the adopters of water harvest pond-based irrigation would have a lower HFCS and HDDS if they had not adopted it. This result aligns with the finding of [85], documenting that the adoption of rainwater harvesting technology has a positive and significant effect on food security. The impacts of water harvesting pond irrigation are not the same on crop revenue and indicators of food security. Water harvesting irrigation increases crop income by 408.09%, the HFCS by 54.95%, and the HDDS by 8.60%. Lump-summing the two irrigation technologies also shows a positive and significant impact on the welfare indicators. The ATTs are positive and significant, indicating that both solar and water harvesting pond irrigations significantly contribute to enhancing farming households' farm income and food security in the study area.

3.6. Challenges and Interventions for Solar Pump and Water Harvesting Pond-Based Irrigation Systems

This study identified challenges that hinder the adoption and scaling up of solar pump and water harvesting pond irrigation systems in the study area. The main challenges of solar-powered irrigation systems are classified into (i) technical challenges, (ii) financial challenges, and (iii) agricultural input and output market challenges. Ref. [90] addressed most of these challenges by reviewing studies that focus on barriers to the adoption of solar-powered irrigation by smallholder farmers in Sub-Saharan Africa. Ref. [91] also highlighted these challenges as determinants for farmers' decisions to adopt solar pump irrigation systems.

Technical challenges: These primarily include the low pumping capacity of solar pumps due to smaller panel sizes; the inaccessibility of solar panels and spare parts in the local markets and shortage of technicians; issues related to the inappropriate location of wells, as a result of which flooding can occur during rainy season; clogging and damage of drippers and drip lines for farmers combining the systems with family drip systems, etc. A small pumping capacity causes farmers to be unable to irrigate areas as large as they demand. As a result, some farmers prefer to use diesel pumps to irrigate larger areas of land. Furthermore, because solar pumps have reduced capacity in the mornings and evenings due to cloud cover, farmers are obliged to irrigate for a few hours of the day. This leads to water losses due to excess evaporation from the soil and thus inefficient water usage. Moreover, some crops, such as cabbage, may not thrive with daytime irrigation [92]. The inaccessibility of solar panels and their spare parts in the local markets, along with a shortage of technicians also pose significant challenges. As solar-powered irrigation technologies are relatively new, the solar panels, spare parts, and post-installation services, such as repair and maintenance, are not available locally. Farmers confirmed that when solar pump irrigation systems are damaged, they do not know where to access the spare parts. In addition, technicians are not readily available locally, and even when they are available, they charge high maintenance fees. The location of wells is also very important, as a poor location often results in the collapse and flooding of the water wells. Interventions to these challenges include (a) the right sizing of solar pump capacities by considering irrigable plot sizes that farmers have for future installations, (b) availing solar pumping technology unit dealers in regional and district towns, and (c) undertaking thoughtful capacity building to local experts to avail solar pump/panel maintenance services locally.

Financial challenges: Smallholder farmers' adoption of solar-powered irrigation is hindered by financial related factors, including a lack of affordable and customized financial services, as well as issues with collateral and lengthy process to access credit. Currently, financial institutions provide financial products and services that are not affordable for smallholder farmers. Furthermore, the financial system fails to provide tailored financial services, including Sharia-compliant services, in rural areas. The lack of accessible and customized financial services puts smallholder farmers at risk when they seek to obtain solar panels through alternative means. For instance, some farmers have bought solar panels for irrigation by making deals with service providers. The farmers are required to pay half of the cost upfront in cash and the rest on credit, with a commitment to repay within a year. Nevertheless, as the agreement is not legally binding, the service providers compel the farmers to settle the entire amount before the deadline. If farmers do not pay the full cost by the specified deadline, the service provider deactivates the solar panel connections and discontinue all services. The bureaucratic processes within financial institutions that make it difficult to obtain credit are also slowing down the uptake of solar-powered irrigation systems. Many farmers expressed the desire to purchase solar panels with adequate pumping capacity through credit from financial institutions. However, the lengthy process of obtaining credit requires multiple trips, causing the farmers to become weary, wasting their farming time and eventually leading them to abandon the endeavor. The religious factor, particularly the Sharia principle, also hinders borrowing from conventional financial institutions among Muslim communities due to the limited accessibility of Sharia-compliant financial services. In order to address these challenges, interventions include (a) providing innovative financing solutions tailored to the underserved groups, such as smallholder farmers and Muslim communities, who have limited access to conventional financial services; and (b) promoting financial literacy among these groups.

Input and output market challenges: Ref. [90] highlighted that market challenges for crops produced with the use of solar pumps, along with constraints on agricultural inputs, hinder the adoption and development of solar pump irrigation. These challenges and constraints are not limited to solar-powered irrigation; they also negatively affect water harvesting pond irrigation. Based on information from the FGD, key informants, and farmers, the primary challenge in the output market is the lack of standardization and grading of agricultural products produced using irrigation technologies. Farmers do not add value to their products as they sell the same ones harvested from the field. Other challenges in the output market include the dominance of brokers, the absence of developed local markets, limited market information, the perishable nature of products, and price fluctuations in agricultural outputs. These challenges were also reported by [93–95]. The challenge with agricultural inputs is due to the lack of easily accessible organic fertilizer and agrochemicals when needed, and their prices are continually rising, making them unaffordable for farmers. The following interventions can be used to address the following issues with agricultural inputs and output: (a) improving market access by expanding infrastructure in rural areas and providing farmers with timely market information; (b) strengthening agricultural cooperatives and farmers' organizations; and (c) designing and implementing government policies that support subsidies for essential agricultural inputs, incentive mechanisms and premium subsidies for crop insurance services.

This study also examined challenges associated with using water harvesting ponds for irrigation, which varied in size. The large-sized ponds were used without being lined with a geo-membrane or any other material. Farmers with large-sized ponds mentioned the excavation cost and sedimentation problems as the main challenges of adopting water harvesting pond irrigation. The costs of excavation using heavy machinery are exorbitant, making them too expensive to afford. Also, these ponds face considerable sedimentation problems sourced within the farm and outside. Even though the farmers try to protect the ponds with good grass buffers, sedimentation is still a challenge. On the other hand, small-sized ponds are manually constructed with the help of farmers' social networks and cooperation. Hence, the monetary expenditure is relatively minimal. Some farmers use geo-membrane lining, while others use the pond without any lining. For farmers with ponds without a geo-membrane, water is lost through seepage, causing the pond to fail to retain water throughout the entire crop period. Refs. [96,97] also addressed seepage losses from earthen ponds along with various lining materials. Furthermore, farmers reported that wild animals often encroach the pond in search of water and damage the geo-membrane lining as the pond lacks a strong fence. Interventions for solar pumps include (a) proper pond design and sizing (larger ponds are more beneficial, but have more development costs), (b) installing ponds with appropriate sediment arresting facilities and methods, (c) minimizing seepage losses (lining), and (d) providing protections of the premises of the ponds with grass buffers.

4. Conclusions

Solar-powered and water harvesting pond irrigation systems have been demonstrated to be promising irrigation water sourcing methods for smallholder famers in the Central Rift Valley, Ethiopia, enabling them to boost their production. Farmers using these systems have the opportunity to reach better productivity of their lands and increase their food security and incomes. The counterfactual analysis, specifically the Average Treatment Effect on the Treated (ATT) of farmers' crop income and household dietary diversity, is positive and statistically significant for both solar-powered irrigation systems and water harvesting ponds. Therefore, it is concluded that solar pump and water harvesting irrigation systems have proven to be useful to boost crop income and improve food security for smallholder farmers. However, this study was conducted for smallholder farmers using shallow groundwater of a maximum depth of 20 m and household water harvesting ponds. While the results are valid for similar contexts in Africa and other developing nations, validity may be limited for different contexts (deeper groundwater levels, larger farming systems, etc.).

Although solar pumps and household water harvesting ponds have shown overall positive outcomes on the financial benefits and welfare indicators of households, the benefits highly vary with the types of irrigated crops, the financing mechanisms, and other farming technology bundles, such as seeds, fertilizers, agronomic practices, etc., supplied with the irrigation technologies. For smallholder farmers to be successful by investing in these systems in Ethiopia as well as SSA, appropriate crop selection is key, as demonstrated in this study for crops having a BCR greater than one and a positive NWV. In the area, solar pump systems were acquired via three financing schemes: NGO-supported, government-supported, and self-purchase, for which farmers' outputs were evaluated against three indicators; namely WP, NWV, and BCR. Overall, NGO-supported farmers demonstrated superior outputs for each indicator, mainly due to the better provision of technology bundles (through not optimum), while this is very limited in the case of government-supported and self-purchase farmers. It was revealed that as the number of agronomic practices in the technology bundle (such as row planting and crop rotation) and agricultural inputs (improved seeds, fertilizers, and agrochemicals) increase, output indicators (WP, BCR, NWV) also increase. The size of the ponds has also emerged as one of the main factors affecting farmers' benefits. The small ponds have resulted in reduced impacts, while the large ones have higher impacts on both household food security and financial viability.

As solar pumps minimize some of the challenges with diesel pumps, such as the lack of access to fuel, maintenance, and spare parts, there is an increasing level of acceptance among smallholder farmers. However, there are factors hindering adoption and success in solar pump irrigation technologies, including technical, access to finance, agricultural input, and output market challenges. The scaling out and up of the irrigation technologies require addressing these constraints. Due to higher initial costs of solar pumping systems and large ponds, farmers' access to affordable and customized credit services through innovative business models is key for a wider adoption and scaling up of these irrigation technologies. Encouraging farmers to adopt agricultural technology bundles for optimum production through the provision of subsidies and other incentive mechanisms is also essential. Furthermore, the government need to continue to support rural development in order to boost the markets for agricultural inputs and products.

Although this research provides valuable evidence on the agricultural productivity and welfare impacts of solar-powered and water harvesting irrigation systems, it has some methodological limitations. It relies on a small sample size and uses cross-sectional data, leaving out unobserved factors that influence the adoption, agricultural productivity, and welfare impacts of these irrigation technologies. The study also does not examine how the irrigation systems can help reduce poverty among smallholder farmers and mitigate the impacts of climate change. Therefore, future research could examine the economic, social, and environmental contributions of the solar-powered and water harvesting irrigation systems by conducting experiments among the smallholder farmers.

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Institutional Review Board Statement: IWMI Research Ethics Coordinator (REC) for the Institutional Review Board (IRB), located at 127 Sunil Mawatha, Pelawatte, Battaramulla, Sri Lanka, has provided ethical clearance to move forward with this project activities under the assumption that the project will in its research activities clearly inform all project participants of any surveys, interviews, etc. about the project, and obtain 'informed consent' from any potentially vulnerable participants who will provide information. Therefore, as long as participants' informed consent is obtained, this study is exempted from ethical review and approval.

Informed Consent Statement: The participants (smallholder farmers) were informed about the purpose of this study. They gave their consent and voluntarily participated in the interview. The interview followed the established standards and guidelines. Throughout the study, the data was kept confidential. The results of the study were presented in summary form, with no personal information disclosed.

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