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Simulating Potential Impacts of Solar MajiPump on the Economy and Nutrition of Smallholder Farmers in Sub-Humid Ethiopia

Jean-Claude Bizimana [1,*], Belainew B. Yalew [2], Tewodros T. Assefa [3], Sisay A. Belay [3], Yonas M. Degu [4], Tafadzwanashe Mabhaudhi [5,6], Manuel R. Reyes [7], P. V. Vara Prasad [7] and Seifu A. Tilahun [3,8,*]

1 Department of Agricultural Economics, Texas A&M University, College Station, TX 77843-2124, USA
2 Faculty of Business and Economics, Bahir Dar University, Bahir Dar, Ethiopia; belayecon@gmail.com
3 Faculty of Civil and Water Resource Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia; ttaffese@gmail.com (T.T.A.); sisayasress@gmail.com (S.A.B.)
4 Faculty of Mechanical and Industrial Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia; yonasmitiku2000@gmail.com
5 International Water Management Institute, Pretoria 0083, South Africa; t.mabhaudhi@cgiar.org
6 Centre for Transformative Agricultural and Food Systems (CTAFS), University of KwaZulu-Natal, Pietermaritzburg 3209, South Africa
7 Sustainable Intensification Innovation Lab, Kansas State University, Manhattan, KS 66506, USA; mannyreyes@ksu.edu (M.R.R.); vara@ksu.edu (P.V.V.P.)
8 International Water Management Institute, Accra GA078, Ghana
* Correspondence: jean-claude.bizimana@ag.tamu.edu (J.-C.B.); s.tilahun@cgiar.org or satadm86@gmail.com (S.A.T.)

Abstract: Irrigation is widely considered a potential means to improve agricultural productivity, nutrition, and income, as farmers can carry out farming and production year-round. However, the feasibility of irrigation technologies is highly dependent on the long-term economic return farmers achieve. Solar-based irrigation could address the challenges of underinvestment in irrigation within Africa. Evidence on the economic viability of the adopted solar pumps such as MajiPump is very scant and focused on ex post evaluation. This study evaluated the income and nutritional feasibility of solar-powered irrigation using the MajiPump in sub-humid Ethiopian highlands using the farm simulation (FARMSIM) model and compared it with the manual pulley system. Results from the FARMSIM model show that farmers' adoption of Maji solar pump technology to grow vegetables is economically feasible with financial support such as credit or loan for initial and capital investment to acquire the pump. The average profit under the solar MajiPump, drip irrigation, and conservation agriculture was 3.6 times higher than that of the baseline scenario. While the pulley technology provides the same amount of irrigation water to grow vegetables, its feasibility is limited due to high labor costs and time, estimated to be more than seven times the baseline. The simulation results show that the alternative scenarios' nutrition level has improved relative to other scenarios and met the minimum daily average nutrition requirement level for proteins, iron, and vitamin A but fell short in fat, calcium, and calories. The results suggest that farmers who adopt improved small-scale irrigation technologies (solar MajiPump and drip system) have a higher potential to increase production and income from irrigated crops and improve their nutrition if part of the income generated is used to purchase supplemental food for their nutrition.

Keywords: economic feasibility; FARMSIM; irrigation technology; nutrients intake; solar-based irrigation

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1. Introduction

Despite worldwide efforts to improve food security in recent years, the number of people affected by food insecurity increased when conflicts and pandemics rose [1]. The reasons for this include the agricultural industry being traditionally subsistent and rainfed, suffering from rainfall variability and frequent drought [2,3]. Consequently, crop failures are unavoidable, and food shortage often turns into food insecurity, affecting the livelihoods of many farmers, especially in Africa [4,5]. With such complexities, donors and researchers advocate expanding irrigation and agriculture technologies to produce more foods to increase income and nutrition.

If sustainably intensified, agriculture in Africa could significantly contribute to food and nutritional security and play an indispensable role in building a healthy society [6]. By 2030, the projection of this food insecurity could likely decrease from 35% to 22% for sub-Saharan Africa, assuming the production continues to improve [7]. One approach is the expansion of small-scale irrigation with nutrition-sensitive crop production, which has been regarded as a promising approach to ensuring food and livelihood security under climate change and population growth [6,8]. Various studies, such as Xie et al. [9] and Passarelli et al. [10], indicated that small-scale irrigation could boost crop yield and income benefits by at least 50%, where most of the income goes to smallholders.

Water availability for irrigation is, however, a limiting factor in Africa, and only 6% of all agricultural land is under irrigation [11]. Similarly, in Ethiopia, only about 4 to 5% of the potential arable land is under irrigation, while over 6 million hectares are suitable for irrigation [3]. The primary causes for the limited national irrigation coverage include a lack of water storage, inadequate conveyance structures, limited access to technology, a limited energy source to pump water, limited options for gravity-fed systems, and fewer enabling settings for credit and finance. [3,12]. Moreover, surface water is usually considered the major source of existing irrigation systems in Africa. Still, these sources need lots of investment [13], and are affected easily by climate and other changes that lead to low flow during the dry period [14] and water quality degradation.

Worqlul et al. [3] and Gowing et al. [15] indicated that groundwater could be an alternative freshwater source for irrigation; however, groundwater use is mostly limited to the domestic water supply. The restricted use of groundwater for irrigation is due to technology constraints, which entail new development, operational costs (including energy), and a lack of understanding of the resource dynamics [15]. Recent studies have shown a reasonable amount of groundwater storage in Ethiopia that can be used for irrigated agriculture [16]. Tilahun et al. [17] showed shallow groundwater's potential to increase food security at least during the first three months in a sloping aquifer. However, this can extend to 6 to 8 months in valley bottom aquifers. To tap this potential from shallow groundwater and benefit farmers, access to efficient and cost-effective water-lifting technology is a major enabling factor [18].

As access to electricity appears less available for the rural community [19], manual and fuel-based water-lifting technologies are preferred by smallholder farmers. Limited access to fuel, high operation (fuel), and maintenance costs are becoming barriers to the use of motor pumps (diesel or petrol), in addition to their adverse effect on the environment [18]. On the other hand, using manual technologies such as pulley or rope and washer water-lifting technologies for irrigation from shallow groundwater sources is labor-intensive, putting more burdens on women and children [20,21]. The labor productivity of such technologies is also low [22]. Thus, high production costs may reduce the margin of farmers' benefit. Several studies suggested using solar-powered pumps as an alternative and sustainable irrigation technology, increasing labor and water productivity and environmental sustainability [23,24].

However, few scientific studies have evaluated the economic, nutritional, and technical feasibility and environmental sustainability of solar pumps or other water-lifting technologies in Ethiopia [25–27]. The utilization of solar pumps for irrigation presents a range of potential environmental impacts, offering both positive and negative consequences. On the positive side, these pumps significantly enhance water use efficiency in agricultural practices [28]. By harnessing renewable solar energy, they minimize reliance on fossil fuels, reducing greenhouse gas emissions associated with traditional fuel-based pumps [24].

However, if not managed sustainably, an increased dependency on groundwater for irrigation poses the risk of more groundwater use and depletion [9,24]. Over-extraction of groundwater for irrigation purposes could lead to a decline in the water table, potentially resulting in long-term environmental and socio-economic implications. Furthermore, the use of solar pumps may exacerbate soil salinity concerns. Hence, while solar pumps offer a renewable and environmentally friendly alternative, their implementation requires careful management with temporal variability and spatial availability information to mitigate adverse environmental effects.

Risk and uncertainty in agricultural enterprises must be accounted for in a comprehensive economic and nutritional analysis of water-lifting technologies. Schmitter et al. [28] found high profits related to solar pumps for irrigation. In contrast, Bizimana and Richardson [29] found lower benefits from the solar pump than the pulley and motor pumps due to higher initial investment costs and low flow rates. For nutritional benefits, both studies have shown a positive effect on household nutrition and food security. Thus, a comprehensive potential evaluation of solar pumps' economic and nutritional benefits is required to promote their extensive adoption in Ethiopia.

This study focuses on the new solar MajiPump as a case study in Ethiopia. MajiPump is a submersible photovoltaic solar pump that lifts water from ponds and shallow groundwater wells. The pump is powered by direct solar power generated from a 24-volt, 200-watt monocrystalline solar panel and delivered to its brushless DC motor via an electric cable. The open flow capacity of the pump is 36 L per minute. The pumping system comprises only three major components: a solar panel, a float switch connected to the pump, and a solar MajiPump. As a result of these design features and fewer parts, the operation is simple and almost maintenance-free. Because there is no battery, the pumping system costs will be less, and it becomes environmentally friendly since there is no disposal of battery chemicals. During the sunshine hour, the pump will pump and store water in a water tank lifted 1.5 m from the ground to create a head for the irrigation system. Assefa et al. [30] evaluated the water-lifting and discharge capacity of the MajiPump under different environmental and agroecological conditions. They worked well with a maximum of 19 m depth of water level for the shallow groundwater.

Unlike prior research, this study seeks to comprehensively assess the economic and nutritional advantages of applying solar pumps with drip and conservation agriculture, particularly within its use in irrigation for vegetable farming. While previous studies have examined aspects of general water-lifting technologies, including solar pumps, little existing research in the literature specifically delves into a comprehensive evaluation of a specific solar pump when integrated with conservation agriculture and drip system for their economic and nutritional benefits. Therefore, the main aim of this study is to evaluate the impacts of adopting agricultural technologies, mainly the solar MajiPump, drip irrigation system, and conservation agriculture practice, to grow irrigated vegetables on household nutrition and farm profitability in Dengeshita, Ethiopia. It addresses a notable research gap and advocates for the widespread adoption of sustainable agricultural practices in developing nations, taking these cases from Ethiopia.

2. Materials and Methods

2.1. Study Area

The experimental study was conducted in the northern Ethiopia highland sub-humid area, mainly in one of the three small-scale irrigation intervention sites from the Appropriate Scale Mechanization Consortium (ASMC) of the Sustainable Intensification Innovation Lab of Feed the Future program. The three sites were Dengeshita (36.85° E, 11.32° N), Affesa (36.83° E, 11.25° N), and Alefa (37.06° E, 10.62° N) kebeles. These kebeles are the intervention areas to pilot the solar MajiPump irrigation technology in Amhara regional state, Ethiopia (Figure 1). For this study, we selected Dengeshita, which had both the solar Maji pump and pulley water-lifting technologies interventions. The 57 km^2 Dengishta kebele or village is located within the Blue Nile Basin of the Lake Tana area and drains to the Gilgel Abay River. The mean annual rainfall is 1745 mm, with 90% from May to October. The elevation of the site ranges from 2036 to 2400 m. The shallow groundwater has a potential of dry period irrigation with a 20% of annual rainfall being a recharge [31].

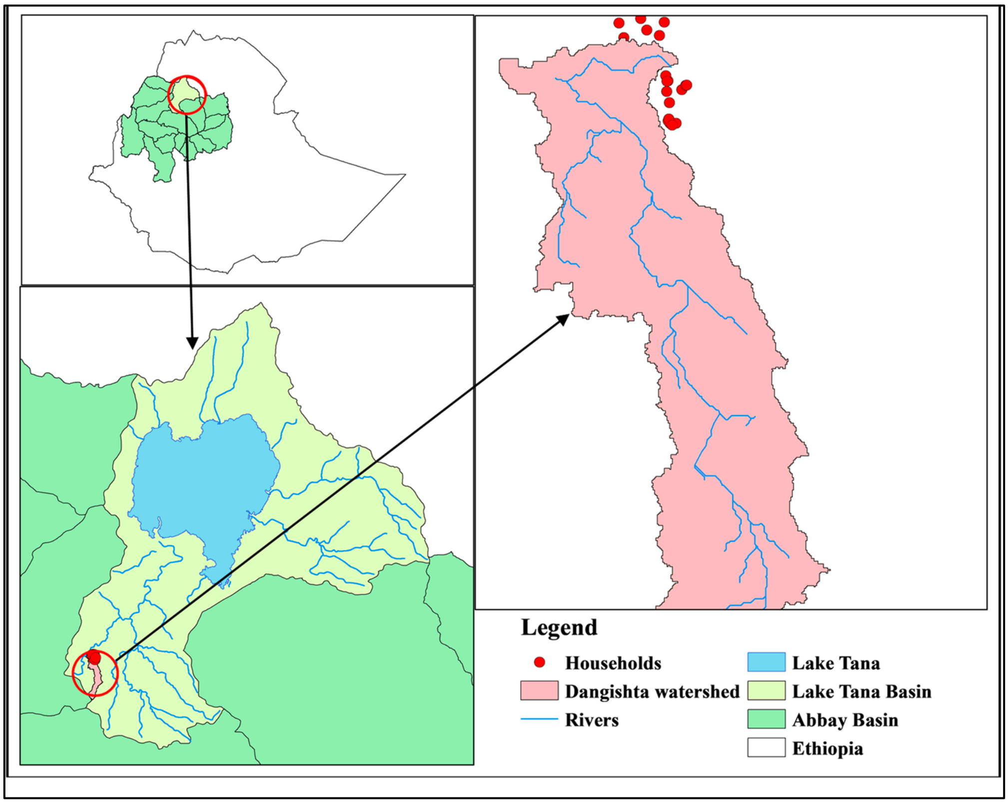

Figure 1. Study sites in the sub-humid Ethiopia (**top left**), Lake Tana watershed with the lake (**bottom left**) and Dengeshita watershed (**right**).

The predominant farming system in the study region is crop–livestock farming, with rainfed production covering 65 percent and irrigation covering only 1 percent. Thirty-two percent (32%) of the watershed is covered by grassland and eucalyptus trees. Farm households' livelihood relies on producing cereals and high-value cash crops in rainy and dry seasons. The dominant rainfed crops are maize, millets, barley, wheat, and teff [30], whereas onion, garlic, potato, cabbage, pepper, tomato, and potato are the dominant irrigated vegetables [32] during the dry period from October to May. Most farm households raise cattle, small ruminants, apiculture, and poultry. Livestock is raised to meet draught power requirements, produce milk, and breed replacement to generate income. The areas are endowed with shallow groundwater wells and open surface water (i.e., rivers) that offer an opportunity for irrigation if small-scale irrigation technologies such as mechanical or solar-powered pumps and water application systems are adopted in the region.

Fertilizer use in Dengeshita was documented during an assessment survey in 2017 by the Bahir Dar University in collaboration with Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI). Rainfed crops are fertilized in divided doses using di-ammonium phosphate (DAP), urea, and organic compost fertilizers. The first application consisting of DAP and compost occurred when crops were planted at the beginning of the rainy season in May or early June. The second application of urea was in July. The average applied P fertilizers from all sources was 27.4 kg P ha^{-1}, and N fertilizer was 76 kg N ha^{-1}.

2.2. Data Collection

In the first stage, the Dangila district was selected purposely based on the existence of irrigation technology. In the second stage, information from the agricultural office of the selected district was used to select one kebele (small unit of administration unit under a district). The kebele is called Dengeshita, located 80 km south of Bahir Dar. The watershed (Figure 1) is also named after the kebele name. Ten farmers with solar photovoltaic MajiPump technology and drip irrigation adopters were applying small-scale irrigation in this kebele. Finally, a proportional random sampling technique was employed to select 50 representative farm households not using the solar Majipump and drip technology. The primary data were collected through field experiments from 10 treated (MajiPump technology adopter) farm households among 60 farm households surveyed in Dengeshita. The survey was conducted in February 2019 to obtain data on agricultural inputs, agricultural productions, and socio-economic conditions of households as part of the ASMC program. Primary data for both baseline and alternative scenarios (use of solar MajiPump and pulley technologies) input were collected from 60 selected farm households.

The primary data on farm input information relating to crop, livestock, liability, investment in solar photovoltaic MajiPump water-lifting technology, input use, yield, price of inputs and products, crop pattern, and operating cost were drawn from the selected representative farm households in February 2020. A summary of inputs and technology procurement costs and crop of production for Dengeshita is found in Appendix A. The baseline input information was complemented by a household survey collected by IFPRI in 2017 under the ILSSI project. The results from this survey show that about 15% of plots surveyed are irrigated, 6% of households obtain water using a diesel pump, and 80% use a hand bucket and hose.

In this study, secondary data from governmental and non-governmental organizations and expert opinion were considered for historical data, mainly for the price of inputs and outputs. The price of the agricultural product was the farmgate price that the farmer sold their product to the first economic agent. The market value of crops produced by farmers using command technology was used to calculate the benefit. Official interest rate and the discount rate from the national bank of Ethiopia were used for calculating interest cost and discounting factor.

2.3. Modelling Methods and Procedures

2.3.1. FARMSIM Model Description

FARMSIM is a Monte Carlo farm-level simulation model that concurrently evaluates a baseline and an alternative technology for a farm. The model is programmed in Microsoft® Excel and uses the Simetar add-in program to include risk and estimate parameters for price and yield distributions, simulate random variables, estimate probability distributions for key output variables (KOVs), and rank technologies [29]. FARMSIM is set up to recursively simulate a five-year planning horizon for a varied agricultural and livestock farm, repeating the simulation for 500 iterations. To simulate each loop, a new sample of random values is drawn. The resultant simulated values for each KOV define the empirical probability distributions for the baseline and alternative farming scenarios. The probability distributions for the baseline and alternative technologies are compared so that the decision-makers can graphically understand the likely consequences of implementing alternative technologies. The FARMSIM model has four major components: crop, livestock, nutritional, and financial.

The model predicts the production and consumption of up to 15 crops based on locally produced and consumed crops. The model estimates annual productivity and herd dynamics across a five-year planning horizon for cattle, oxen, chickens, sheep, goats, and swine. The livestock section, particularly the cattle group, is extremely thorough. It considers the various age and gender cohorts along the value chain. It evaluates animal and animal source product output, consumption, and sale due to improved animal production methods. To account for risk, the model simulates yield parameter distribution and stochastic price, estimates key output variables (KOVs) distribution over five years, and ranks alternative technologies [29].

The FARMSIM model compares simulated values of KOVs of alternative scenarios technology or intervention with the baseline scenario to assess the technology's possible economic and nutritional impacts (e.g., solar MajiPump). FARMSIM uses similar equations to model the baseline and alternative farming technology scenarios; the variation in the outcome (e.g., profit, family income, and nutrition) is exclusively attributable to technology and their anticipated yield distributions.

2.3.2. Economic Analysis

Over the five-year time horizon, economic analysis of FARMSIM model results focuses on key output variables (KOVs) such as annual net cash farm income (or profit), benefit–cost ratio (BCR), internal rate of return on investment (IRR), and net present value (NPV) of technology.

Revenue and costs are separately computed to estimate the net economic benefit or net cash farm income (NCFI). Revenue was calculated as a product of farm products (crop and livestock) and their corresponding market price. Then, total costs were estimated as a composite of variable and fixed costs. These costs comprise costs of input such as labor, fertilizer, chemical, weeding, land preparation, harvesting, irrigation, and other costs.

The net present value (NPV), internal rate of return (IRR), and benefit–cost ratio (BCR) are the major metrics used to evaluate the profitability of SSI technologies that require capital investment in the form of water pumping equipment (solar MajiPump), irrigation tools, and water storage facilities. The difference between the discounted value of farm benefits and cost over five years was used to calculate the net present value at the farm household level. The IRR is the discount rate that results in a zero NPV. If the IRR of a project surpasses the cost of capital (i.e., the return on capital invested elsewhere), it is accepted. The project is not advised if the IRR is less than the cost of capital. The BCR is the ratio of the present value of the benefits to the present value of the costs. If this ratio is greater than one, the project is recommended.

2.3.3. Nutrition Analysis

The nutrition study assesses changes in nutrition self-sufficiency in daily calorie, vitamin A, protein, iron, calcium, and fat consumption. It compares them to the daily minimum need per adult equivalent to identify nutrient shortfall or surplus [29].

Total calories, protein, fat, calcium, iron, and vitamin A available to the farm family were computed by multiplying the total kilogram of produced and purchased crops for consumption and donated food by their respective nutrient weight. Similarly, the nutrition from livestock was determined using the nutrient value of the family's animal intake, which includes cattle, oxen, milk, butter, poultry, eggs, mutton, and lamb. The total nutrition level of the household was calculated by adding up food consumption (crop and livestock), including donated food, and comparing it to the FAO daily minimum necessary standard for adult equivalent [33–35].

Graphical and analytical tools were used to represent financial and nutrition outcomes and rank the risky alternative scenarios. The estimated results were represented using the cumulative distribution function (CDF) and stoplight chart to accurately reveal the probable outcome compared to a single estimation point. CDF graph represents the cumulative density of the given outcome, and the further to the right the CDF graph is from the origin, the higher the performance. The stoplight chart graphs depict the probabilities of each scenario/technology being less than a lower cut-off value (the lowest mean) and greater than an upper cut-off value (the highest mean). The probabilities of the economic indicator of each technology exceeding the uppercut-off value are presented numerically and assigned the green color. The yellow segments represent the probability that values fall between the lower and upper cut-off values, and the red represents the probability that the values are below the lower cut-off.

To simulate the key output variables (KOVs), the FARMSIM model uses various equations to compare the impacts of the technology. Equations used to compute the KOVs of this study are detailed in Bizimana and Richardson [29].

2.4. Baseline and Alternative Scenarios

Several scenarios, including a baseline and alternative farming systems, were simulated for five years using the FARMSIM model to analyze the impact of solar MajiPump water-lifting technology on income and nutrition in Ethiopia's sub-humid area [29]. FARMISM considers changes in crop and livestock production, crop and livestock mix, cost of technology and related inputs, farm product prices, annual family food consumption and food purchase, and animal feed requirement when modeling technology's economic and nutritional impacts. The scenarios were solely selected based on the experimental trials and interventions conducted under the ASCM project mentioned above, which mainly included the use of the solar Maji pump, drip irrigation and tillage practices in Dengeshita.

The scenario analysis looks at how water-lifting technology (pulley and solar MajiPump) and fertilizer applications affect crop irrigation, production, and consumption at the household level. Given that groundwater from wells is used for irrigation in Dengeshita, two distinct water-lifting technologies, a pulley–bucket–tank and solar MajiPump systems, were assessed for capacity and affordability. For the alternative scenarios, optimal fertilizer applications during field interventions are evaluated, whereas existing fertilizer rates from the baseline survey are used for this study's baseline analysis.

Three major cereal crops (maize, teff, and millet) consistent with the cropping system in Dengeshita and grown during the rainy season were considered in this study. In addition to cereal crops, onion and pepper were analyzed in the model (Appendix A). There is no yield difference in cereals between the baseline and alternative scenarios as the input technology (e.g., fertilizer, chemicals) and the management practices are the same for rainfed agriculture. From the survey conducted in 2017 by the Bahir Dar University in collaboration with the Innovation Lab for Small Scale Irrigation (ILSSI), phosphorus fertilizers from all sources (i.e., DAP and compost) were 27.4 kg P ha^{-1} and nitrogen fertilizers from UREA, DAP, and compost were 76 kg N ha^{-1}. According to the survey, most homes used conserved seeds from the previous harvest for the following planting season, and chemical use was limited. In addition, the volume of farm labor recruiting was comparable under the baseline scenario for cereals. However, more hired labor was contemplated in the alternate scenarios, particularly for irrigation activities.

The irrigated crops grown during the dry season consist mainly of onion and pepper under conservation agriculture (CA) and conventional tillage (CT) practices. The difference between the baseline and alternative scenarios is due to the application of conservation agriculture and conventional tillage with combined Maji solar pump and drip technologies. Assefa et al. [33] showed how CA treatments save labor and water compared to conventional tillage by smallholder farmers in the Dengeshita area. Farmers irrigated vegetables with a watering can for the first 1.5 years and drip irrigation for the remaining years. Based on the local farmer practices, urea (46-0-0) fertilizer was applied at 200 kg ha^{-1} in both CA and CT treatments. Local grass (*Pennisetum macrourum Trin*) was harvested before seed development and dried before utilizing it as a mulch on the CA plots. Throughout the experiment, the dried grass was applied at 4 Mg ha^{-1} as mulch cover twice per cropping period (i.e., 8 Mg ha^{-1} $year^{-1}$). Livestock (i.e., cow) manure was applied on five occasions in both CA and CT at a rate of 5 Mg ha^{-1}. Onion was harvested from February to March, and pepper from July to August. Crop residues from both management systems were not removed. The difference between the baseline and alternatives was mainly the technology used to lift water, such as pulley and solar pump, mulch application through CA, and drip used to apply water. Improvement under alternative scenarios was due to increased irrigation yields, reduced labor costs, and water saving.

The following is a short description of the four scenarios under study. The baseline scenario relates to crop cultivation (mainly grains) in the rainy season (or rain-fed agricultural system) and the use of conventional tillage and minimum irrigation when needed in the dry season for vegetables.

Alternative scenarios include: (1) irrigation of crops (vegetables of onion and pepper) using MajiPump and drip in addition to growing rain-fed crops, all under conventional tillage, with optimal fertilizers application; (2) irrigation of crops (vegetables of onion and pepper) using MajiPump and drip in addition to growing rain-fed crops, all under conservation agriculture with optimal fertilizers application; and (3) irrigation of crops (vegetables of onion and pepper) using the pulley system in addition to growing rain-fed crops, all under conventional tillage with optimal fertilizers application. The first alternative scenario is referred to as Alt.1_MP_CT, the second as Alt.2_MP_CA, and the third as Alt.3_P_CT.

2.5. Assumptions

To consider the potential of adopting new technology, we first assumed that alternative irrigation methods had been fully implemented, as evidenced by field trials of MajiPumps by intervention farmers in Dengeshita [30]. According to the ASMC project's household survey, over 90% of the selected homes (intervention and non-intervention) used fertilizers and pesticides. Nonetheless, 56% of them used enhanced seeds. To ensure sustainability, the cost of capital for irrigation technologies (solar MajiPump and pulley) was projected to be paid through a microfinance loan. It was incorporated into the model as a liability (loan). The project, on the other hand, furnished the pumps for testing. In FARMSIM, the adoption rate refers to the percentage of land or animals under new farming or livestock techniques that a home or community (kebele) has embraced.

Second, because the farmer's profit is mostly determined by the amount of crop and livestock goods sold at markets, the farmer's access to markets is critical. In this study, crop and livestock markets were considered open and competitive, with no distortions where the supply and demand determine market prices. However, the five-year economic prediction assumed that the market selling price in each of the five years would equal the average selling price of year one for each crop sold, which would be the best guess if no anticipated prices were known.

Third, based on preliminary profitability and food item purchase schedule simulations, households in alternative scenarios one and two (Alt.1 and Alt.2) related to the use of MajiPump have allocated up to 40% of their net profit that is available to purchase supplemental foodstuffs such as potatoes, chicken, beef, and butter to improve nutrition. Households in alternative scenario three (Alt.3) associated with the pulley spent up to 70% of their profit on the same supplemental food item. In comparison, households could only afford a quarter (40%) of the supplemental food under the baseline scenario. Animal-source foods were targeted because of their low consumption, as revealed by the baseline survey, while potatoes assisted in increasing vitamin A intake. No milk purchase is recorded, but about 65% of on-farm milk production is processed into butter; 20% is sold, while only 15% is consumed at home. Last, we assumed a discount rate of 10% for the five forecasting years to account for the time value of money and kept it at the same level as the inflation rate.

3. Results and Discussions

3.1. Economic Impacts

This study used several economic indicators such as net present value, net cash farm income (profit), ending cash, and benefit–cost ratio to assess the impacts of adopting small-scale irrigation technology and tillage practices in Dengeshita. The NPV simulation findings in Dengeshita show a positive NPV value for all scenarios, demonstrating the potential benefits of investing in SSI technologies such as solar MajiPump and tillage practices (Table 1). The use of MajiPump irrigation technology to lift water, complemented by drip irrigation in Dengeshita, provided higher NPV values for farmers relative to baseline with limited irrigation technology and the use of a pulley as an irrigation system. The MajiPump alternative scenario (Alt.2) under the conservation agriculture farming technique had the highest NPV value due to better production yields and vegetable sales. The baseline scenario had a lower NPV value due to low crop yields, vegetable sales, and high production costs (labor and input). However, there is no significant difference in NPV values between the alternative scenarios or between the alternative and baseline scenarios.

Table 1. Economic impacts of the SSI technologies in Dengeshita.

	Baseline	Alt.1_MP_CT	Alt.2_MP_CA	Alt.3_P_CT
Averages values in Birr/family in year 3				
Net present value (5 years)	195,580	255,592	269,258	241,449
Average net profit	4760	15,477	17,250	8604
Percent change in profit: alt./baseline		225%	262%	81%
Benefit–cost ratio: alt/baseline		1.18	1.37	0.49
Internal rate of return: alt/baseline		0.17	0.25	−0.04

Note: MP = MajiPump, CT = conventional tillage; CA = conservation agriculture, and P = pulley.

The simulated annual net cash farm income (NCFI), which represents economic profit at the household level, shows that in year three, the average profit under alternative scenarios (Alt.1, Alt.2, and Alt.3) is 1.8 to 3.6 times higher than that of the baseline scenario, with a percentage increase in profit ranging from 81 to 262% (Table 1). Alternative scenarios one and two (Alt.1 and Alt.2), associated with the MajiPumps and drip irrigation under conventional tillage and conservation agriculture practices, yielded the highest yearly average profit. The profit value for the baseline scenario was the lowest, followed by the alternative scenario associated with the pulley and drip irrigation system (Alt.3).

The net cash income (profit) distribution, on the other hand, indicated a one percent likelihood of having a profit (NCFI) equal to or less than zero (loss) for Alt.1 and Alt.2 (MajiPump scenarios) and a 21% probability of having a profit (NCFI) equal to or less than zero for the baseline and Alt.3 scenarios (pulley system) (Figure 2). The cumulative distribution function (CDF) graphs and simulated profit values reveal that the profit loss ranges from 0 to ETB 12,230, with the baseline and pulley scenarios resulting in the greatest losses. Although the profit associated with MajiPump and drip irrigation technologies is higher than the baseline and pulley system, the distribution results also highlight the risk associated with improved production and water-lifting technologies (such as MajiPump) costs involved in the SSI technologies investment. High-income variability and de facto risk were noted, owing mostly to a large range in yields and price figures (minimum and maximum) and ox-earned income, which resulted in high variability in receipts and profits. The pulley system’s low-profit value was mostly due to the manual pulley technology’s high labor cost and low efficiency.

The stoplight chart graph option can also compare and rate scenario performance. The chart summarizes the likelihood that the baseline and risky alternative scenarios will be less than (in red) or more than (in green) a lower target value. The chance of each scenario falling between the two targets is shown in yellow in the table [29]. Stoplight makes ranking scenarios easier by presenting a table of probabilities and a graph depicting the possibilities of each range. In this study, the NCFI (profit) stoplight chart predicts the probability of NCFI being less than ETB 0 (red), larger than ETB 20,000 (green), and between the two target values (yellow) in year three of the five years.

The graph shows that the baseline and alternative scenario three (Alt.3) associated with the pulley system have a 21 and 23% probability of having the NCFI less than ETB 0 (loss). The alternative scenarios associated with Maji pump and drip irrigation systems under CA and CT practices (Alt.1 and Alt.2) have a 1 and 2% probability of incurring a loss (Figure 3). Additionally, alternative scenarios associated with MajiPump and drip system have a 30 and 34% chance of having their NCFI or profit higher than ETB 20,000 in year three. That probability is 2% for the baseline and 14% for the pulley system. The low performance of the baseline and Alt.3 associated with the pulley system is linked to high production costs and low profits. Although higher production and sale of vegetables due to irrigation were made under Alt.3 (pulley), the profit was offset by high production costs, especially those related to labor. For example, irrigation labor costs for growing vegetables were 7 to 10 times higher under the pulley system than the average labor costs in the baseline scenario. Labor costs for Alt.1 and Alt.2 under MajiPump and drip systems were significantly reduced (10 times lower than the baseline scenario), allowing for the allocation of the profit to other uses such as supplemental food purchases.

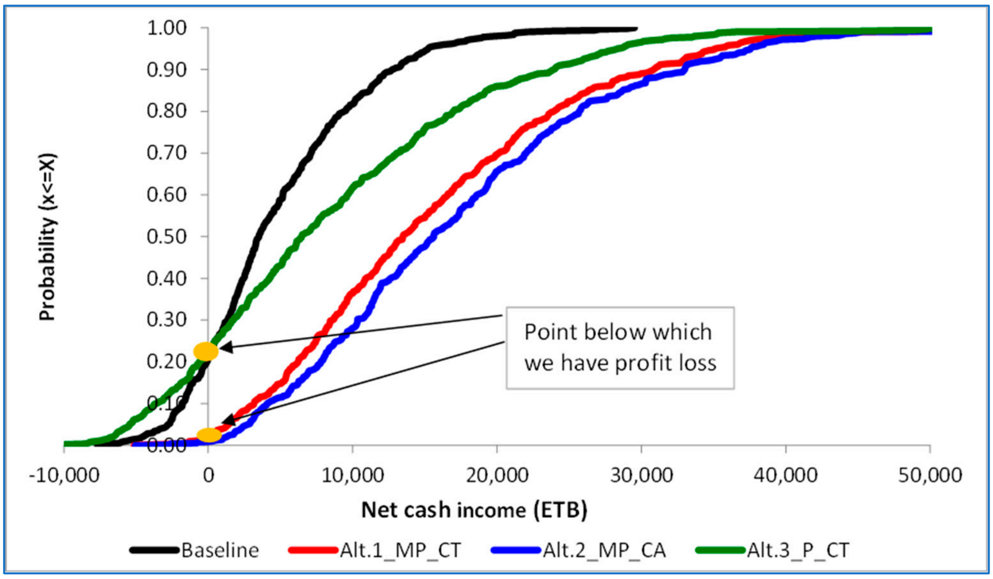

Figure 2. Cumulative distribution of net cash farm income per family in Dengeshita.

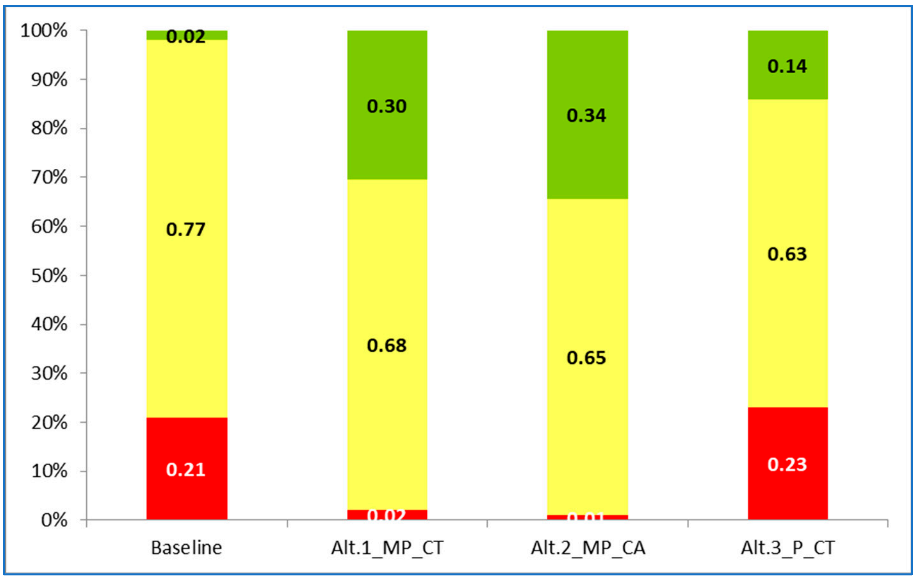

Figure 3. Probability of net cash income less than 0 (red), greater than ETB 20,000 (green) and in-between (yellow) per-family in Dengeshita kebele.

To determine whether the benefits outweigh the investment costs or enterprise feasibility, a cost–benefit analysis (CBA) is performed, which employs two NPV-related metrics: the benefit–cost ratio (BCR) and the internal rate of return (IRR). The two measures provide information on the profitability and return on investment of a new business or enterprise, in this case, an investment in small-scale irrigation technology (SSI) like MajiPump, fertilizers, and drip irrigation. Furthermore, the cost–benefit analysis shows the probability distribution of the BCR from the FARMSIM simulation results (Figure 4).

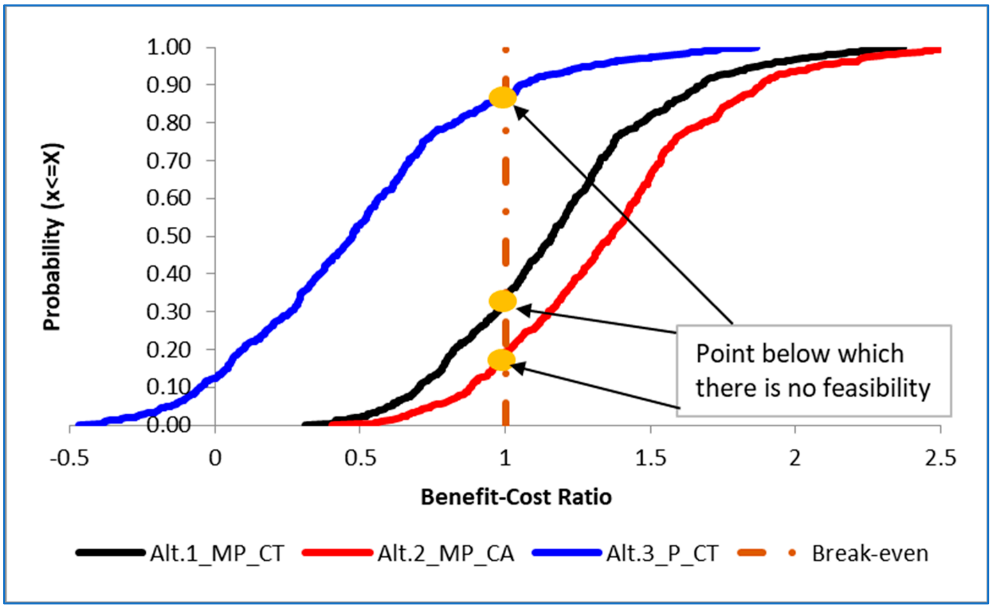

Figure 4. Cumulative distribution of the benefit–cost ratio for alternative scenarios.

The results indicate, on average, BCR values greater than one (feasible) for alternative scenarios associated with MajiPumps and drip irrigation (Alt.1 and Alt.2) and BCR values less than one (not feasible) for the alternative scenario associated with the pulley and drip irrigation system (Table 1 above). Average BCR values equal to or greater than one (threshold value) indicate break-even or profitability of the investment under alternative scenarios associated with using MajiPumps and drip irrigation systems compared to the baseline.

However, an examination of the full distribution of the BCR values reveals that the BCR simulated values have approximately 17% and 34% probability for Alt.1 and Alt.2 associated with the MajiPump to fall below their threshold value of one, indicating a negative return on investment or loss (Figure 4). For the pulley system scenario (Alt.3), the chance of a negative return on investment (non-feasibility) is 85 percent. The pulley system option is less feasible, mainly due to high investment costs in irrigation labor, which is 100 times higher than the labor costs under the Maji solar pump and takes up between 66% and 71% of the total input and production costs of onion and peppers. While labor costs may be the main reason for the low feasibility of adopting a pulley system, costs of investment in tools such as the MajiPump are also a factor in low BCR values as these figures are measured in the present value difference between the baseline and the alternative technology costs. Although high investment costs (operational and capital) are recorded under alternative scenarios associated with technology and labor, revenues from the production and sale of irrigated vegetables (accounting for 80% of all revenues) have increased the overall profitability.

3.2. Simulation of Nutrition Impacts

We evaluate nutrition indicators, in this case, nutrients, and compare them to daily minimum requirements per adult equivalent (AE) to determine adequacy in calories, proteins, fat, calcium, iron, and vitamin A intake available to the household. In the analysis, farm families consume food grown on the farm and/or purchased at the market for nutritional requirements. A preliminary analysis of food items consumed by the household in Dengeshita kebele was carried out using household survey data collected in 2015 and 2017 in Ethiopia (The data were collected through a collaborative research project between the Innovation Lab for Small-scale Irrigation (ILSSI) at Texas A & M University and the Sustainable Intensification Innovation Lab at Kansas State University to evaluate the implications of sustainable intensification of crop and livestock production systems

(SIPS) on human nutrition in northern Ethiopia). Using a household diet diversity score (HDDS) technique based on a basic count of food groups [36], survey findings reveal a cereal-centered diet with a significant lack of animal-source products such as meat, eggs, milk, and seafood intake. For example, 0 to 2% of questioned households said they ate fresh meat, organic meat, eggs, and fish, but 98 to 100% said they ate cereals/grains (see Appendix C). Only households in alternate scenarios might utilize up to 70% of their profit to purchase food for nutrition enhancement, with a preference for food of animal origin based on the quantity of profit available and nutrition demands. However, the profit level only allowed households to buy potatoes, poultry, meat, and butter from markets. In the model, households under the baseline scenario did not have enough net cash to purchase the same amount of supplemental foods as those under the alternative scenarios. Only 40% of the same amount of food purchased under the alternative scenario was afforded under the baseline scenario, leading to some nutrients, such as vitamin A deficiency.

The crops farmed and consumed by the family in Dengeshita kebele were mostly maize, teff, millet, peppers, onions, and lentils, to which moderate purchases of teff, millet, onions, potatoes, and butter were added. Milk, butter, eggs, chicken, sheep, and beef produced and consumed by the household on the farm were also included in the analysis for all scenarios.

Because of moderate crop production gains due to farming technologies, simulated amounts of nutrition variables (calories, proteins, fat, calcium, iron, and vitamin A) available to farm families did not differ significantly between the alternative and baseline scenarios. The main technological variation between the sampled households is the usage of solar irrigation MajiPump and agricultural practice (e.g., CA versus CT), while other agricultural technologies (use of fertilizers, seeds) are consistent throughout the households. On the other hand, purchases account for considerably larger changes in increased food availability and consumption under alternative scenarios compared to the baseline scenario.

According to the simulation results, the volume of milk sought and consumed by families in Dengeshita kebele, for example, increased by 50% in all possible scenarios associated with MajiPumps, drip irrigation, and pulley systems. Similar increases in the amount requested and consumed by farm families were reported for chicken (87%), beef (44%), teff (111%), butter (142%), and potatoes (154%), which might be attributed, in part, to purchase. Notably, increased yield and production from enhanced irrigation technologies resulted in high increases (six times) in the number of vegetables (peppers and onions) accessible for eating at home under alternative scenarios compared to the baseline.

The simulation results for each nutrient in this study are explained below (Table 2). One of the primary assumptions in nutrition simulation states that the fraction of crops consumed by the family and reported in the household survey would be consistent for all crops in the baseline and alternative scenarios unless there is a need to increase the fraction consumed. However, compared to the baseline and pulley situations, the increase in food products and nutrients accessible for consumption at home was primarily due to purchases made under improved alternative farming technologies and practice scenarios connected with MajiPumps. The affordability of purchasing supplemental foods under the baseline scenario was very constrained by the lack of cash, while the purchase exhausted almost all the cash reserves or profits under the pulley system. The change in available nutrients from the baseline to alternative scenarios one and two (Alt.2) related to MajiPump and Alt.3, related to the pulley, shows higher food production and purchase increases in the alternative than the baseline. However, increases in the pulley system are slightly lower than those in the MajiPump system, highlighting the benefits of adopting the MajiPump and conservation agriculture alternative compared to the pulley system and conventional agriculture.

Calorie intake: The calorie simulation results for a representative household in Dengeshita kebele reveal, on average, available daily intake of 1838 and 2000 calories for the baseline and alternative scenarios, respectively (Table 2 and Figure 5). These intakes fall short of the global average's daily minimal need of 2353 calories per adult equivalent

(AE) [33]. Farm families in both the baseline and alternative scenarios have insufficient calorie consumption. According to the simulation results, households in both the baseline and alternative scenarios have a 70–80% chance of consuming fewer calories than the recommended minimum of 2353 kcal/AE/day.

Table 2. Nutrition impacts for SSI technologies in Dengeshita.

	Baseline	Alt.1_MajiP_CT	Alt.2_MajiP_CA	Alt.3_Pulley_CT	% Change in Nutrients: Base/Alt	
Nutrients: Min req.	Average daily nutrients in Year 5				Base/ Alt.2	Base/ Alt.3
Energy (calories/AE): 2353	1838	2042	2078	1938	13	5
Proteins (g/AE): 41.2	42	48	49	45	15	7
Fat (g/AE): 51	32	41	43	37	35	16
Calcium (g/AE): 1	0.12	0.20	0.21	0.17	77	44
Iron (g/AE): 0.009	0.013	0.014	0.014	0.013	12	4
Vitamin A (µgRAE/AE): 600	340	945	1082	698	218	105

Notes: Base/Alt.2: % change from baseline to alternative scenario two associated with MajiPump and conservation agriculture. Base/Alt.3: % change from baseline to alternative scenario three associated with pulley and conventional tillage. Unit for vitamin A = µg RAE/AE (RAE/AE: retinol activity equivalent/adult equivalent). Min req.: minimum required; numbers in red mean deficit.

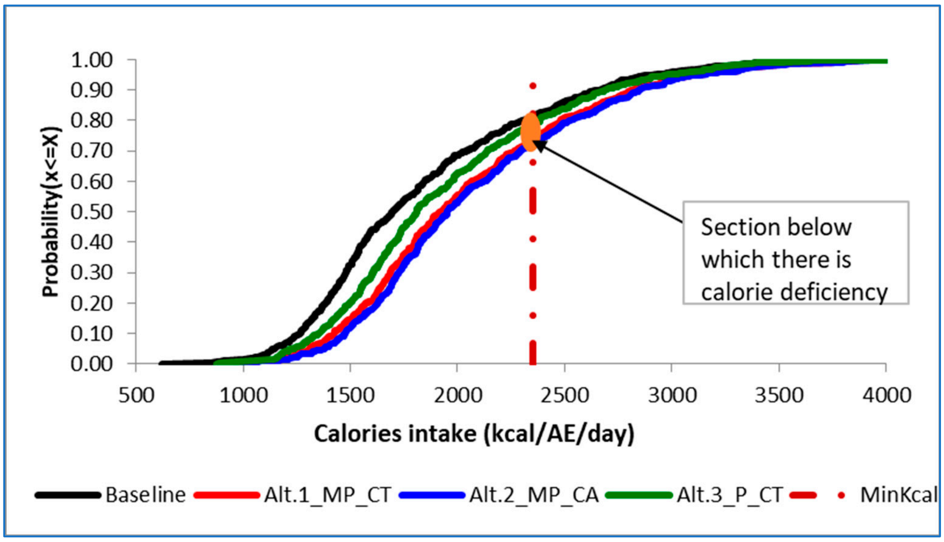

Figure 5. Cumulative distribution of calorie intake (kcal) per AE per day in Dengeshita.

The low-calorie intake may be related to a comparatively low consumption fraction of cereal-based food crops grown on the farm, such as maize and millet. Although maize is the largest source of calories for a typical Dengeshita household, accounting for 67% on average, its consumption portion in a home is about 51%.

Protein intake: The protein intake simulation results show that, on average, a representative household has 42 and 47 g/AE of protein intake available under the baseline and alternative scenarios, which meet and exceed the daily minimum requirement of 41 g/AE (Table 2 and Appendix D.1). However, simulation findings reveal a more comprehensive picture of the distribution, with households under baseline and alternative scenarios having between 24 and 56% risk of falling below the minimal protein requirement per adult (AE) daily (See Appendix D.1).

Fat intake: Fat intake simulation results show a significant deficit in fat, with a likelihood ranging from 79 to 94% for families falling below the minimum required under both the baseline and alternative scenarios (Table 2 and Figure 6). Although there is an improvement in fat intake between the baseline and alternative scenarios in relation to MajiPump and pulley use, their respective averages of 32, 42, and 37 g are still less than the daily minimum fat requirement average of 51 g for an adult. The improvement and increase in available fat intake from the baseline to the alternative scenarios is around 40%, with butter and beef consumption accounting for 56% of the available fat.

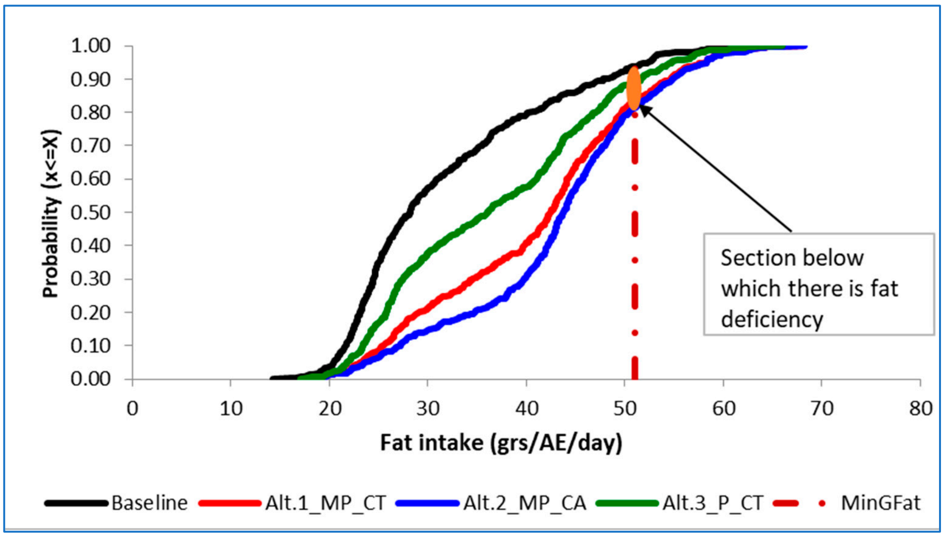

Figure 6. Cumulative distribution of fat intake (g) per AE per day in Dengeshita.

Calcium intake: Both the baseline and alternative scenarios show a significant deficiency in calcium intake (Table 2). The average calcium intake per AE per day for the baseline and the three alternative scenarios (Alt.1, 2, and 3) is 0.12 and 0.20 g, respectively, falling short of the daily minimum requirements of one gram per AE. The whole calcium intake distribution revealed that, although being in deficit, the best-performing scenarios (Alt.1 and Alt.2) are alternative scenarios related to the MajiPump and drip irrigation use (Figure 7). Teff, maize, onion, and milk products are the top contributors to calcium intake.

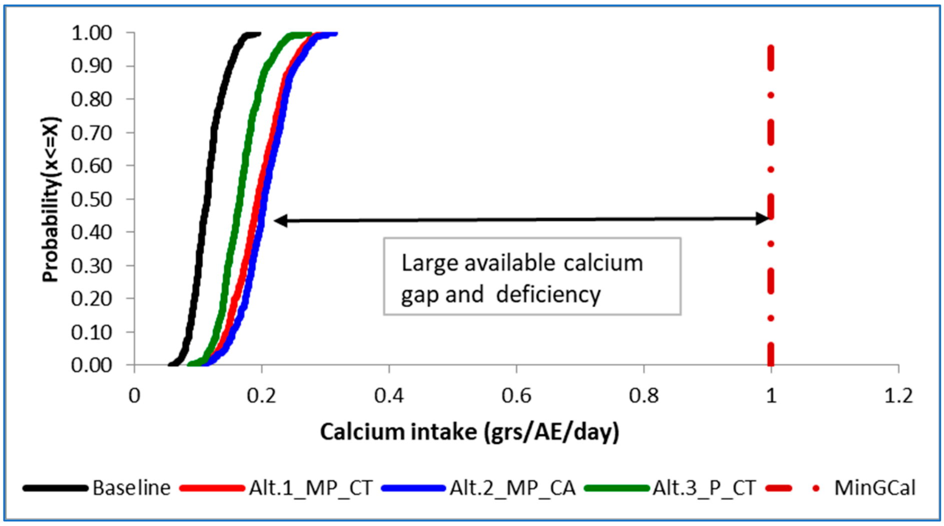

Figure 7. Cumulative distribution of calcium intake (g) per AE per day in Dengeshita.

The large and consistent gap in calcium intake in the current study reflects the existing concern regarding low calcium intake observed in developing countries (vs. developed countries) due to low animal product access and consumption (FAO, 2001b [34]). Moreover, due to a mismatch between the calcium intake data and the relatively high intake requirements, a revised US/Canada Dietary Reference Intakes (DRIs) recommends replacing the recommended daily allowance (RDA) with the acceptable intake (AI) of calcium. Another concern related to calcium requirements is the wide difference between gender and age, making it difficult to find an acceptable average requirement.

Iron intake: Based on the minimum requirements, the simulation results indicate that in 90% of the cases, households in Dengeshita kebele obtain more than the required minimum levels of iron, with between 1 and 10% likelihood of falling below the minimum amount required across scenarios (Appendix D.2). The average iron intake available per AE per day for all scenarios, estimated at 0.013 g, is 45% more than the daily minimum requirement of 0.009 g per AE (Table 2). Moreover, there was a slight improvement in iron available between the baseline and the alternative scenarios associated with using the MajiPump, which averaged 0.14 g. Note that about 64% of available iron for the household comes from maize consumption.

Vitamin A intake: The simulation results for available vitamin A intake, expressed regarding retinol activity equivalent (RAE), indicate adequate to surplus vitamin A intake levels for alternative scenarios associated with using MajiPump and drip irrigation systems (Table 2). However, the results for the baseline scenario show a deficit, while those associated with the pulley system are slightly above the minimum required (600 μg RAE). The average levels of vitamin A intake for the baseline and alternative scenarios with MajiPump were 340 μg RAE and 1014 μg RAE, respectively. The full distribution of available vitamin A intake shows that there is between 55 and 80 percent chance for households under the baseline and pulley system scenarios to fall below the minimum required vitamin A while that probability stands between 25 and 36 percent for alternative scenarios associated with the use of MajiPump (Appendix D.3).

3.3. Impacts of Technologies on Nutrition

Generally, the nutrition simulation results show that the food products consumed by families in the baseline and alternative scenarios meet the minimum daily requirements only for available proteins and iron intake (and vitamin A to some extent), while available calories, fat, and calcium are in deficit (Table 2). An unusual deficit in calories is observed for all the scenarios. Maize consumption lead the supply of calories to farm families by contributing between 63 and 71% of the total available calorie intake. However, this amount is insufficient to cover the nutritional deficits in calories. To close the calorie gap and reach the minimum daily requirements, increasing the consumption of butter and cereals produced on the farm or purchasing at the market to supplement farm production and consumption is recommended. For example, the allocation of financial resources to purchase onions under the alternative scenarios, as reported in the baseline survey, could be used to purchase supplemental millet and butter to increase available calorie intake.

Large deficits in calcium are observed, with averages ranging from 0.12 to 0.21 g per day per adult equivalent (AE) and are below the one-gram daily minimum required per adult. A close look at calcium intake probability distribution from simulated values indicates no chance or probability for the available calcium to exceed the minimum required. Two previous nutrition simulation studies in Ethiopia have also shown a consistent deficiency in calcium, probably due to the relatively high level of the minimum requirements and a diet low in calcium [37].

Calcium deficiency can be caused by one of two factors. First, there is the issue of low consumption of calcium-rich foods (in comparison to industrialized countries) [38]. Low milk, cheese animal products, and egg consumption in underdeveloped nations, whether through production or purchase, may have resulted in low accessible calcium intake in this study. It is worth noting that teff, maize, onion, and milk consumption contributed around 70% of the total available calcium intake. Milk is at the top of the list, accounting for approximately 32 percent. Second, the acceptable level of minimum necessary calcium intake for nutrition analysis is still being debated. The present threshold of one gram looks to be somewhat higher than what a human body would ordinarily require. The other reason could be the wide range of calcium requirements between gender and age, making it difficult to find an acceptable average requirement.

Increasing the consumption of dairy products such as milk, cheese, and eggs can significantly improve the available calcium intake and cut down the current deficits [38,39]. In this study, households under Alt.1 and Alt.2 associated with MajiPump, which has enough additional income from profits, can afford to increase the quantity of supplemental animal source foods through purchase to cut the nutrition deficit in calcium.

Deficits are also observed for fat in the baseline and all alternative scenarios, with major fat deficiencies associated with the baseline and alternative scenario under the pulley system. In contrast, relatively low deficiencies are observed under alternative scenarios associated with MajiPump and drip irrigation systems. Although the simulated fat intake available for farm families increased between 132 and 140% in alternative scenarios compared to the baseline, to cut the fat deficits significantly and improve family nutrition in Dengeshita kebele, there is a need to mainly increase the consumption of butter and beef but also chicken and mutton. The simulated nutritional results in fat intake show a 35% increase in available fat under the MajiPump scenario compared to 16% under the pulley, all compared to the baseline (Table 2 above). The results also indicate that these increases came mainly from family purchases, contributing between 50 and 85% of additional consumed quantities in beef and butter.

3.4. Impacts of Technologies in Sub-Saharan Africa

The adoption and appropriate use of improved irrigation technologies contributed to an increase in the quantity and variety of crops produced at the household level, mainly due to dry season crop production. The simulated total cultivated area in Dengeshita for dry season crops (onions and pepper) increased, on average, eight times compared to the baseline scenario. The land area increase, combined with improved productivity (yield) from using fertilizers and other agricultural management practices such as conservation agriculture, led to increased food production and consumption in alternative scenarios. For example, the quantity of onions and peppers available for consumption at the household level in alternative scenarios associated with using the MajiPump, increased seven to eight times from the baseline. The quantity of onions and pepper available for sale increased 11 to 14 times in alternative scenarios associated with MajiPump compared to the baseline and the pulley scenarios, leading to an increase in potential revenues.

A study on the impacts of small-scale irrigation on household dietary diversity in Ethiopia and Tanzania showed that potential pathways to food diversity and better nutrition were most likely through increased income rather than directly through production [40,41]. A similar outcome in a study in Sub-Saharan Africa indicates that irrigation systems improved the consumption of food products of animal origin and nutrition due to potential increases in income and improved livestock productivity from feeds [37,41].

The simulated nutritional results indicate a consistent increase in available nutrient intake between the main alternative scenarios (under MajiPump and pulley) and the baseline scenario, with noticeable nutritional improvement under the MajiPump alternative scenario. The alternative scenarios (Alt.1 and Alt.2) under the MajiPump and drip irrigation systems had the most impact on nutrition, followed by the pulley system, partly due to increased crop production and income from improved irrigation methods and conservation agriculture practices. Using improved technologies such as solar pumps and drip irrigation alongside conservation agriculture practices has significantly reduced labor costs compared to using a pulley system or a bucket for irrigation in the baseline scenario.

4. Conclusions and Recommendations

This study aimed to assess the effects of improved agricultural technologies (solar pump, drip irrigation system, and conservation agriculture practices) to grow irrigated vegetables on household nutrition and farm profitability in Dengeshita kebele, Amhara region of Ethiopia. A baseline scenario using existing practices (fertilizer and irrigation system) was compared to three alternative scenarios using solar Maji Pumps, drip irrigation, a pulley system, and conservation agriculture.

Households in the alternative and improved irrigation technologies scenarios associated with the MajiPump and drip irrigation systems earned more than those in the baseline and pulley systems. Although the expenses of purchasing the solar MajiPump and drip system increased for the initial expenditure, simulation results show a return over time due to improved production and sale. However, credit or financial help to support the initial and capital investment and the credit payback over five years was critical to farmers' success under the MajiPump alternative scenario. Higher labor costs, which were not financed, were one of the causes of overall low performance and profit for the pulley and drip irrigation systems. One of the key impacts of profit was the opportunity for households to purchase additional foodstuffs, especially animal sources food for family nutrition.

This study achieved increased vegetable yield and total production for consumption and market income generation through improved small-scale irrigation technologies such as solar MajiPump in conjunction with conservation agriculture practices. The simulation results demonstrate the viability and profitability of these businesses in comparison to the baseline scenario or present practices. Policymakers should prioritize facilitating access to financial support and credit options to assist smallholder farmers in acquiring and sustaining these technologies, as demonstrated by their positive long-term return on investment. As a result, adopting enhanced irrigation technology (MajiPump) and conservation agriculture, which minimize labor time and cost while improving vegetable yield, has a strong potential to improve environmental and nutritional wellbeing.

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Data Availability Statement: Data used in this article can be obtained by communicating with the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

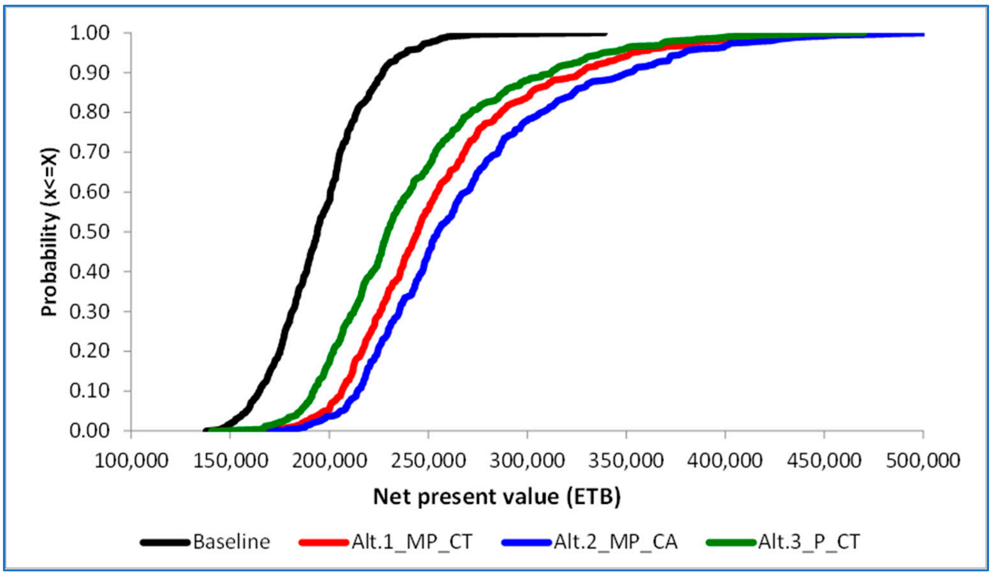
AE: Adult equivalent; **AI**: acceptable intake; **ASMC**: Appropriate Scale Mechanization Consortium; **BCR**: benefit–cost ratio; **CA**: conservation agriculture; **CDF**: cumulative distribution function; **CT**: conventional tillage; **DAP**: di-ammonium phosphate; **DRI**: dietary reference intakes; DC: direct current; **ETB**: Ethiopian Birr (local currency); **FAO**: Food and Agriculture Organization; **FARMSIM**: farm simulation model; **GHI**: Global Hunger Index; **IFPRI**: International Food Policy Research Institute; **ILRI**: International Livestock Research Institute; **ILSSI**: Innovation Laboratory for Small-scale Irrigation; **IWMI**: International Water Management Institute; **IRR**: internal rate of return; **KOVs**: key output variables; **LIVES**: livestock and irrigation value chains for Ethiopian smallholders; **MDR**: minimum daily requirements; **NCFI**: net cash farm income; **NPV**: net present value; **OECD**: Organization for Economic Cooperation and Development; **RDA**: recommended daily allowance; **RNI**: recommended nutrients intake; **SIMETAR**: simulation and econometrics to analyze risk; **SSA**: Sub-Saharan Africa; **SSI**: small-scale irrigation; **USAID**: United States Agency for International Development.

Appendix A. Summary Model Input Data for the Baseline and Alternative Scenarios

Crops	Baseline Scenario											
	Average Yield (kg/ha)	Planted Area (ha)	Seed (ETB/ha)	Fertilizer (ETB/ha)	Chemicals (ETB/ha)	Land Preparation (ETB/ha)	Planting (ETB/ha)	Weeding (ETB/ha)	Irrigation (ETB/ha)	Harvest (ETB/ha)	Other (ETB/ha)	Average Price (ETB)
Maize	2000	87	720	3120	1500	1491	1080	156	0	2000	103	12
Millet	800	39	520	2350	560	3200	1280	144	0	2280	13	14
Teff	600	10	1750	3256	600	4800	1280	300	0	2580	0	32
Onion	2400	1	12,000	2400	923	6750	12,600	1354	0	778	11,965	19
Pepper	2504	1	1600	2500	923	6750	10,600	1353	0	550	300	22

Crops	Alternative Scenario											
	Average Yield (kg/ha)	Planted Area (ha)	Seed (ETB/ha)	Fertilizer (ETB/ha)	Chemicals (ETB/ha)	Land Preparation (ETB/ha)	Planting (ETB/ha)	Weeding (ETB/ha)	Irrigation (ETB/ha)	Harvest (ETB/ha)	Other (ETB/ha)	Average Price (ETB)
Maize	2000	21	720	2920	1500	1491	1080	156	0	2000	103	12
Millet	800	21	520	1560	560	3200	1280	144	0	2280	13	14
Teff	600	4	1750	2950	600	4800	1280	300	0	2580	0	32
Onion	3200	8	12,000	2400	923	6750	12,600	1354	968	778	11,965	19
Pepper	3504	8	1600	2400	923	6750	10,600	1354	1000	590	450	22

Appendix B. Cumulative Distribution Function of the Net Present Value (ETB)

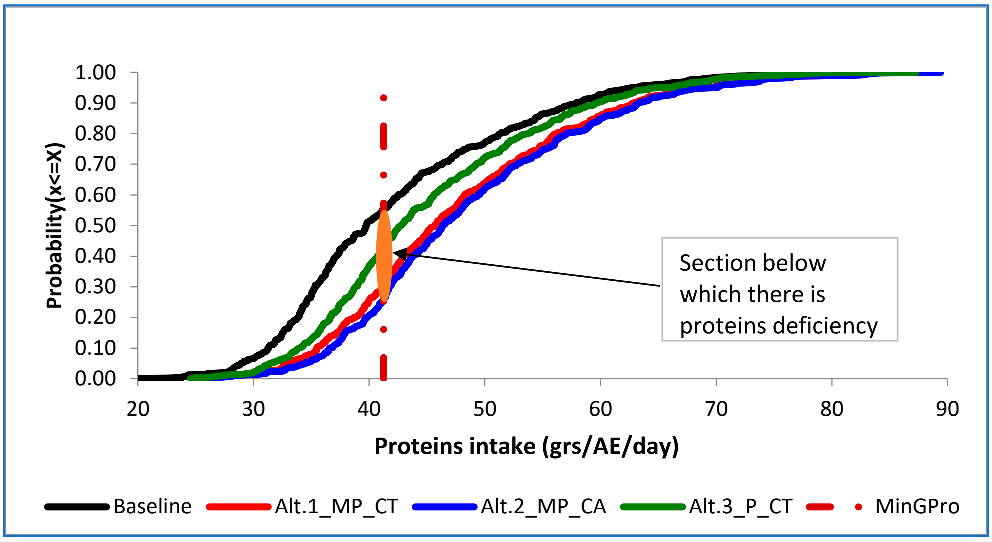


Appendix C. Household Dietary Diversity Score (HDDS) for Dengeshita

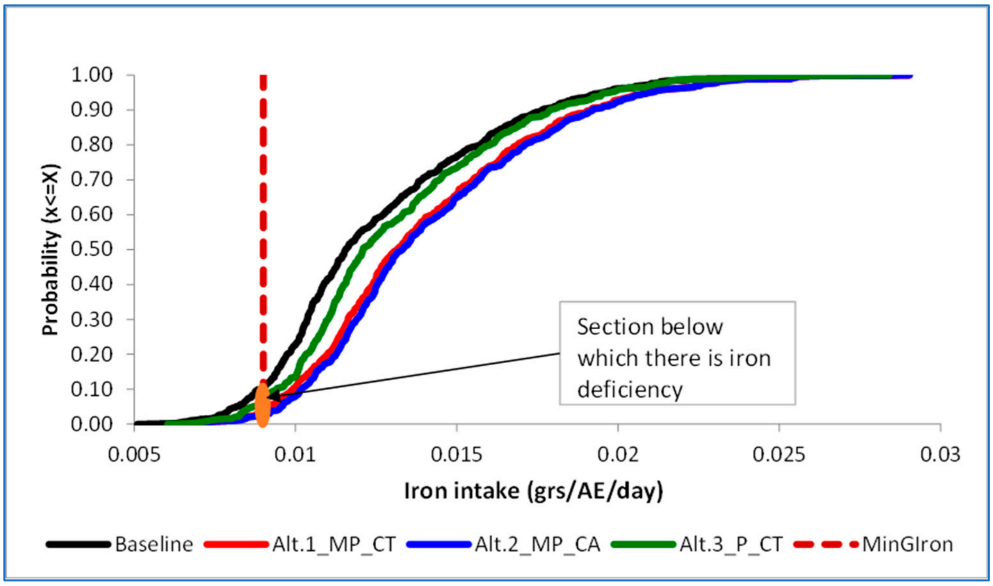
Food Groups	Examples	Food Group Consumption Score (Yes = 1 or No = 0)					
		Baseline Survey—2015		Score	Endline Survey—2017		
		Yes (%)	No (%)		Yes (%)	No (%)	Score
Cereals/grains	Maize, rice sorghum, millet	98	2	1	100	0	1
White roots and tubers	Potatoes, yam, cassava	41	54	**0**	43	57	**0**
Vitamin-A-rich vegetables and tubers	Pumpkin, carrot, pepper, sweet pot	10	90	**0**	15	85	**0**
Dark green leafy vegetables	Spinach, kale, amaranth	15	84	**0**	9	90	**0**
Other vegetables	Tomatoes, onions, eggplants	80	20	**1**	95	4	**1**
Vitamin-A-rich fruits	Mango, apricot, papaya, peach	5	95	**0**	5	93	**0**
Other fruits	Apple, orange, grape	0	100	**0**	2	98	**0**
Organ meat	Liver, kidney, heart	0	100	**0**	1	99	**0**
Flesh meat	Beef, pork, lamb, goat	0	100	**0**	1	98	**0**
Eggs	Eggs from chicken, duck	1	98	**0**	2	98	**0**
Fish and seafood	Fresh or dried fish	1	99	**0**	0	100	**0**
Legumes, nuts, and seeds	Beans, peas, lentils, nuts	95	5	**1**	96	3	**1**
Milk and milk products	Milk, cheese, butter	23	77	**0**	19	80	**0**
Oils and fat	Oils, fat, or butter	60	40	**1**	95	5	**1**
Sweets	Sugar, honey, candies	44	55	**0**	22	77	**0**
Spices, condiments, beverages	Pepper, salt, condiments, soda, coffee	98	1	**1**	99	1	**1**
	Total HDD score			**5**			**5**

Appendix D.

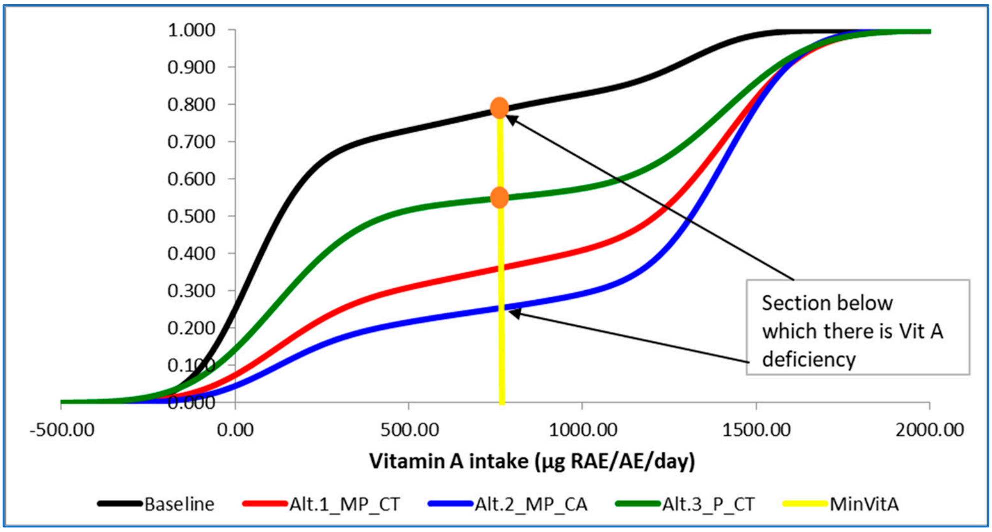
Appendix D.1. Cumulative Distribution Function of the Proteins Intake



Appendix D.2. Cumulative Distribution Function of the Iron Intake



Appendix D.3. Cumulative Distribution Function of the Vitamin a Intake



References

1. Fan, S.; Teng, P.; Chew, P.; Smith, G.; Copeland, L. Food system resilience and COVID-19–Lessons from the Asian experience. *Glob. Food Secur.* **2021**, *28*, 100501. [CrossRef] [PubMed]
2. Lobell, D.; Gourdji, S. The influence of climate change on global crop productivity. *Plant Physiol.* **2012**, *112*, 208298. [CrossRef] [PubMed]
3. Worqlul, A.W.; Jeong, J.; Dile, Y.T.; Osorio, J.; Schmitter, P.; Gerik, T.; Srinivasan, R.; Clark, N. Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. *Appl. Geogr.* **2017**, *85*, 1–13. [CrossRef]
4. Assefa, T.; Jha, M.; Reyes, M.; Srinivasan, R.; Worqlul, A.W. Assessment of suitable areas for home gardens for irrigation potential, water availability, and water-lifting technologies. *Water* **2018**, *10*, 495. [CrossRef]
5. Rosegrant, M.W.; Cline, S.A. Global food security: Challenges and policies. *Science* **2003**, *302*, 1917–1919. [CrossRef]
6. Assefa, T.; Jha, M.; Reyes, M.; Tilahun, S.; Worqlul, A.W. Experimental evaluation of conservation agriculture with drip irrigation for water productivity in Sub-Saharan Africa. *Water* **2019**, *11*, 530. [CrossRef]
7. Thome, K.; Smith, M.D.; Daugherty, K.; Rada, N.; Christensen, C.; Meade, B. *International Food Security Assessment, 2019–2029*; Electronic Outlook Report from the Economic Research Service; USDA ERS: Washington, DC, USA, 2019.
8. Uccello, E.; Kauffmann, D.; Calo, M.; Streissel, M. *Nutrition-Sensitive Agriculture and Food Systems in Practice*; FAO: Rome, Italy, 2017.
9. Xie, H.; You, L.; Wielgosz, B.; Ringler, C. Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agric. Water Manag.* **2014**, *131*, 183–193. [CrossRef]
10. Passarelli, S.; Mekonnen, D.; Bryan, E.; Ringler, C. Evaluating the pathways from small-scale irrigation to dietary diversity: Evidence from Ethiopia and Tanzania. *Food Secur.* **2018**, *10*, 981–997. [CrossRef]
11. You, L.; Ringler, C.; Wood-Sichra, U.; Robertson, R.; Wood, S.; Zhu, T.; Nelson, G.; Guo, Z.; Sun, Y. What is the irrigation potential for Africa? A combined biophysical and socio-economic approach. *Food Policy* **2011**, *36*, 770–782. [CrossRef]
12. Bacha, D.; Namara, R.; Bogale, A.; Tesfaye, A. Impact of small-scale irrigation on household poverty: Empirical evidence from the Ambo district in Ethiopia. *Irrig. Drain.* **2011**, *60*, 1–10. [CrossRef]
13. Inocencio, A.B. *Costs and Performance of Irrigation Projects: A Comparison of Sub-Saharan Africa and Other Developing Regions*; IWMI: Colombo, Sri Lanka, 2007.
14. Abebe, W.B.; Tilahun, S.A.; Moges, M.M.; Wondie, A.; Derseh, M.G.; Nigatu, T.A.; Mhiret, D.A.; Steenhuis, T.S.; Camp, M.V.; Walraevens, K.J.W. Hydrological foundation as a basis for a holistic environmental flow assessment of tropical highland rivers in Ethiopia. *Water* **2020**, *12*, 547. [CrossRef]
15. Gowing, J.; Walker, D.; Parkin, G.; Forsythe, N.; Haile, A.T.; Ayenew, D.A. Can shallow groundwater sustain small-scale irrigated agriculture in sub-Saharan Africa? Evidence from NW Ethiopia. *Groundw. Sustain. Dev.* **2020**, *10*, 100290. [CrossRef]
16. Cobbing, J.; Hiller, B. Waking a sleeping giant: Realizing the potential of groundwater in Sub-Saharan Africa. *World Dev.* **2019**, *122*, 597–613. [CrossRef]
17. Tilahun, S.A.; Yilak, D.L.; Schmitter, P.; Zimale, F.A.; Langan, S.; Barron, J.; Parlange, J.Y.; Steenhuis, T.S. Establishing irrigation potential of a hillside aquifer in the African highlands. *Hydrol. Process.* **2020**, *34*, 1741–1753. [CrossRef]
18. Nigussie, L.; Lefore, N.; Schmitter, P.S.; Nicol, A. *Gender and Water Technologies: Water Lifting for Irrigation and Multiple Purposes in Ethiopia*; International Livestock Research Institute (ILRI): Nairobi, Kenya, 2017. Available online: https://core.ac.uk/download/pdf/132688965.pdf (accessed on 25 October 2021).
19. IEA. *Africa Energy Outlook: A Focus on Energy Prospects in Sub-Saharan Africa*; Technical Report; IEA: Paris, France, 2014.

20. Belete, B.; Melak, S. Impacts of small-scale irrigation technology on the nutritional well being of children in the Amhara national region of Ethiopia. *Ethiop. J. Econ.* **2018**, *27*, 29–56.
21. Gurovich, L.; Oyarce, P. New approaches to agricultural land drainage: A review. *Irrig. Drain. Sys Eng* **2015**, *4*, 2.
22. Colback, R.C.H.; Kolb, T. *Handbook for Scaling Irrigation Systems*; World Bank: Washington, DC, USA, 2022.
23. Biswas, S.; Iqbal, M.T. Dynamic modelling of a solar water pumping system with energy storage. *J. Sol. Energy* **2018**, *2018*, 8471715. [CrossRef]
24. Gupta, E. The impact of solar water pumps on energy-water-food nexus: Evidence from Rajasthan, India. *Energy Policy* **2019**, *129*, 598–609. [CrossRef]
25. Van de Zande, G.; Amrose, S.; Winter, A. Evaluating the potential for low energy emitters to facilitate solar-powered drip irrigation in sub-saharan Africa. In Proceedings of the Design Society: DESIGN Conference, Online, 26–29 October 2020; Cambridge University Press: Cambridge, UK, 2020; pp. 2177–2186.
26. Bricca, D.; Bocci, E.; Santini, E. Technical and economic analysis of solar pumping irrigation system for rural areas in Ethiopia. In Proceedings of the 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Genova, Italy, 11–14 June 2019; pp. 1–6.
27. Otoo, M.; Lefore, N.; Schmitter, P.; Barron, J.; Gebregziabher, G. *Business Model Scenarios and Suitability: Smallholder Solar Pump-Based Irrigation in Ethiopia. Agricultural Water Management–Making a Business Case for Smallholders*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2018.
28. Schmitter, P.S.; Tegegne, D.; Adie, A.; Baudron, F.; Blümmel, M.; Lefore, N.; Barron, J. Evaluation of Suitable Water Lifting and On-Farm Water Management Technologies for the Irrigation of Vegetables and Fodder in Lemo District, Ethiopia. 2016. Available online: https://core.ac.uk/download/pdf/132691601.pdf (accessed on 25 October 2021).
29. Bizimana, J.-C.; Richardson, J.W. Agricultural technology assessment for smallholder farms: An analysis using a farm simulation model (FARMSIM). *Comput. Electron. Agric.* **2019**, *156*, 406–425. [CrossRef]
30. 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. Evaluating Irrigation and Farming Systems with Solar MajiPump in Ethiopia. *Agronomy* **2021**, *11*, 17. [CrossRef]
31. Walker, D.; Parkin, G.; Schmitter, P.; Gowing, J.; Tilahun, S.A.; Haile, A.T.; Yimam, A.Y. Insights From a Multi-Method Recharge Estimation Comparison Study. *Groundwater* **2018**, *57*, 245–258. [CrossRef] [PubMed]
32. Yimam, A.Y.; Assefa, T.T.; Adane, N.F.; Tilahun, S.A.; Jha, M.K.; Reyes, M.R. Experimental evaluation for the impacts of conservation agriculture with drip irrigation on crop coefficient and soil properties in the sub-humid Ethiopian highlands. *Water* **2020**, *12*, 947. [CrossRef]
33. Food and Agriculture Organization (FAO). *Human Vitamin and Mineral Requirements: Report of a Joint FAO/WHO Expert Consultation*; Food and Nutrition Division FAO: Rome, Italy, 2001; 303p.
34. Food and Agriculture Organization (FAO). *Human Energy Requirements: Report of a Joint FAO/WHO/UNU Expert Consultation*; FAO Food and Nutrition Technical Report Series 1; FAO: Rome, Italy, 2001; 96p.
35. Institute of Medicine. *Dietary Reference Intakes: The Essential Guide to Nutrient Requirements*; The National Academies Press: Washington, DC, USA, 2006. [CrossRef]
36. Kennedy, E.H.; Krogman, N.; Krahn, H. Sustainable consumption and the importance of neighborhood: A central city/suburb comparison. *Can. J. Sociol./Cah. Can. Sociol.* **2013**, *38*, 359–382. [CrossRef]
37. Bizimana, J.-C.; Richardson, J.W.; Clarke, N.P. Household Food Security and Nutrition Analysis Using a Farm Simulation Model (FARMSIM): Case Study of Robit in Amhara Region, Ethiopia. *ES Food Agrofor.* **2020**, *2*, 22–41. [CrossRef]
38. Agueh, V.D.; Tugoué, M.F.; Sossa, C.; Métonnou, C.; Azandjemè, C.; Paraiso, N.M.; Ouendo, M.-E.; Ouédraogo, L.T.; Makoutodé, M. Dietary calcium intake and associated factors among pregnant women in southern Benin in 2014. *Food Nutr. Sci.* **2015**, *6*, 58729. [CrossRef]
39. Southey, F. EAT-Lancet Diet: Increased Intake of Animal Source Foods Recommended by Researchers to Fill Micronutrient Gap. 31 March 2023. Available online: https://www.foodnavigator.com/article/2023/03/31/eat-lancet-diet-increased-intake-of-animal-source-foods-recommended-by-researchers-to-fill-micronutrient-gap?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright (accessed on 25 October 2021).
40. Aseyehegn, K.; Yirga, C.; Rajan, S. Effect of Small-Scale Irrigation on the Income of Rural Farm Households: The Case of Laelay Maichew District, Central Tigray, Ethiopia. *J. Agric. Sci.* **2012**, *7*, 43–57. [CrossRef]
41. Domènech, L.; Ringler, C. *The Impact of Irrigation on Nutrition, Health, and Gender: A Review Paper with Insights for Africa South of the Sahara*; IFPRI Discussion Paper 01259; International Food Policy Research Institute (IFPRI): Chicago, IL, USA, 2013.