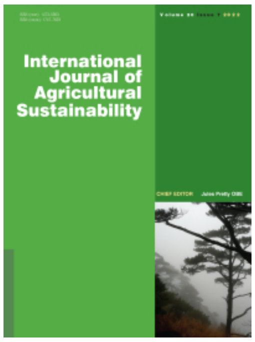

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Lessons learned on socio-ecological drivers of innovation uptake by smallholder farmers–a case study in Kenya

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ABSTRACT

Socio-economic and environmental conditions play an important role in driving technological transformation and sustainability. Based on an innovation project conducted in Kenya, this study demonstrates how socio-ecological analyses can facilitate the adoption of agricultural technologies. This project focused on subsurface water retention technology (SWRT), a climate adaptation approach for sandy soils with proven effectiveness under different ecological conditions. Using maize production data to represent local biophysical conditions, we conducted a cost–benefit analysis (CBA) of SWRT to assess its profitability under current conditions and alternative investment scenarios. We also conducted a livelihood survey and stakeholder dialogue to assess what farmers can afford and identify possible enabling factors for technology adoption and sustainability. The CBA results for maize suggest a long-term return on investment, mainly due to high initial investment costs in terms of labour requirements for SWRT installation (about 70% of initial costs) and a need for irrigation during droughts. In simulations of investments, the break-even point varied depending on the specific investment measures taken alongside SWRT adoption. The livelihood survey indicated that farmers possess resources that could cover the initial investment in SWRT on small plots. However, uptake at scale would require a range of enabling factors, including information on suitable crops and the benefits of investment, and incentives from input and service suppliers. The current yields and prices of maize are not enough for the scaling-up of SWRT. Future studies should incorporate cost–benefit information on high-value crops and analyses of how farmers, and input and service suppliers can better share the investment risks.

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Innovation uptake; business development; climate adaptation; subsurface water retention technology; sustainability

1. Introduction

Various methods and frameworks have been tested worldwide to promote the diffusion of agricultural innovation on farms (Chen & Li, 2022; Dunchev & Beluhova-Uzunova, 2023; Kuyah et al., 2021; Manzano & Perez, 2023). Most research in this area is multidisciplinary in nature, but the methods and frameworks are context-specific and dynamic. For example, to encourage the adoption of agro-environmental technologies by European farmers, diffusion efforts have moved from adoption behaviour and action schemes to result-based schemes (Elmiger et al., 2023). This move was driven by a need to improve the effectiveness of European agricultural policy (Elmiger et al., 2023). In China, the new system for agricultural technology diffusion is based on 295 national agricultural science and technology parks across the country (Chen & Li, 2022). For smallholder farmers, schemes to promote the diffusion of innovative technologies generally involve new methods such as on-farm experiments, demonstration plots, and options-by-context diffusion of technologies (Sinclair & Coe, 2019). The options-by-context method gives farmers the flexibility to adapt

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technologies to their socio-economic circumstances, instead of adopting technologies as fixed packages. All these methods and frameworks aim to enhance social, economic, and environmental sustainability.

Social, economic and environmental circumstances are the main drivers of technological transformation. In agriculture, the socio-ecological systems that link people and nature are complex (Holling, 2001) and affect the performance of all farm activities and crop performance (Nkurunziza et al., 2020). A better understanding of these systems is essential for the successful promotion of innovative solutions. Studies have shown that technology is not scale-neutral (Fischer, 2016). This means that theoretical expectations derived from a range of diffusion models may be more applicable to other products and services such as industrial innovation than agricultural technologies (Sultan et al., 1990). In such models, the rate of adoption is described as a 'coefficient of innovation', leading to a modified exponential diffusion curve or a 'coefficient of imitation', whereby market growth follows a logistic curve (Kumar et al., 2018; Sultan et al., 1990). The coefficient of innovation is affected by external influences on the adopter population (e.g. advertising), while the coefficient of imitation is affected by either internal influences or both internal and external influences.

In a previous study building on logistic curve models (Bacaer & Bacaer, 2011; Gordon et al., 2017; Rogers, 2003), we applied a stochastic model to predict potential benefits and trade-offs of subsurface water retention technology (SWRT) on sandy soils in eight countries in Sub-Saharan Africa (Nkurunziza et al., 2019). The results indicated the high potential of SWRT, provided that non-technical barriers can be overcome. Within the context of climate adaptation in semi-arid conditions, we then established an innovation project in Makueni County, Kenya, testing SWRT on smallholder farms. This paper shares the lessons learned on the complexity of agricultural innovation diffusion and highlights some of the challenges and opportunities in smallholder farming systems.

For smallholder farmers, innovation uptake is often constrained by limited financial capacity and know-how (Kuyah et al., 2021). Innovations are often promoted by local and international development agencies, generally in project format or in government-supported programs, which has been questioned for their lack of sustainability, and new methods are being developed to integrate local knowledge and co-develop locally adapted innovations (Sinclair & Coe, 2019). To achieve greater diffusion and sustainability of innovative technologies, other approaches such as the establishment of new businesses in established companies, business incubators, or start-ups have been used (Fabrício et al., 2015; Tola & Contini, 2014; Zhang et al., 2022). In one such case in Kenya, seed money from the Nordic Climate Facility was used to introduce a start-up business model that involved SWRT, a technology with proven effectiveness in water and nutrient conservation technology in agriculture. The start-up business approach fulfils the dual role of promoting the sustainability of project outcomes and creating a win–win situation for the business and adopters, meaning that both internal and external influences are addressed (Kumar et al., 2018). However, few studies have examined the effect of business creation on the diffusion of innovative solutions for smallholder farmers. More case studies are therefore needed to highlight the challenges and opportunities in promoting innovative agricultural technologies.

The main objective of this study was to use SWRT as a case of climate adaption innovation to highlight the complexity of agricultural innovation uptake among smallholder farmers. Specifically, we share lessons learned from a project, including on-farm demonstrations of the technology, a CBA, a livelihood survey and a start-up business component aimed at promoting the diffusion of agricultural innovations. This study is the first comprehensive assessment of social and ecological barriers to SWRT adoption in Sub-Saharan Africa and other regions with smallholder farming on sandy soils.

2. Materials and methods

We used cost–benefit analysis (CBA) for the valuation of investments, based on input and output data from demonstration farms obtained under local ecological conditions (e.g. high drought levels and a need for irrigation). We then used socio-economic analyses of a livelihood survey to identify farmers' sources of income and their levels of investment in assets other than agricultural production. As a sustainability check, we used stakeholder dialogue to review the willingness of stakeholders to engage with supporting services for SWRT.

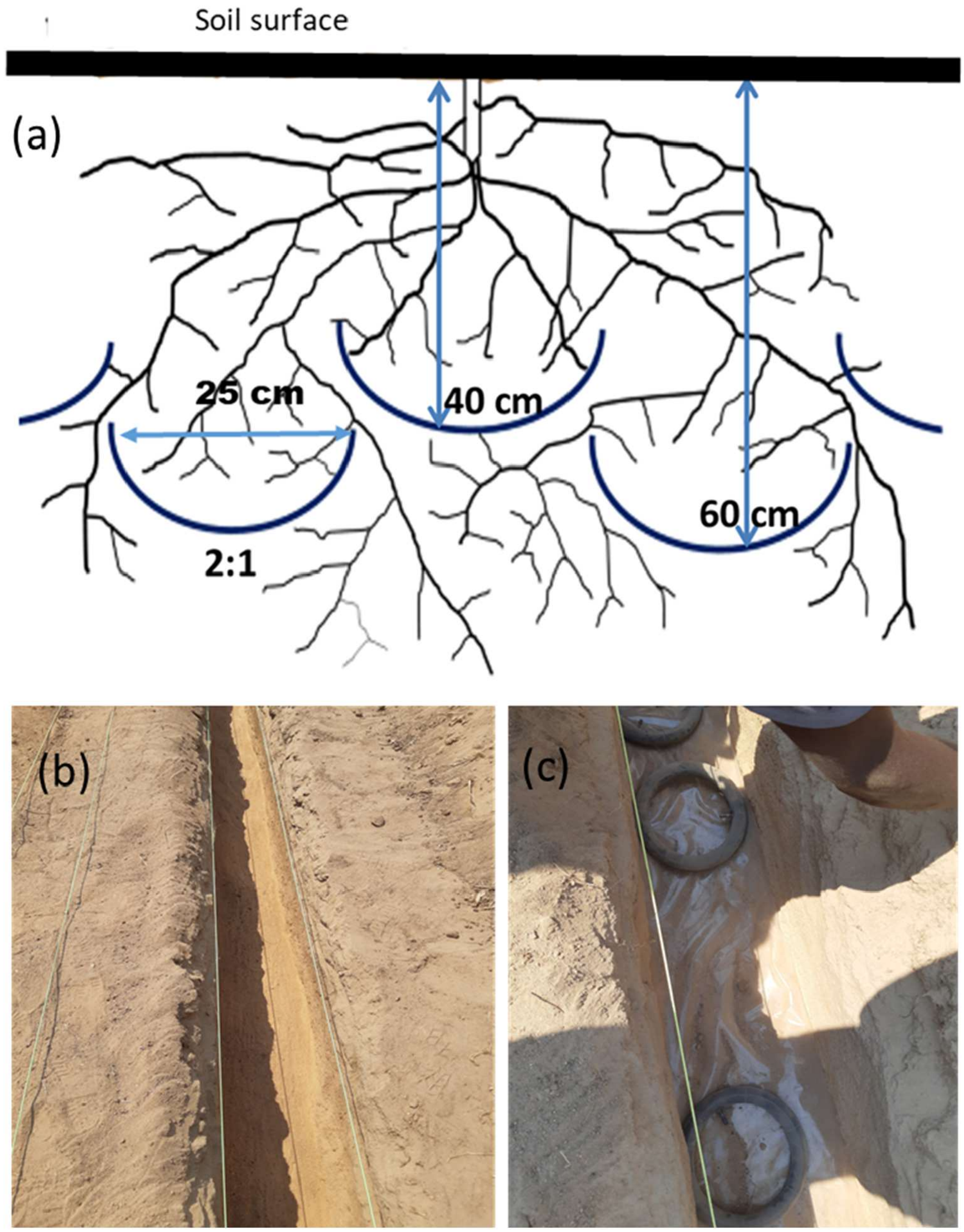

Figure 1. Visual representation of SWRT: (a) location and aspect ratio of U-shaped subsurface water retention technology (SWRT) membranes (25 cm wide) installed in the rootzone in on-farm plots (modified from Kavdir et al., 2014), (b) installation of SWRT with the tranches (left), and (c) laying of the membranes (right).

2.1. Bried technical description of SWRT and its effectiveness

The SWRT method is a relatively new in-field water-harnessing strategy designed to promote sustainable food production on coarse-textured soil. It is a zero-maintenance technology based on engineered impermeable water micro-reservoirs located below and/or adjacent to plant root zones (Kavdir et al., 2014) (Figure 1). SWRT reduces the amounts of water and nutrients lost through deep percolation in coarse-textured soils, resulting in high soil water content in the rootzone of most field-grown plants (Guber et al., 2015). Dual layers of spatially arranged water-saving membranes retain much of the water added to the soil surface by rainfall or irrigation over prolonged periods (Kavdir et al., 2014). The shape and layout of the membranes have a major impact on the amounts of water and nutrients retained. In SWRT membrane modelling, Guber et al. (2015) found that a 2:1 aspect ratio of U-shaped SWRT membranes best retained and maintained soil water, nutrients, and oxygen in the plant rootzone, supplying crop water demand for 5–7 days longer than in sandy soils without water-retaining membranes. According to Kavdir et al. (2014), SWRT can last for over 40 years once installed, and the investment costs are covered within 2–5 years, depending on the crop and market prices. Therefore, SWRT is an appropriate innovative technology with the potential to increase agricultural productivity on sandy soils in semi-arid regions.

Analyses of SWRT application in field and greenhouse experiments have shown increased crop productivity and water savings compared with control conditions. In the USA, SWRT combined with irrigation of maize resulted in an average yield increase of approximately 200% and a water saving between 37% and 72% in coarse-textured soils, while for vegetables, the increase in yield was 50%–200%, with a water savings of approximately 30% (Smucker et al., 2016; Smucker et al., 2018; Kavdir et al., 2014). In field tests of SWRT in semi-aridar regions of Turkey, Demirel and Kavdir (2013) found that SWRT increased the yield of the highest quality turfgrass by 33% while using only 60% of the irrigation water. Two studies with high and low soil salinity in Iraq (Isa, 2016) and an irrigated arid region in Iran (Amirpour et al., 2016) reported that the yield of tomatoes grown with SWRT increased by 10%–89% with a water use efficiency of approximately 80% and a water savings of 67%. In Kenya, demonstration farms for SWRT showed increases of 50% in maize grain yield, 100% in cob number, 150% in cob weight, and 170% in maize stover biomass (Nkurunziza et al., 2022). Increased plant biomass can improve soil health through increased accumulation of soil organic carbon and increased biological activity triggered by increased soil carbon and water retention (Manzoni & Katul, 2014, Védère et al., 2022).

2.2. Description of the study area and on-farm demonstration

The present study was conducted in Makueni County (1°35′–3°00′S; 37°10′–38°30′E) in south-eastern Kenya. Ecological conditions including soil characterization, rainfall pattern, temperatures were presented by Nkurunziza et al. (2022). The rainfall is bimodal, including long and short rain seasons. The long rain season is from March to May, while the short rain season is from October to December. Rainfall during short rain season are more reliable than the long rain season. The low-lying part of Makueni county receives a mean annual rainfall of between 250 and 400 mm while the hilly parts receive between 800 and 900 mm (Makueni Country Integrated Development Plan, 2018). The mean monthly temperature varies from 20 to 26 °C in hilly areas and can reach 35.8 °C in low-lying areas. The combination of low rainfall and high temperatures contributes to high potential evapotranspiration, which causes losses of maize yields and even crop failure.

To foster the diffusion of SWRT in the study region and beyond, we performed on-farm demonstrations on 18 smallholder farms with sandy soil of at least 1 m depth. Installation of SWRT started in July 2020 after training manual installers. To confirm the soil texture and depth on the selected farms, we used an auger to sample the soil at 15-cm intervals to 135 cm depth and determined the soil texture at each interval using a quick field test outlined by Jaja (2016). In each on-farm experiment, three 10 m × 20 m plots were prepared, and SWRT was installed in two of these plots, while the third plot, without SWRT, was used as a control. The capillary rise method described by Goebel et al. (2004) was used to determine the membrane installation depth. The membrane used was a linear low-density polyethylene film that has been shown to improve water and nutrient retention in the crop rootzone (Guber et al., 2015; Kavdir et al., 2014). In the two 200 m^2 SWRT plots in each on-farm demonstration, three U-shaped lengths of the membrane (25 cm width) were installed at 60, 40 and 60 cm depth (see Figure 1). These alternating depths were designed to enable up to 95% interception of vertical soil water flow while still allowing the soil to drain to avoid waterlogging during excessive rainfall (Guber et al., 2015). The crop spacing of the maize was 75 cm × 20 cm, with one seed per 5 cm deep hole. The crop and surface soil management practices of the SWRT plots and control plots were similar for all farms. All plots received 150 kg ha^{-1} of di-ammonium phosphate (DAP) fertilizer (27 kg N ha^{-1}, 69 kg P ha^{-1}) and 4 t ha^{-1} farmyard manure during the planting period. In addition, maize was top-dressed at six weeks after emergence with 90 kg ha^{-1} granulated calcium ammonium nitrate (CAN, 24.3 kg N ha^{-1}). All the plots were kept weed-free by hand and were watered twice during the growing season. The maize stemborer was controlled by standard applications of the pesticides Dudurthrin and Lotus. Aphids in cowpea crops were controlled by dual spraying of the pesticide GOLAN 20 SP (acetamiprid, 200 g L^{-1}).

Maize was grown for three growing seasons as a demonstration to potential adopters and service providers. Two demonstration fields with irrigation achieved good crops during a season when the maize

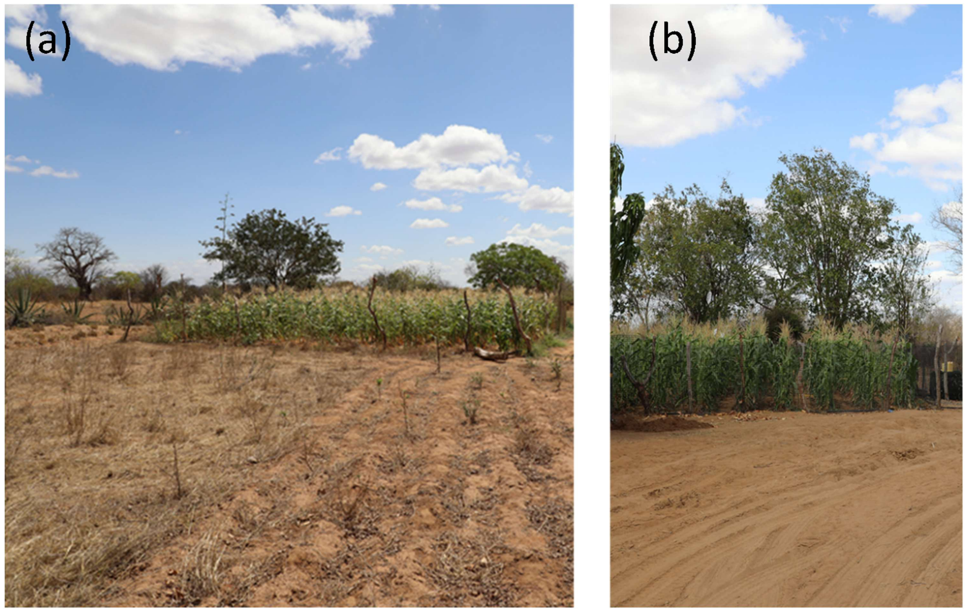

Figure 2. Demonstration farms in Ulilinzi (a) and Kiambani (b) during a season when the maize crop was unable to germinate without proper water management. The pictures show maize on SWRT plots with irrigation.

crop failed in the study area (Figure 2). All field inputs and outputs were recorded and used in the CBA. Maize was harvested in each plot by separating cobs from stover and cutting the stover at 5 cm above ground level. The fresh weight yield of stover and cobs was determined on-site, using a spring balance. Random samples of maize stover were chopped, mixed and their fresh weights were determined. The samples were oven-dried at 65 °C to a constant weight. The biomass of stover was determined by multiplying the total fresh weight per plot by the dry matter content (dry weight/fresh weight ratio). The maize cob samples were air-dried and threshed, and the weights of the grain and shelled cobs were determined.

2.3. Cost–benefit analysis

Farmers, like all small business managers, assess the economic viability and profitability of an innovation before adoption. The CBA plays a critical role in this process, where it serves as a systematic tool for evaluating the economic feasibility of the innovation. By comparing the costs and benefits associated with traditional farming practices (business-as-usual, BAU) with those associated with improved practices, CBA provides quantitative insights into the potential returns on investment and overall economic impact. This helps farmers and stakeholders to understand the financial implications for adopting these improved practices sustainably, ultimately contributing to evidence-based decision-making.

2.3.1. Cost–benefit analysis based on collected data

The CBA involved a combination of real data from the demonstration farms (in Ulilinzi, Kiambani and Kilombelo) and simulation methods where additional measures were tested. We modelled traditional farming approaches (e.g. rain-fed cultivation of maize), the introduction of SWRT membranes without irrigation to sandy soils, the introduction of SWRT membranes with irrigation, and the introduction of SWRT membranes combined with both irrigation and the resulting increase in organic carbon, soil moisture and microbial activity leading to improved soil health.

The improvement in soil health is called ‘soil improvement’. Following Ng’ang’a et al. (2021), we meticulously gathered data on the costs associated with implementing both the BAU practices and the improved practices. Implementation costs are one-time expenditures incurred during the establishment of an innovation and are linked to activities such as land preparation, equipment and/or machinery acquisition, inputs, labour, and harvesting. Maintenance costs are associated with the resources necessary throughout the innovation's lifespan to ensure optimal performance until its end-of-use. Operation costs refer to the ongoing expenses directly tied to the day-to-day running of the irrigation system and farming activities required throughout the growing season. These costs are essential for maintaining productivity during each farming cycle. They include expenses related to irrigation (such as fuel or transportation), labour for managing farm and crop care, as well as costs for agricultural inputs such as fertilizers and pesticides. Operation costs also cover activities such as harvesting, pruning, and other routine crop management tasks.

Our methodology aligned with the requirements of a comprehensive CBA to gain a comprehensive understanding of the installation, maintenance, and operational costs of SWRT and its influence on input demand, yield fluctuations, and the cost of capital. To accomplish this, a thorough comparative assessment was performed, itemizing variable inputs, services, yield per hectare, and market prices per unit of output for both the improved practices and the BAU. The delineation of production costs encompassed labour (including planting, fertilizer application, weeding, operation, and harvesting), equipment and machinery, variable inputs (i.e. seeds, fertilizer and labour) and services (i.e. transportation). Benefits assessed included gains related to increased yield. Yield includes the quantity consumed, sold, and losses associated with post-harvest, pests and diseases, as well as reductions in maintenance and operational costs.

2.3.2. Simulation of scenarios in cost–benefit analysis

In parallel with the implementation and evaluation of SWRT on farmers' plots, we used simulation modelling to delve deeper into the intricate dynamics of the costs of various scenarios to obtain nuanced insights into the variables exerting the most substantial impacts on costs. This approach was deemed crucial because key variables identified in the different scenarios could potentially motivate or attract the involvement of additional and diverse stakeholders, such as credit institutions, county governments, and agricultural ministries. These stakeholders, with a vested interest in different components, could collaborate to ensure that farmers' investments are not only sustainable but also economically viable.

The scenarios analyzed aimed to improve understanding of seven pivotal aspects of the SWRT approach: (i) a 50% reduction in the cost of irrigation tanks for irrigated farming, (ii) a 50% reduction in irrigation labour costs (exclusively for irrigated farms), (iii) a 50% reduction in overall labour costs (applicable to both irrigated and non-irrigated farms), (iv) a 33% reduction in interest rates on borrowed capital (for both irrigated and non-irrigated farms), (v) a 50% reduction in the cost of SWRT per hectare (for both irrigated and non-irrigated farms), (vi) a 75% reduction in the cost of SWRT per hectare (for both irrigated and non-irrigated farms), (vii) a 90% reduction in the cost of SWRT per hectare (for both irrigated and non-irrigated farms), and (viii) a simulation scenario termed 'SWRT + soil improvement'. This scenario aimed to capture the enhancement in soil quality brought about by installing the SWRT membrane. It was assumed that this improvement would lead to a yield increase of 10% in the first 10 years, 5% in the subsequent 5 years, and stabilize at 2% annually thereafter. These simulated scenarios aimed to provide a more granular understanding of the potential cost impacts associated with varying parameters, ultimately contributing to robust decision-making for all stakeholders involved.

2.3.3. Analytical model and profitability indicator

We employed a cost accounting template to systematically account for initial investment costs, implementation expenditures, and ongoing maintenance and operational outlays. In most cases, costs were incurred upfront, followed by subsequent maintenance and operation expenditures, with tangible benefits typically realized after a minimum of one cropping season. Future values were subjected to discounting, with the rate applied determined by the prevailing government-issued interest rate guide for Kenya during the study period. CBA involves aggregating, in monetary terms, all costs and benefits attributable to both private and public investments to ascertain their viability. Private costs and benefits of gains accrued and costs borne by those directly engaged in the consumption and production associated with improved practices are computed from the perspective of farmers (i.e. the implementers). Sometimes, public costs and benefits encapsulate the indirect societal costs and benefits incurred due to the adoption of improved practices (Ng'ang'a et al., 2017). However, in this study, the analysis focused solely on financial costs and benefits from the farmers' perspective. An ex-post CBA model was applied to assess the costs and benefits of innovations by estimating their profitability from the standpoint of farmers.

The benefits of improved practices were quantified as the difference between the net benefits of the improved practice and those of the business-as-usual (BAU) scenario (Equation (1)).

$$\Delta NPV_t = \sum_{t=1}^{T} \frac{(B_{it} - C_{it})\,Improved\,practice\,(j) - (B_{it} - C_{it})\,BAU)}{(1 + r)^t} \quad (1)$$

where

t is the time in years since investment in the improved practice.

B_{it} are the benefits (in US$) for plot i at time t.

C_{it} are the costs (US$) for plot i at time t.

r is the discount rate (15%)[1].

T represents the number of financial periods (years).

The unit of analysis was one hectare; however, the study was conducted on smaller plots (10 m × 20 m). The results were extrapolated to a per-hectare basis by scaling values using the ratio of the plot area to 10,000 m^2 (Equation (2)).

$$Value\,per\,hectare = Value\,on\,plot \times \frac{10{,}000}{A_{Plot}} \quad (2)$$

Common profitability indicators include the net present value (NPV), internal rate of return (IRR), and payback period (PP). This study employed NPV because it reflects the difference between the present value of cash inflows and outflows over a specified period. The NPV is widely used to assess investment profitability; an investment is considered viable if the NPV is positive and if the IRR exceeds the discount rate. NPV was computed as shown in Equation (3):

$$\mathrm{NPV} = \frac{1}{N}\sum_{i=1}^{N}\left\{\sum_{t=1}^{T}\frac{(B_{it} - C_{it})\,Improved - (B_{it} - C_{it})\,BAU}{(1 + r)^t}\right\} \quad (3)$$

where

N is the total number of plots.

All other terms as defined above.

Time horizon: T = 10 years.

2.3.3. Values used in calculations

Average yield per hectare for BAU, the improved practice lifecycle, affected crops, and the average change in yield per hectare following implementation of SWRT were estimated using data collected from field plots, integrating data from surveyed lead farmers. To simulate the physical response curves for activities influenced by the innovation, it was hypothesized that the yields of the affected crops adhered to a response function marked by a lag period initiating upon SWRT implementation, progressing until noticeable changes in yield, and culminating in a linear plateau change (for an in-depth elucidation, see Beattie et al., 1985). Differences in installation costs (equipment, services, inputs and labour), as well as maintenance and operational costs incurred due to SWRT implementation, were also extracted from project implementation records.

2.4. Assessment of farmers' livelihood and partnership building

Following a request from stakeholders to perform CBA, it was important to determine whether local farmers can raise partial or full funds to invest in the technology and what would be the benefits drawn from it. Therefore, sources of livelihood for the targeted farmers were assessed. A survey was conducted using a questionnaire to interview 60 farmers in the study area. The respondents were from three administrative wards (Mtito Andei, Masongaleni and Kitengei). The majority of the respondents were from Mtito Andei (62%) and Masongaleni (37%) wards.

The survey covered demographics, sources of cash, and socio-economic status which are required for the purchase of inputs and services associated to SWRT installation and maintenance (Supplementary material

1). Data on demographics included the gender and age of the household head, formal education level, household size, etc. To identify sources of cash, respondents were asked if they sell crop produce or livestock from their farms or if they have other sources of income outside their farming activities. To gain an understanding of socio-economic status, the respondents were assessed for 12 parameters (type of house, land area, basic furniture (i.e. sofa set and dining set), source of water, type of cooker, cooking fuel, source of power, water storage, means of transport, major household appliances (i.e. refrigerator and television) and other sources of income). These parameters require substantial funds and indicate the possibility of a farmer covering part of the initial investment in SWRT. Each household was assessed against a matrix that consisted of these parameters, rated with a score from one to five in each category. A household could thus potentially score anywhere between the highest possible score of 60 and the lowest possible of 12. To better interpret socio-economic status, we also asked several questions about access to credit, information, extension services, etc.

In addition to the use of on-farm demonstration plots and continuous data collection to conduct CBA, field visits, workshops, and discussions with product and service providers were organized to pave the way for SWRT uptake at scale in the region and beyond. Four field visits involving farmers, extension officers, private companies, and local and regional administration representatives were conducted, and three workshops were organized to show the effectiveness of SWRT and to promote its diffusion. Workshops give stakeholders the opportunity to discuss methods of diffusion at the scale of the technology through the mitigation of risks along the agricultural commodity value chain (Nkurunziza et al., 2022). To boost business development by using SWRT, efforts were made to establish partnerships between a start-up company at one project partner (Jomo Kenyatta University of Science and Technology Enterprises, JKUATES) and input and service suppliers. We started by providing training on the manual installation of SWRT. Twenty installers were trained, six of which were certified and placed in the SWRT expert pool to undertake installation in the event of demand from new adopters. A business developer was hired to engage in conversations with farmers, farmers' organizations, extension officers, input suppliers and service suppliers such as micro-finance suppliers and banks. Over the course of the project, different media outlets (television, blogs, factsheets, newspapers, etc.) were used to communicate the project results and success stories. A selection of communication materials is listed in Supplementary material 2.

3. Results

3.1. Cost–benefit analysis

3.1.1. Maize production under current conditions

Under current conditions, CBA on the introduction of SWRT suggested a negative NPV ranging from USD −6,862 to USD −10,870, depending on the location and on whether maize was irrigated or not (Table 1). In Ulilinzi (see Figure A1 in the Appendix), combining SWRT with soil improvement but without irrigation (which accounted for approximately 9% of the total implementation costs) resulted in an NPV of USD −8,972 per hectare, while implementation of SWRT without irrigation and soil improvement marginally reduced the value to USD −9,071 per hectare when encompassing both the long-rain and short-rain[2] seasons. The application of SWRT with soil improvement (excluding irrigation) to plots dedicated to maize cultivation further reduced the NPV to USD -6,862. Implementing SWRT without soil improvement and

Table 1. Net present value (NPV, USD ha^{-1}) of implementing subsurface water retention technology (SWRT) on non-irrigated and irrigated farms at different study locations. SWRT yield represents benefits associated with per-hectare yield in both the long-rain and short-rain season, while SWRT Yield (S01YD) represents benefits associated with per-hectare yield only in the long-rain season.

	Location	SWRT yield + soil improvement	SWRT Yield	SWRT yield + soil improvement – (S01YD)	SWRT yield (S01YD)
Non-irrigated	Ulilinzi	−8,972	−9,071	−6,862	−6,941
	Kilombelo and Kiambani	−10,470	−10,870	−9,576	−10,270
Irrigated	Kitengei	−9,413	−9,752	−8,336	−8,727

NB: The units are US$ per hectare. All financial figures are presented in nominal terms (USD) and are based on the year data collection was conducted (2020). The results are normalized to a per-hectare basis.

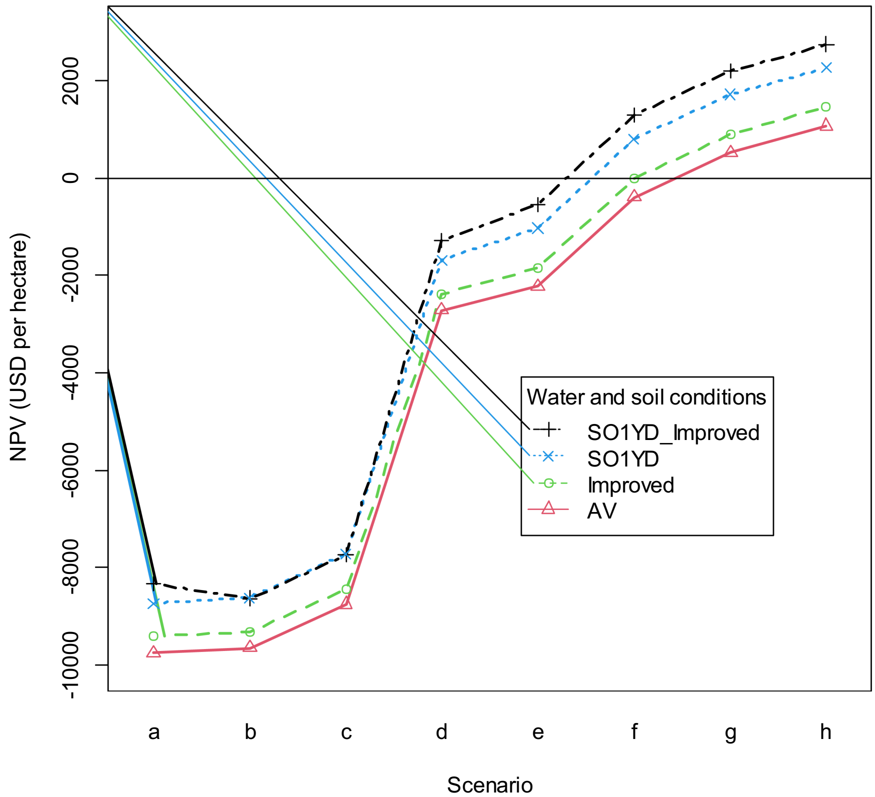

Figure 3. Results (per hectare) of cost–benefit analysis on subsurface water retention technology (SWRT) implementation on irrigated farms in Kitengei Ward in four different soil and water management scenarios: SWRT yield in both long- and short-rain seasons (AV); SWRT yield in both the long- and short-rain seasons with soil improvement (Improved); SWRT yield in the long-rain season with soil improvement (SO1Y_Improved); and SWRT yield in the long-rain season only (SO1YD). Scenarios: (a) lower tank cost, (b) lower tank cost, (c) lower tank cost and lower installation cost, (d) lower tank cost and installation cost, and 50% lower labour cost, (e) lower tank cost and installation cost, 50% labour cost and 33% discount rate, (f) lower tank cost and installation cost, 50% labour cost, 33% discount rate and 50% SWRT cost, (g) lower tank cost and installation cost, 50% labour cost, 33% discount rate and 75% SWRT cost, (h) lower tank cost and installation cost, 50% labour cost, 33% discount rate and 90% SWRT cost.

irrigation on these plots yielded an NPV of USD −6,941 when the assessment included yield during the long-rainy season[3].

In Kilombelo and Kiambani, a combination of SWRT with soil improvement but no irrigation resulted in a very unfavourable NPV of USD −10,447 per hectare. The implementation of SWRT without irrigation slightly reduced the NPV to USD −10,870 per hectare, spanning both the long-rain and short-rain seasons (Figure A2 in the Appendix). The integration of SWRT with soil improvement (excluding irrigation) on maize plots improved the NPV to USD −9,576. Implementing SWRT without soil improvement and irrigation on these plots resulted in an NPV of USD −10,270, which was based on yield during the long-rain season.

The findings for irrigated maize demonstrated the effects of introducing SWRT to farm plots cultivating maize coupled with soil improvement and irrigation, which led to an unfavourable NPV of USD −9,413 per hectare. The implementation of SWRT with irrigation slightly decreased the NPV to USD −9,752 per hectare for both the long-rain and short-rain seasons. However, the NVP improved to USD −8,336 when SWRT was applied jointly with soil improvement and irrigation on plots dedicated to maize cultivation. The implementation of SWRT with irrigation but without soil improvement in these plots resulted in an NPV of USD −8,729, which was based solely on yield during the long-rainy season.

3.1.2. Scenario analyses of maize production

Figures 3 and 4 show the effects of introducing diverse improvement practices under scenarios involving irrigation, with specific modifications. In scenario (a), elimination of installation costs for irrigation tanks resulted in a notable increase in NPV across all improvement practices of approximately USD 105. In (b), the

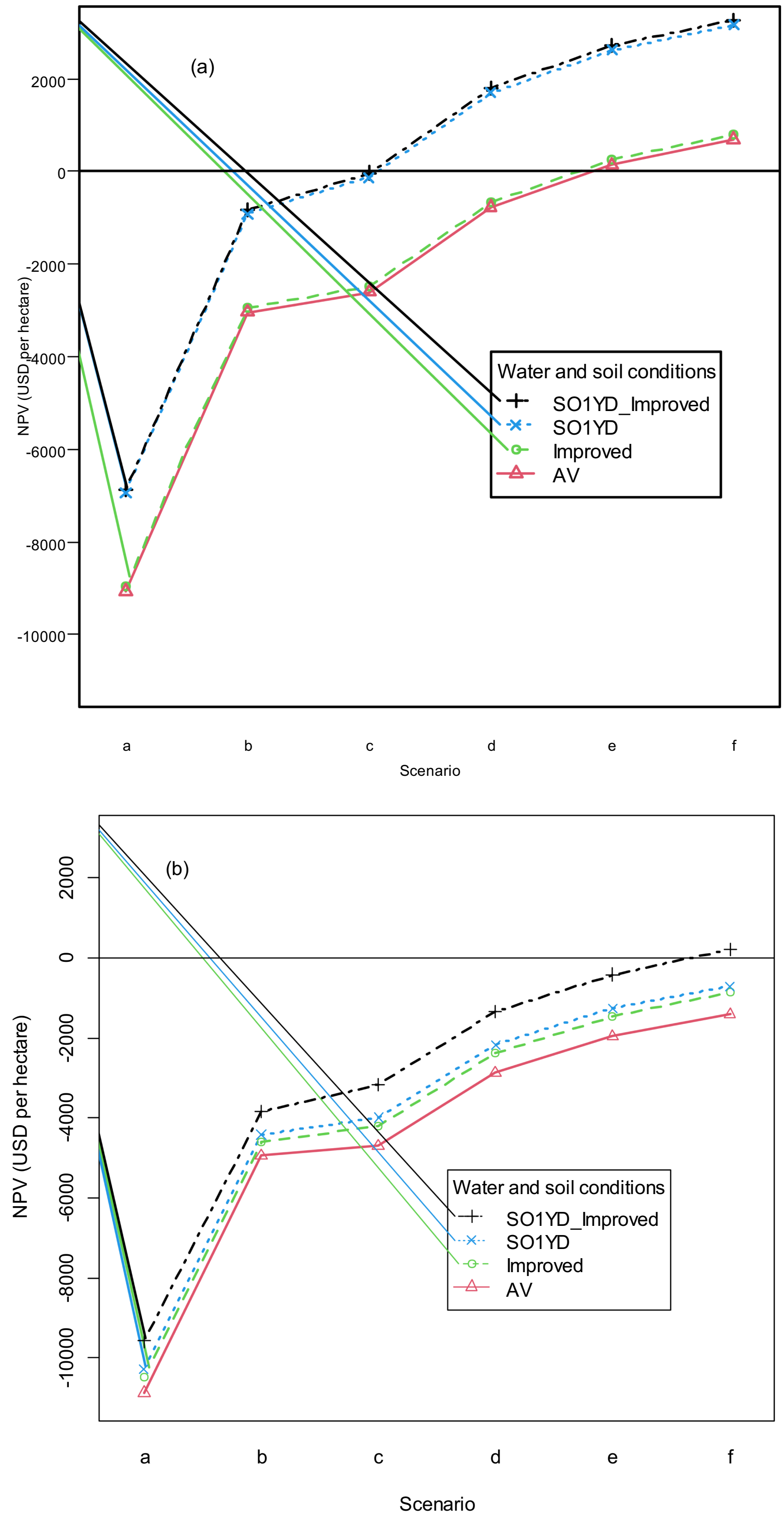

Figure 4. Results (per hectare) of cost–benefit analysis on subsurface water retention technology (SWRT) implementation on non-irrigated farms in (a) Ulilinzi and (b) Kilombelo and Kiambani in four different soil and water management scenarios: SWRT yield in both long- and short-rain seasons (AV); SWRT yield in both the long- and short-rain seasons with soil improvement (Improved); SWRT yield in the long-rain season with soil improvement (SO1Y_Improved); and SWRT yield in the long-rain season only (SO1YD). Scenarios: (a) as-is, (b) 50% labour cost, (c) 50% labour cost and 33% discount rate, (d) 50% labour cost, 33% discount rate and 50% SWRT cost, (e) 50% labour cost, 33% discount rate and 75% SWRT cost, (f) 50% labour cost, 33% discount rate and 90% SWRT cost.

elimination of tank costs had a more substantial impact, increasing NPV by approximately USD 900 across all scenarios. In scenario (c), a 50% reduction in the labour time required resulted in a substantial increase in the NPV of approximately USD 6,000. In (d), a 33% reduction in interest rates led to an increase in NPV of approximately USD 600. In (e), a 50% reduction in the cost of the SWRT membrane increased the NPV by USD 1,800 across all improved practices. Therefore, nuanced adjustments in these selected factors influenced the economic viability of SWRT. Figure 3 illustrates the magnitude of impacts at the Kitengei site. Similar trends in NPV were observed in Kitengei (Table A1 in the Appendix), Ulilinzi (Table A2), Kilombelo (Table A3) and Kiambani.

3.2. Livelihood conditions in the target farmer group

3.2.1. Demographics

The majority of the respondents (80% or 48%) were female, of which 14 did not have partners because of death or separation. The majority had a primary school education (67%), while 22% had attained secondary school education. A few respondents (5%) had no formal education, and a similar number had attained tertiary education in the form of a diploma. The respondents' ages ranged from 20 to over 70 years, with a median age of 50–59 years. In line with the rest of Kenya, the farming population in Makueni County is ageing, with almost two-thirds of the respondents over 50 years of age and fully 73% of the respondents aged 40 years and above. In addition, Kenyan farmers have a lower level of education and much fewer professional qualifications compared with those engaged in other occupations, which has negative implications for the future of farming in the country.

The 60 households surveyed included a total of 262 people, of whom 199 were children and 55 were grandchildren. Relatives and a few workers ($n = 8$) also resided in the households. One-third of the respondents' children were away because they were either growing up and living elsewhere or attending school or college. The average number of people living in a household was between 5 and 6.

3.2.2. Sources of livelihood

The farmers surveyed reported that they do not obtain their livelihood solely from agriculture. Almost all the respondents engaged in various agricultural activities but also in other forms of economic activities, including micro-business (69%) or casual labour (32%) and formal employment e.g. teaching (one respondent). The micro-businesses included retail kiosks, charcoal burning, tailoring, local (bicycle and motorcycle) transport, and providing training in various agricultural skills. Casual labour included work in agriculture, construction, and loading/offloading commercial vehicles. In addition to the income streams of the respondents, their spouses (45%) are also engaged in small businesses, casual labour, and employment. Many households (47%) had a third income stream from spouses who worked away or grown-up children who were economically active and contributed to the household livelihood. Approximately 32% of the households received more than Ksh 30,000 per annum (~USD 240, October 2022).

The total cash flow in the previous year deriving from crops, livestock, and other remittances ranged from zero to 709 USD, with average and median total cash flows of 231 USD and 223 USD, respectively. Figure 5 shows cash flow sources, including farming activities (sold crops or livestock) and remittances from relatives. The sources of cash flow depend on the age class of the respondent (Figure 5a). All age classes received remittances, which were the most significant cash source (above 100 USD), except for the 'over 70 years' group. Livestock sales were the next largest source of cash flow for the age classes 20 s, 30 s, 40 s and over 70 years. On average, crop sales yield less than 50 USD per year. Cash flow classification by gender (Figure 5b) revealed that cash from farming activities was gender-sensitive, with income from livestock sales going to males and that from crop sales to females. The levels of remittances obtained by gender were comparable (Figure 5b).

3.2.3. Matrix of socio-economic status

Overall, the standard of living was found to be low among the farmers surveyed. The highest score in the matrix of socio-economic status was 40, and the lowest score was 17 (Figure 6). This means that none of the respondents had a high standard of living, although 10% were above the mid-point score of 36. However, 43% achieved scores of 24 and below, placing them in the lowest category. The mean score was 27, the median was 26, and the mode was 22. Each of the parameters included in the evaluation of socio-economic

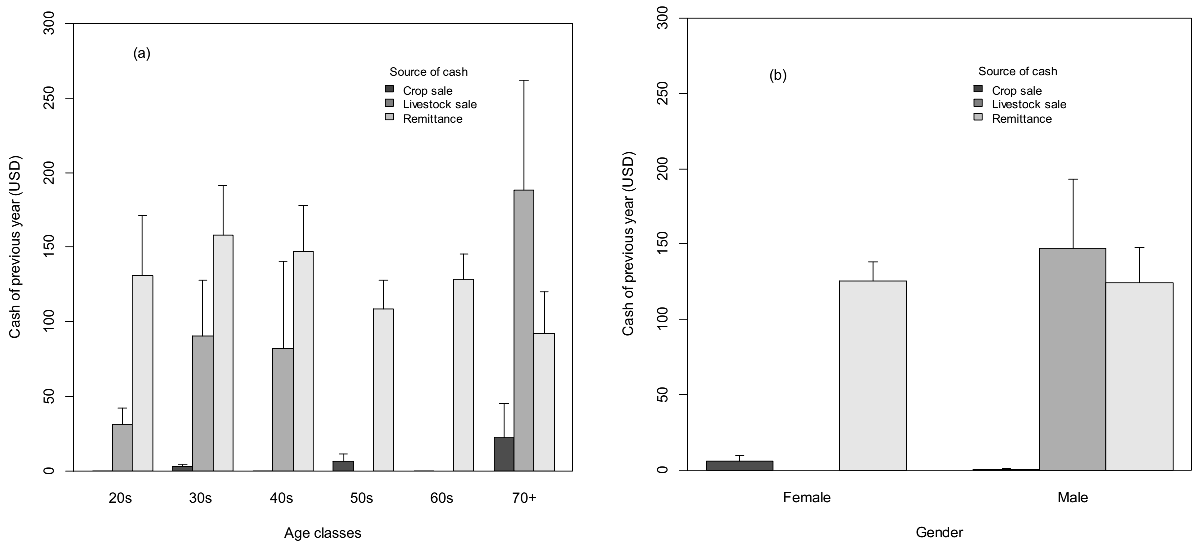

Figure 5. Cash flow of respondents ($n = 60$) from different sources (crop sales, livestock sales, and remittances from relatives) in the year preceding the survey in relation to (a) respondent age class: 20 s ($n = 7$), 30 s ($n = 9$), 40 s ($n = 8$), 50 s ($n = 21$), 60 s ($n = 9$), and over 70 ($n = 6$), and (b) gender: male ($n = 14$), female ($n = 46$).

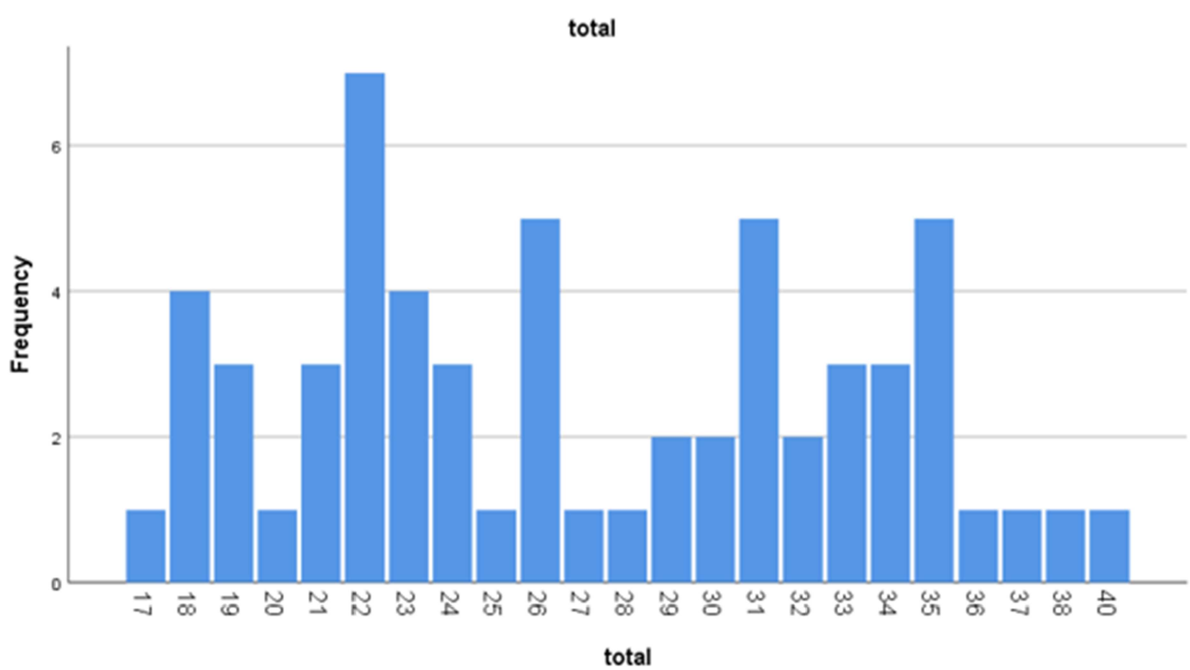

Figure 6. Frequency of scores of socio-economic status, derived by summing up scores for 12 parameters (type of house, land size, basic furniture, source of water, type of cooker, cooking fuel, power, source of water, water storage, means of transport, major household appliances, and other sources of income. Each parameter was rated on a scale from zero to five, with a possible maximum score of 60.

status explained differences in household livelihoods. Overall, socio-economic status was positively correlated with the total cash flow of the farmer, with $R^2 = 0.21$ and P-value < 0.001 (Figure 7). When analyzed on a gender basis, the correlation was maintained for households headed by females ($R^2 = 0.32$, P-value < 0.001) but the relationship was lost with households headed by males (non-significant correlation).

The respondents scored highly on the socio-economic indicator 'housing', with approximately 75% living in permanent houses constructed using locally made bricks and iron roofing sheets. This type of construction is common among the local community (Kamba) and thus relatively accessible to many households. Approximately 20% of the remaining respondents lived in semi-permanent housing and a small minority

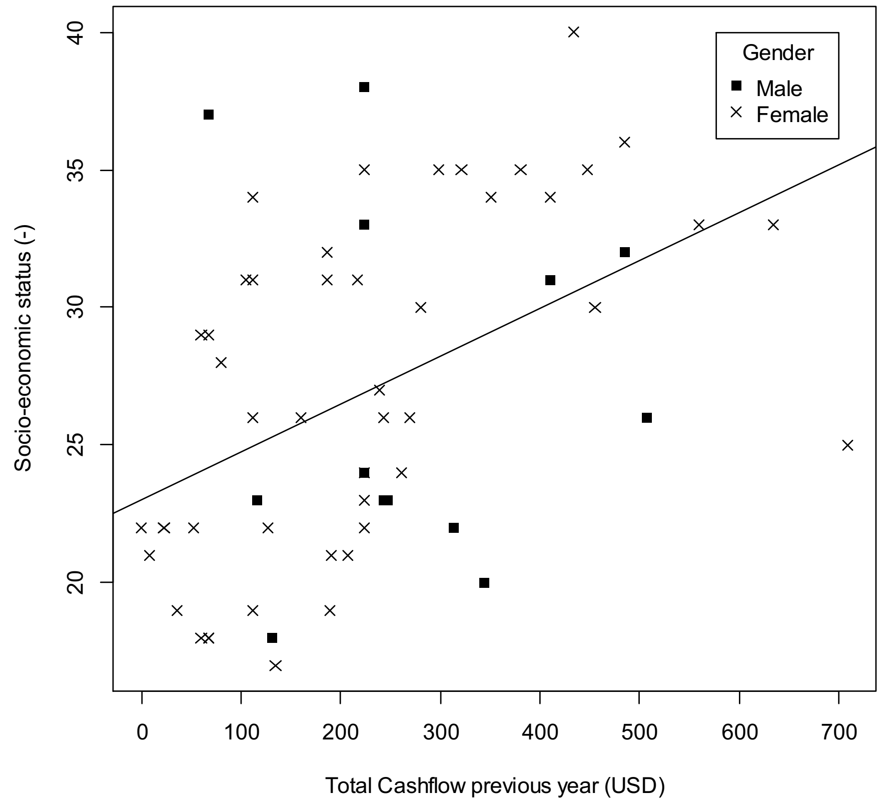

Figure 7. Relationship between socio-economic status of the respondents and their total cash flow in the year preceding the survey.

(6%) lived in temporary housing. When asked how they had obtained money to build their houses, most respondents attributed it to a combination of farming, small and medium enterprise activities, and casual labour. A few reported that their children had built a house for them, while one respondent said it was funded by the sale of land. Another important indicator in which the respondents scored highly was 'powering the home', with the vast majority (85%) using solar power.

Land ownership and land use differed among households. All the respondents owned the land they farmed, with approximately 44% owning more than one tract and a few farming several tracts. Two-thirds of the respondents held title deeds to the land they farmed, with the rest still waiting for the government to complete land demarcation. Approximately 68% of the farmers operated a holding of 2–4 acres, with 25% having 5–10 acres and 3% owning more than 10 acres. Apart from the main parcels of land that the respondents farmed, 37% had other tracts of land available elsewhere.

Most households scored low for seven of the 12 parameters considered. With respect to the 'type of cooker', 97% used stones, and 100% used firewood as cooking fuel. Approximately 97%, 73% and 98% had no sofa set, dining set, and refrigerator, respectively. All households owned a radio, with 75% describing it as their most reliable source of information, while 12% were dependent on their mobile phones and a minority cited word of mouth. The greater majority did not own any means of transport and depended on their feet or public means (mostly bicycles or motorbikes) to get around. Approximately 55% of the respondents owned water tanks, 25% had access to piped water, and another 25% had sunk shallow wells. Half the respondents had to buy water (delivered by donkey carts), which was a major budget item for those respondents. During the rains, they were able to harvest some water and/or fetch from seasonal streams for a short period. When they fetched water themselves, they used wheelbarrows or hired bicycles or motorcycles.

3.3. Outcomes of the follow-up of investment and partnership establishment

Project partners (led by JKUATES as the future promoter of the SWRT), equipped with a pool of SWRT installers and experience with the technology, identified and initiated partnerships with four key partners:

Bobmil (SWRT membrane provider), farmer organizations (e.g. Kenya Smallholders Farmer Forum, KSFF), World Relief (International NGO) and Agrimech Africa. The aim was to exploit the potential of SWRT and to garner support from different stakeholders. Agrimech Africa is a private company specializing in mechanization to reduce SWRT installation labour costs. Other partners specialize in the provision of agricultural technologies such as irrigation techniques, seeds, agricultural inputs, and microfinance. Four initiatives were developed. First, the project partners-initiated efforts to find new investments, together with Agrimech Africa, for the mechanical installation of membranes as a way to increase installation efficiency, thus reducing costs. Second, together with World Relief, which has 13 years of experience with irrigation systems for smallholder farmers in Kenya, the project team sought follow-up investments to find suitable irrigation systems for high-value crops. Third, Bobmil agreed to a payment plan over a reasonable period rather than an upfront payment at purchase. Fourth, synergies within the farmers' organization KSFF that might facilitate the acquisition of group loans and other sources of funding were promoted.

4. Discussion

4.1. Social, environmental and economic sustainability

The CBA provided valuable insights into the intricate relationships among technological, environmental, and socio-economic factors in agricultural decision-making. As in other regions in Sub-Saharan Africa, the farmers in the study area have a lower level of education than workers engaged in other occupations (Lindsjö et al., 2021), which has negative implications for decision-making. The CBA results highlighted the intricate dynamics associated with the introduction of SWRT in maize farming at all three sites (Ulilinzi, Kilombelo and Kiambani), whether under irrigation or not.

Importantly, the negative NPV values observed when SWRT was implemented without irrigation underscore a critical policy implication: water management interventions must be integrated into any SWRT scaling strategy. This finding signals the need for enabling policies that support irrigation infrastructure development, financial incentives, or subsidies to offset the high upfront costs. In comparison with findings in other CBAs conducted on land and water management practices in Kenya (McHaro & Maghenda, 2021), the cost of SWRT installation together with irrigation of maize in our study area was more than 10-fold greater. A previous CBA conducted on climate-smart soil and water conservation practices in Southern Africa showed economically viable results (Mutenje et al., 2019). Interestingly, combining SWRT with soil improvement, excluding irrigation, substantially improved the NPV, suggesting that the synergistic effects of these practices can enhance economic outcomes. In contrast, implementing SWRT without soil improvement or irrigation resulted in less favourable NPV values, emphasizing the importance of comprehensive agricultural strategies that consider multiple factors, including soil quality and water management. Season-specific assessment further underscores the need for nuanced approaches tailored to specific ecological conditions. Farmers in Makueni County have experienced severe and extreme droughts on a regular basis since the 1990s (Mutua et al., 2015), necessitating the use of irrigation for increased efficiency of SWRT.

Installation of SWRT involves a range of costs, including the purchase of membranes and water storage tanks for irrigation, installation of the tanks, manual labour, interest rates in cases of loans, etc. While irrigation is needed to successfully increase maize productivity under SWRT, it requires additional investments that may not offset the costs associated with the technology, as shown by the incremental increase in NPV resulting from elimination of installation and tank costs (Figure 3). The other major investments are labour costs, SWRT membranes, and interest rates used in the calculation of NPV. The reductions in these improved NPVs underscore the economic sensitivity of SWRT to various financial parameters. These findings highlight that policy instruments such as tax exemptions on SWRT membranes, government-backed credit facilities at reduced interest rates, and labour-saving mechanization programs could substantially increase the economic feasibility of SWRT. This creates a strong case for involving multiple stakeholders, including policy makers, private sector suppliers, and financial institutions, to share the upfront investment burden and create an enabling environment for adoption.

The comprehensive visual representation provided in this paper aids in understanding the magnitude of these impacts, offering a holistic perspective for informed decision-making. The consistent trends observed across Ulilinzi, Kilombelo and Kiambani further validate the generalizability of these findings across different agricultural contexts. However, it is important to note that most costs associated with SWRT are upfront expenses and that the membranes have remained in the field for ~40 years (Kavdir et al., 2014), which is not the case for other agricultural practices. Moreover, the common practice of smallholder farmers is to invest mostly in short-term practices (Kansanga et al., 2021).

To improve uptake, a multi-stakeholder approach is required. Financial institutions could design accessible credit packages, farmers' associations could negotiate favourable terms for group purchases, and policy makers could incentivize technology providers to lower prices through subsidies or tax reductions. These partnerships would not only reduce initial costs but also align SWRT adoption strategies with broader national goals on food security and climate resilience.

The results of the sensitivity analysis were multi-faceted and can be significant in guiding decision-making processes related to agricultural improvement practices, particularly those involving irrigation. The key findings were the significance of upfront expenses and the need to leverage these expenses from stakeholders to contribute the products and services needed for the successful implementation of SWRT. The NPV value increased across all improvement practices when installation costs for irrigation tanks were eliminated, indicating high sensitivity to upfront expenses. This implies that targeted subsidy programs for irrigation infrastructure could serve as a policy lever to improve technology uptake.

The substantial rise in NPV (by approximately USD 900) when tank costs were abolished underscores the importance of considering and potentially subsidizing or incentivizing the acquisition of irrigation tanks. This finding also indicates that financial interventions targeting tank costs could significantly enhance the economic outcomes of agricultural improvement practices. The substantial increase in NPV (approximately USD 6,000) resulting from a 50% reduction in labour costs emphasizes the economic efficiency that can be gained through labour cost optimization. Strategies focused on enhancing labour productivity or reducing associated costs could play a pivotal role in increasing the financial viability of agricultural improvement practices. The noticeable increase in NPV (by ~USD 600) due to a 33% reduction in interest rates highlights the sensitivity of these practices to financing considerations. Lower interest rates could substantially improve the economic attractiveness of such initiatives, suggesting that financial instruments with favourable terms may contribute to their success. The consistent increase in NPV, exceeding USD 1,800, resulting from a 50% reduction in the cost of SWRT membranes underscores the cost-efficiency impact of advances or cost reductions in technology components. Innovations or measures that contribute to reducing technology-related expenses could increase the overall economic feasibility of these approaches.

Overall, our findings provide insights into the economic dynamics of agricultural improvement practices in sandy soils under various scenarios. These findings have direct policy relevance, as they indicate that without targeted cost-reduction strategies, SWRT adoption will remain limited. Therefore, stakeholder-driven approaches, including public–private partnerships, credit schemes and input subsidies, are essential for scaling up SWRT in smallholder systems.

4.2. Challenges and opportunities in smallholder farming systems

The high degree of investment in solar power (85% of households surveyed) can be attributed to clever marketing by solar power providers, who have covered the study area with an innovative package that provides a solar panel, battery and five light bulbs for Ksh 18,000 (~USD 150 in October 2022, when the survey was performed), paid in instalments. For just slightly more, a household can obtain a connection for a television. The advantage of this scheme is that Makueni County experiences bright sunlight all year round, so most people can charge their phones and light up to five rooms at no extra charge. This successful uptake encourages the adoption of agricultural technologies such as SWRT, since despite a relatively low standard of living, the local population is willing and able to pay for technology that improves their lives if it is packaged in ways that make it accessible to them. While the farmers surveyed were definitely low income, they were not food insecure, as might have been expected (Frelat et al., 2016). The families were able to meet their food, shelter, health and education needs, with a small margin for unseen costs specific to their environment (van de Ven et al., 2021).

While cash flow from crop sales remained very low (since most production was consumed within the household), the survey showed that households generated income from economic activities outside farming. Diversification of income sources among small-scale farmers is common (Giller et al., 2021), and the income range reported was within that reported in a previous study (Hammond et al., 2017). Without counting income from activities other than farming, crop and livestock sales together with remittances could amount to approximately USD 700 per year. If properly used, part could contribute to investments in agricultural innovations. Farmers could start with small plots (e.g. 100 m^2) per year and add more plots over time. While maize is a rain-fed crop worldwide, there is evidence that the irrigation of maize increases grain yield (Allakonon & Akponikpè, 2022). In terms of food security, smallholder farmers at risk rely on maize (Kombat et al., 2021), in which case profit could be derived from crops other than maize, e.g. vegetables grown in rotation with maize, which would quickly improve the NPV. This diversification could complement SWRT adoption by generating early income streams that offset upfront costs, making the technology more attractive and sustainable for farmers.

The income generated could then be used for expansion of technology and would probably attract more service providers such as membrane manufacturers, micro-credit institutions, etc. Remittances are very important to low-income households in that they enable better housing, access to clean water, better diets, decent clothing, access to healthcare, clean energy, and business initiatives (Turiján-Altamirano et al., 2015). They could also cover some of the costs associated with initial investments in agricultural innovation. Policy interventions could tap into remittance flows by creating matching grant programs or remittance-based savings schemes targeted for agricultural technology adoption.

However, remittances also have negative effects (Piras et al., 2018) in that they provide disincentives for agricultural production and encourage a brain drain and breakdown of social structures (e.g. most men or young people leave, causing social imbalance). Approximately 90% of the respondents in our survey reported that they had no access to credit, which was consistent with the fact that they had no collateral for loans. However, as indicated by the fact that most farmers have purchased solar power through credit and repaid loans without many problems, this barrier can be overcome using credit systems that make sense to smallholder farmers. This suggests that successful adoption of SWRT depends on tailored financial products, such as microcredit, savings groups, or bundled service packages. Stakeholders, including microfinance institutions, local cooperatives, and agribusinesses, can play a central role in offering these solutions.

A lack of access to information and knowledge can contribute to a low uptake of agricultural technologies such as SWRT. The farmers in Makueni County were found to have a low level of education, with only 22% having attained high school education, leading to significant gaps in understanding the relevance of agricultural innovations and production among smallholder farmers with declining yield per acre over time. For example, the average yield of the staple crop maize in Kenya on smallholder farms currently stands at 30% of the potential yield, i.e. 1.77 tons per hectare against a potential yield of 6 tons per hectare (Njeru et al., 2022), while in Makueni County, the yield gap is much worse, with total crop failure occurring in three out of five years according to local farmers. This can be attributed to the lack of the technical skills and training needed for significant improvement in farming, resulting in depleted soils and increased plant disease and pest loads.

Limited water resources and inadequate infrastructure in rural areas pose challenges to smallholder farmers. In semi-arid areas of Makueni County farming often requires irrigation, but most farmers are not near the electrical grid, there is no provision for irrigation, and internet connectivity is rare. All the farmers surveyed had basic mobile phones, and most had access to radio and extension services, but this did not appear to have improved agricultural production. In addition to the above challenges, social and cultural factors encourage resistance to change, downplay perception of benefits, and amplify fears of risk associated with the unknown. A case in point is that Makueni County is not ideal for maize production under current climate conditions, yet farmers prefer to plant it season after season despite repeated crop failure.

4.3. Business creation to sustain outcomes of innovation

Analysis of the partnership efforts demonstrated that business creation can drive the sustainability of agricultural innovation and its impacts. The four participating organizations (Bobmil, KSFF, World Relief, and Agrimech Africa) recognized the potential of SWRT and were willing to share the installation burden with farmers, which would reduce the initial investment in a win-win situation. This aligns with the CBA findings, which highlighted the economic sensitivity of SWRT to upfront costs, indicating that collaborative models between businesses and farmers are key to making SWRT viable.

If successful, mechanization could reduce labour costs, which are currently estimated to constitute 70% of the initial investment. However, for this to happen, business developers need to be committed and engaged in more actions. Their commitment may also need to go beyond businesses and include institutions. Public–private partnerships involving government agencies, financial service providers, and input suppliers should be strengthened to reduce costs through bulk procurement, subsidies, and efficient supply chains.

Our finding of gender inequality in income levels supports the need to consider power and resource allocation within households (Quisumbing, 2003) for better uptake of agricultural innovations. This means that business strategies around SWRT should include gender-sensitive financing and training to ensure that women – who often bear much of the agricultural labour – are not excluded from the benefits of innovation.

Lack of access to markets also plays an important role in discouraging smallholder farmers from investing in new technology and has been identified as a risk in the study region, where smallholder farmers are subjected to suboptimal prices and heavy losses due to deterioration of produce on-farm (Nkurunziza et al., 2022). Since SWRT aims to improve productivity, market-oriented interventions must accompany its adoption strategy. The development of aggregation models, linking farmers to buyers, and investing in rural infrastructure will ensure that productivity gains translate into income, making the investment worthwhile.

5. Conclusion

The findings from this study provide two insights that are needed to optimize crop production on sandy soils in semi-arid areas. First, for maize growing under the ecological conditions of Makueni, SWRT will be beneficial only when irrigation is added to the initial investment. This is because uncertain rainfall prevents the SWRT from effectively increasing its value. Second, the socio-economic conditions of households need the interventions of other actors to enhance their uptake. Therefore, agricultural technology scaling requires a thorough understanding of the package coming with a technology in given agro-ecologies and the innovative enabling factors to increase the socio-economic conditions that will sustain the uptake.

Based on these findings, we recommend the following:

- The government should provide targeted subsidies or tax incentives for irrigation infrastructure and SWRT membranes, develop supportive policies for credit access, and invest in rural water infrastructure to make irrigation feasible.
- NGOs can play a critical role in capacity building through farmer training, demonstration plots, and awareness campaigns to improve understanding of SWRT benefits and technical requirements.
- The private sector, including microfinance institutions and agribusinesses, should develop innovative financing models (e.g. pay-as-you-go systems) and bulk procurement mechanisms to reduce upfront costs for farmers.

Owing to time limitations, this study focused solely on the financial dimension of the CBA, excluding environmental and social aspects. Future research should incorporate comprehensive economic, environmental, and social analyses of SWRT over the long term, while also examining gender dynamics and equity considerations to promote inclusive adoption strategies.

Endnotes

1. Based on the average interest rate applied by commercial banks in Kenya during 2020–2024.
2. In our study area, the long-rains (March–May) and short-rains (October–December) define the region's bimodal rainfall pattern, which is crucial for agriculture and water availability. The long rains are typically more reliable and intense, supporting the planting and growth of staple crops like maize, sorghum and beans, while replenishing water sources. In contrast, the short rains are less intense and more erratic but still vital for cultivating fast-

maturing crops such as cowpeas and green grams. These seasons significantly influence livelihoods, livestock production and water access.

3. Since there was only one farmer in Kiambani, we combined their data with that of Kilombelo for the sake of analysis. 'This is why Site 2 is labelled "Kilombelo and Kiambani," as it represents data from farmers in both locations'. This means that the results of Kilombelo and Kiambani is one and the same thing.

Author contributions

Libère Nkurunziza initiated and led the writing of the paper, with contributions of Stanley Karanja Ng'ang'a for the cost-benefit analysis, and Winifred Karugu for the livelihood study. Shem Kuyah and Sylvia Nyawira contributed with valuable comments during the study design and manuscript preparation. All co-authors participated in the whole process of writing.

Disclosure statement

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Appendices

Appendix 1: Survey questionnaire

DATE:
RA:

QUESTIONNAIRE

SOCIOECONOMIC SURVEY - MAKUENI

BACKGROUND INFORMATION

1) What is your name……………………….
   a) Gender
      i) Female
      ii) Male
2) What is the name of your ward?
   ____
3) What is your tribe?
   ____
4) Are you married?
   a) Yes
   b) No
   c) Other (specify) ___________________
5) If the answer to question 4 is yes, where is your spouse?
   a) Home
   b) Urban migrant
   c) Dead
   d) Divorced
   e) Other (specify) ___________________

6) How many people live here?
   a) 1–2
   b) 3–4
   c) 5–6
   d) 7–8
   e) 9–10
   f) over ten
7) What is your relationship with them? (indicate number in each category)
   a) Children ____________________
   b) Grand children _______________
   c) Employees &tenants ___________
   d) Parents ____________
   e) Nieces & nephews ____________
   f) Brothers & sisters _____________
   g) Grand parents ________________
   h) Other (specify) _______________
8) What is your age?
   a) Under 20 years
   b) 20–29 years
   c) 30–39 years
   d) 40–49 years
   e) 50–59 years
   f) 60–69 years
   g) 70 and above
   h) Doesn't know
   i) Other (specify) ______________
9) What is your religion?
   ____
10) What is the level of your education?
   a) Adult Education
   b) Primary
   c) Secondary
   d) Certificate
   e) Diploma
   f) Degree
   g) None
   h) Nursery
   i) Other (specify) ____________
11) How many children do you have? What is their age?

Number of children
1–2
2–3
3–4
4–5
5–6
7–8
9–10
Over 10
Other specify…

12) Choices for question 12 (Where are they and why)
   a) Pre-school
   b) School
   c) Post school training
   d) Working

e) Staying at home because of sickness & joblessness
f) Other (specify) _______________

13) Where are they and why?
a) Home
b) Boarding school
c) Post school training
d) Working
e) Other (specify) _______________

SOCIO-ECONOMIC STATUS

14) Apart from farming, what other economic activities do you engage in?
a) Formal employment (specify) _______________
b) Self-employment (specify) __________________
c) Casual labourer (specify) ___________________
d) Other (specify) ____________________________

15) Apart from farming, do you have other sources of income?
a) Yes
b) No
c) Other (specify) __________________________

16) If the answer to the above question is yes please indicate the source
a) Spouse
b) Children
c) Other (specify) _________________________

17) Indicate the value of any additional income you received during the last 12 months (September 2021–August 2022)
a) None
b) Less than 1,000
c) Less than 5,000
d) 6,000–10,000
e) 11,000–20,000
f) 21,000–30,000
g) Over 30,000
h) Other (specify) _______________________

18) What is the size of your land in acres?
a) 1–2
b) 3–4
c) 5–6
d) 7–8
e) 9–10
f) Over Ten
g) Other (specify) ____________________

19) How much of it do you utilize for agricultural production?
a) Less than 1 acre (specify) _____________
b) 1–2 acres
c) 3–4 acres
d) 5–6 acres
e) 7–8 acres
f) 9–10 acres
g) Over ten acres
h) Other (specify) __________________

20) Is there a title deed for your land?
a) Yes
b) No
c) Other (specify) _________________

21) If the answer to question 19 is yes, in whose name is the title deed?
a) Self
b) Spouse
c) Parents
d) Grand parents
e) Brothers

f) Children
g) Other (specify) ________________

22) How is the owner related to you?
a) Spouse
b) Parents
c) Grand parents
d) Children
e) In-laws
f) Other (specify) _________________

23) Who uses the land?
a) Me
b) Children
c) Brothers & sisters
d) Parents
e) In-laws
f) Grand parents
g) Tenants
h) Other (specify) ________________

24) Who used it before you?
a) In-laws
b) Parents
c) Previous owners
d) Other (specify) _______________

25) Who will use it after you?
a) Sons
b) Daughters
c) Grand children
d) Other (specify) ______________

26) Can you dispose of this land (sell, give, bequeath, etc.)?
a) Yes
b) No
c) Other (specify) _______________

27) If not, who can?
a) Spouse
b) Parents
c) Children
d) Other (specify) ________________

28) Do you utilize other pieces of land apart from this one?
a) Yes
b) No

29) If yes, how many parcels?
a) 1–2
b) 3–4
c) 5–6
d) over 6

30) If yes, do you?
a) Own them
b) Rent them
c) Other (specify) _________________

31) How do you utilize these extra parcels of land?
a) Farming
b) Lease out
c) Other (specify) _________________

32) What kind of house do you live in?
a) Permanent
b) Semi-permanent
c) Temporary
d) Other (specify) _________________

33) How did you obtain money to build your house?
a) Formal employment

b) Self-employment
c) Farming
d) Parents
e) Children
f) Other (specify) ____________________

34) What do you cook with?
a) Three stones
b) Stove
c) *Jiko*
d) Cooker (specify) __________________
e) Other (specify) ___________________

35) What form of cooking fuel do you use?
a) Firewood
b) Coal
c) Kerosene
d) Gas
e) Electricity
f) Other (specify) __________________

36) What form of lighting do you use?
a) Hurricane lamp
b) Gas
c) Electricity
d) Solar energy
e) Other (specify) __________________

37) Do you own?
a) Sofa set
b) Fridge
c) Dining set
d) Water tank
e) Other (specify) __________________

38) What is your usual mode of transport?
a) *P*.S.V.
b) Bicycle
c) Motor cycle
d) Vehicle
e) Other (specify) ___________________

39) What is your most usual form of reliable information?
a) Radio
b) Newspaper
c) Television
d) Mobile phone
e) Other (state) ____________________

40) What is your access to water?
a) River
b) Rain water
c) Well
d) Borehole
e) Piped water
f) Other (state) _________________

41) Do you pay for access to water?
a) Yes
b) No
c) Other (specify) ________________

42) How did you obtain money to pay for borehole, well or piped water?
a) Formal employment
b) Self-employment
c) Farming
d) Parents
e) Other (specify) ________________

Crop production and soil management

43) Indicate the crops that you grow and acreage

Crop	Specify type and/or variety	Acreage
Maize		
Beans		
Potatoes		
Bananas		
Vegetables		
Fruits		
Napier grass		

44) Please indicate the value of farm produce you sold last season

Crop	Amount (Ksh)

45) Has soil testing ever been done on your farm?
   a) Yes
   b) No
   c) Other (specify) _____________
46) If yes, how was it done?
   a) Own testing
   b) Laboratory test
   c) Observation
47) What proportion of your farm is sandy? ____________
48) Do you practice crop rotation on your farm?
   a) Yes
   b) No
   c) (Other specify) ________________
49) If yes, which crop combination?
   a) Maize/Bean
   b) Maize/cowpea
   c) Cowpea/Groundnut
   d) Beans/Groundnuts
   e) Other (specify) ______________
50) Do you have SWRT membrane installed on your farm?

a) Yes
b) No

51) If yes, what crop was previously grown on the farm where SWRT is installed?
a) Maize
b) Cow pea
c) Groundnuts
d) Beans
e) Kales
f) Spinach
g) Others (Specify) _______________

52) What soil management practice do you practice in your farm?
a) Crop residue incorporation
b) Cereal-legume rotation
c) Farm yard manure
d) Use of compost
e) Mineral fertilizers
f) Natural fallows
g) Minimum tillage
h) Other (specify) _______________

53) How do you handle stover post-harvest?
a) Leave on farm
b) Sold
c) Livestock feed
d) Other (specify) _______________

LIVESTOCK PRODUCTION

54) Do you have livestock?
a) Yes
b) No

55) If the answer to question 40 is yes, indicate the type and number of livestock.
a) Cattle _______________
b) Goats _______________
c) Chickens ____________
d) Rabbits _____________
e) Donkey _____________
f) Other (specify) _________________

56) How did you obtain money to buy these livestock?
a) Formal employment
b) Self-employment
c) Farming
d) Parents
e) Other (specify) __________________

57) Did you sell any livestock or livestock product in the last 12 months (September 2021–August 2022)?
a) Yes
b) No
c) Other (specify) _______________

58) Indicate the value of livestock or livestock products sold this year

Livestock Or Product	Amount (Ksh)

ACCESS TO SUPPORT SERVICES

59) Do you know whether there are extension agents who work in this sub-location?
  a) Yes
  b) No
60) When did you last talk to her/him about farming?
  a) This month
  b) Last month
  c) This year
  d) Last year
  e) Two years ago
  f) Never
  g) Other (specify) ______________
61) Where did you meet him/her?
  ____
62) What did you talk about?
  ____
63) Has the extension agent ever advised you on farming matters?
  a) yes
  b) no
64) Why?
  ____
65) Do you keep farm records and accounts?
  a) Yes
  b) No
66) Indicate membership in groups and when last attended?
  a) Women group
  b) Church group
  c) Farm co-operatives
  d) Other (specify) ______________
67) Indicate how often you attend *barazas*?
  a) Every meeting
  b) Frequently
  c) Seldom
  d) Never
  e) Other (specify) ______________
68) When did you last attend a *baraza*?
  ____
69) Indicate whether farming issues are discussed in the following:-
  a) Women's group
  b) Church group
  c) Co-operative
  d) *Baraza*
  e) None
70) Have you ever attended a course at a Farmers Training College (FTC)?
  a) Yes
  b) No
  c) Other (specify) ______________
71) If not, why?
  ____
72) Would you like to attend?
  a) Yes
  b) No
73) If yes, when attended and why?
  ____
74) Describe the course you attended at the F.T.C.
  ____
75) Have you ever attended an extension demonstration?
  a) Yes
  b) No

76) When did you last attend an extension demonstration?
____
77) Describe the demonstration you attended?
____
78) Some people think the extension agent is helpful, some do not. What do you think?
   a) Yes
   b) No
   c) Other (specify) ________________
79) How many bags or smaller units of produce did you retain last season?
____
80) Do you purchase inputs for cultivating your crops?
   a) Yes
   b) No
81) If yes, how much did they cost you?
____
82) Do you employ labour?
   a) Yes
   b) No
83) If yes, how many?
____
84) If yes how much do you pay them
____
85) Are you a member of any local coop/society?
   a) Yes
   b) No
86) If so in whose name is the membership?
87) In what form did you obtain credit?
   a) Direct loan
   b) Bank overdraft
   c) Inputs
   d) Other (specify) ________________
88) What problems did you experience when marketing your crops and livestock?
____
89) What solutions do you suggest for these problems?
____

Appendix 2: Selected communication material

List of selected communication material including links to videos and newspaper publications

1) Citizen TV in English: https://youtu.be/Mp5RFV3aeUo October 8th, 2022.
2) Citizen TV in Swahili: https://youtu.be/WsYU4YNPeuU October 8th, 2022.
3) Jomo Kenyatta University of Agriculture and Technology (jkuat.ac.ke) October 6th, 2022.
4) US Technology Helps Improve Crop Yields in Drought-Stricken Africa (voanews.com) October 25th, 2022.
5) Membranes offer hope to farmers in arid area Jul. 28, 2022.

Appendix 3: Additional illustrations of the CBA results

Table A1. Net present value (NPV) associated with different scenarios on irrigated smallholder farms in Kitengei, Makueni County, Kenya.

Investment scenario	Net present value (NPV) in USD ha^{-1} associated with different interventions			
	SWRT + soil improvement (Improved)	SWRT (AV)	SWRT + soil improvement (S01YD)	SWRT (S01YD)
As-is	−9,413	−9,752	−8,336	−8,729
(Lower) tank installation cost	−9327	−9644	−8624	−8617
(Lower) tank cost & installation cost	−8426	−8743	−7723	−7716
(Lower) tank cost & installation cost, & 50% labour cost	−2397	−2713	−1293	−1687

Table A1. (*Continued*)

Investment scenario	SWRT + soil improvement (Improved)	SWRT (AV)	SWRT + soil improvement (S01YD)	SWRT (S01YD)
	Net present value (NPV) in USD ha^{-1} associated with different interventions			
(Lower) tank cost & installation cost, 50% labour cost, & 33% discount rate	−1839	−2225	−549	−1029
(Lower) tank cost & installation cost, 50% labour cost, 33% discount rate, & 50% SWRT cost	−7.3	−393	1282	802
(Lower) tank cost & installation cost, 50% labour cost, 33% discount rate, & 75% SWRT cost	909	522	2197	1718
(Lower) tank cost & installation cost, 50% labour cost, 33% discount rate, & 90% SWRT cost	1458	1071	2747	2267

Table A2. Net present value (NPV) associated with different scenarios on non-irrigated smallholder farms in Ulilinzi, Makueni County, Kenya.

Investment scenario	Non-irrigated (SWRT yield + soil improvement)	Non-irrigated (SWRT yield)	Non-irrigated (SWRT yield + soil improvement) (S01YD)	Non-irrigated (SWRT yield) (S01YD)
	Net present value (NPV) in USD ha^{-1} associated with different interventions			
As-is	−8972	−9071	−6862	−6941
50% labour cost (LC)	−2943	−3042	−832	−913
50% LC & 33% interest rate (IR)	−2487	−2606	−30	−128
50% LC, 33% IR, & 50% SWRT cost	−655	−776	1801	1703
50% LC, 33% IR, & 75% SWRT cost	264	139	2717	2619
50% LC, 33% IR, & 90% SWRT cost	809	689	3267	3169

Table A3. Net present value (NPV) associated with different scenarios on non-irrigated smallholder farms in Kilombelo, Makueni County, Kenya.

Investment scenarios	Non-irrigated (SWRT yield + soil improvement)	Non-irrigated (SWRT yield)	Non-irrigated (SWRT yield + soil improvement) (S01YD)	Non-irrigated (SWRT yield) (S01YD)
	Net present value (NPV) in USD ha^{-1} associated with different interventions			
ASIS	−10477	−10870	−9576	−10270
50% labour cost (LC)	−4599	−4943	−3831	−4416
50% LC & 33% interest rate (IR)	−4206	−4702.9	−3159	−3988
50% LC, 33% IR, & 50% SWRT cost	−2374	−2871	−1327	−2171
50% LC, 33% IR, & 75% SWRT cost	−1458	−1955	−411	−1255
0% LC, 33% IR, & 90% SWRT cost	−838	−1405	219	−706.3

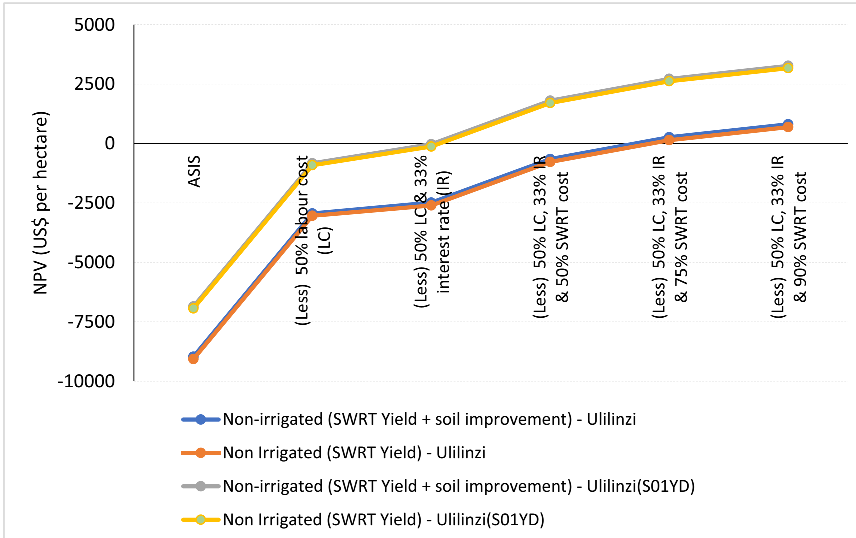

Figure A1. Cost-benefit analysis results per hectare for non-irrigated smallholder farms in Ulilinzi. *SWRT: subsurface water retention membrane; SWRT yield: benefits per hectare associated with the yield derived from both the long-rain and short-rain seasons with SWRT installed; SWRT yield (S01YD): benefits per hectare associated with yield in the long-rain season only.*

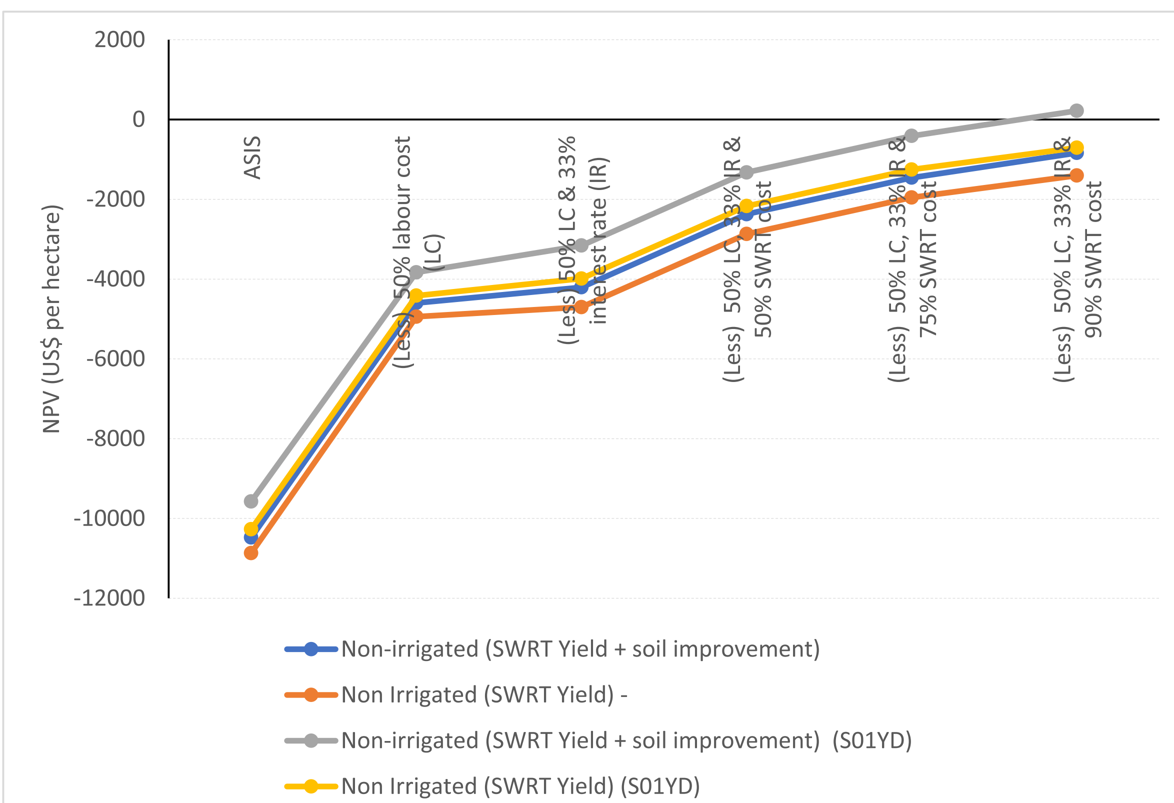

Figure A2. Cost-benefit analysis results per hectare for non-irrigated smallholder farms in Kiambani and Kilombelo. *SWRT: subsurface water retention membrane; SWRT yield: benefits per hectare associated with the yield derived from both the long-rain and short-rain seasons with SWRT installed; SWRT yield (S01YD): benefits per hectare associated with yield in the long-rain season only.*