

Article

Experimental Evaluation of Conservation Agriculture with Drip Irrigation for Water Productivity in Sub-Saharan Africa

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Abstract: A field-scale experimental study was conducted in Sub-Saharan Africa (Ethiopia and Ghana) to examine the effects of conservation agriculture (CA) with drip irrigation system on water productivity in vegetable home gardens. CA here refers to minimum soil disturbance (no-till), year-round organic mulch cover, and diverse cropping in the rotation. A total of 28 farmers (13 farmers in Ethiopia and 15 farmers in Ghana) participated in this experiment. The experimental setup was a paired ‘t’ design on a 100 m² plot; where half of the plot was assigned to CA and the other half to conventional tillage (CT), both under drip irrigation system. Irrigation water use and crop yield were monitored for three seasons in Ethiopia and one season in Ghana for vegetable production including garlic, onion, cabbage, tomato, and sweet potato. Irrigation water use was substantially lower under CA, 18% to 45.6%, with a substantial increase in crop yields, 9% to about two-fold, when compared with CT practice for the various vegetables. Crop yields and irrigation water uses were combined into one metric, water productivity, for the statistical analysis on the effect of CA with drip irrigation system. One-tailed paired ‘t’ test statistical analysis was used to examine if the mean water productivity in CA is higher than that of CT. Water productivity was found to be significantly improved ($\alpha = 0.05$) under the CA practice; 100%, 120%, 222%, 33%, and 49% for garlic, onion, tomato, cabbage, and sweet potato respectively. This could be due to the improvement of soil quality and structure due to CA practice, adding nutrients to the soil and sticking soil particles together (increase soil aggregates). Irrigation water productivity for tomato under CA (5.17 kg m⁻³ in CA as compared to 1.61 kg m⁻³ in CT) is found to be highest when compared to water productivity for the other vegetables. The mulch cover provided protection for the tomatoes from direct contact with the soil and minimized the chances of soil-borne diseases. Adapting to CA practices with drip irrigation in vegetable home gardens is, therefore, a feasible strategy to improve water use efficiency, and to intensify crop yield, which directly contributes towards the sustainability of livelihoods of smallholder farmers in the region.

Keywords: water productivity; conservation agriculture; drip irrigation; water management; sustainable intensification; Sub-Saharan Africa

1. Introduction

More than 60% of the population in Sub-Saharan Africa (SSA) depends on agriculture for their livelihood, primarily on crop production [1]. However, a majority of the farmers are smallholders, constituting about 80% of all farms [2] and producing far below potential due to various factors [3–5]. The challenges for agricultural development in the region include water scarcity [6], small farm size [7], soil degradation [8,9], climate change and variability [10], and unsustainable agricultural intensification [11]. The current farming practice is traditional with poor soil and water management strategies resulting in soil degradation [12–14]. Soil degradation is one of the major causes of low agricultural productivity in the region [12,15]. On the other hand, the ever-increasing population demands a significant increase in food supply [16,17] and improvements in the nutritional wellbeing as malnourishment is also a serious challenge in the region [18]. Sustainable pathways are required to maximize food supply with minimum effect on the environment. This process is called sustainable intensification [19]. Agriculture, if sustainably intensified, can provide a significant contribution towards food security and economic development in SSA [20]. Sustainability is a key component of modern agricultural practices [21]. Vegetable Home Gardens (VHG), an effective strategy to build a sustainable agriculture system [17], refers to producing vegetables (and other high-nutrition crops) on a small plot around the household or at a walking distance [17,22]. The strategy seems to play a significant role in building a healthy society, especially mothers and children that are most vulnerable to malnutrition [23].

The lack of food security and nutritional well-being of the region underscores the need to identify and adopt innovative water and land management alternatives that can intensify crop production while improving soil quality and water productivity. Crop water productivity is defined as the yield per unit volume of water consumed [24]. Several studies including [24,25] indicated that improved water productivity refers to an increase in water sustainability and food security. Irrigation plays an essential role in addressing the high rainfall variability in the region [15,26] and increasing the cycle of crop production [27,28]. Irrigation development in SSA is limited to technologies with higher water use efficiency as water scarcity is a challenge. The use of efficient soil and water management technology potentially improves water use efficiency; harvests rain by increasing soil water infiltration and soil holding capacity, decreasing soil evaporation; improves soil quality; and enhances sustainable crop production [29].

Conservation agriculture (CA) constitutes an important part of the in situ conservation method [30]. CA in this study refers to minimum soil disturbance (no-till), continuous mulch, and biologically diverse cropping in the rotation. CA is a new approach in the region, which can recover soil quality through the decomposition of mulch material and biologically diverse cropping. On the other hand, drip irrigation technology is a leading technology worldwide not only for water saving but also as a means of increasing crop productivity [22,31]. The combination of CA with drip irrigation would potentially increase water use efficiency, enhance soil ecosystem and health, reduce weeds, enhance the quality of leafy and fruit vegetable, and increase yield and quality [32–37].

Several studies examined the effects of CA, no-till (NT), and minimum tillage (MT) practices on crops, water, soil quality, and other environmental variables as compared to conventional tillage (CT). Erkossa et al. [38], Olaoye [39], and Ike [40] found significant crop yield increase and economic benefit under NT practice. Similarly, increased grain yield was observed under NT with mulch (crop residue) [41–47] and CA practice [48–54]. Soil moisture was found to increase under the NT [40,55,56] and NT with mulch [42,43,45,57,58] when compared with CT practice. Reduced runoff, lower erosion rate, and increased infiltration [44,46,57,58] and higher water use efficiency [47] were observed under NT with mulch than CT. Soil organic carbon, total soil nitrogen, available phosphorus, and soil microbial biomass significantly increased under CA practice than CT [48]. Moreover, weeds are suppressed and minimized in CA practice with the application of crop residue (mulch) [59–62]. Similarly, Shilling, Worsham and Danehower [61] found about 80% weed control with the application of mulch when compared with no-mulch practice.

Most previous studies emphasized evaluating the impacts of individual components of CA on the yields of grain crops and other environmental variables in the rainfed system. The impacts of CA (no-till, mulching, and rotation) combined with drip irrigation in vegetable home gardening in the region with irrigated agriculture is missing. The main objective of this study is, therefore, to examine the impact of CA in the VHGs with drip irrigation on crop water productivity and identify opportunities to expand this technology in the region. The result of this study would assist stakeholders and decision makers in planning and advancing agriculture system for smallholder farmers.

2. Materials and Methods

2.1. Study Area

This study was conducted in two countries in SSA with three study sites (Figure 1); Dangishita and Robit (Ethiopia), and Yemu (Ghana). A total of 28 farmers participated in this experiment: 7 farmers in Robit, 6 farmers in Dangishita, and 15 farmers in Yemu. Robit and Dangishita *Kebeles*, the smallest administrative unit, are found in Amhara Regional State, in the northern part of Ethiopia. Whereas Yemu is found in Savelugu-Nanton District, in the Northern Region of Ghana. Considering the rainfall from 2010 to 2017 in Ethiopia and 2010 to 2016 in Ghana, the average annual rainfall based on a nearby climate station is about 1700 mm, 1400 mm, and 1000 mm for Dangishita, Robit, and Yemu sites, respectively. The major rainy seasons in Dangishita and Robit ranges from June to September whereas in Yemu the rainy season ranges from July to September. The rainy season contributes about 75%, 82%, and 54% of the annual rainfall in Dangishita, Robit, and Yemu, respectively. The average elevations extracted from 30 m resolution Digital Elevation Model of the study sites indicated 2044 m, 1842 m, 154 m above seas level for Dangishita, Robit and Yemu, respectively. The soil type for Dangishita and Robit sites is Chromic Luvisols (sandy clay loam, 51% sand) whereas for Yemu is Ferric Luvisols (sandy loam, 68% sand). Farmers in Robit and Dangishita use shallow groundwater wells for irrigation during the dry season (no or minimum rainfall) and manual pulley system was used as water-lifting techniques to fill water storage tanks. Yemu community farmers use a nearby river pond for fetching water to fill the water storage tanks in the dry season. More details of the study sites characteristics could be found in Assefa et al. [29]. Women were the main actors for the vegetable gardening experiment assisted by children of both genders.

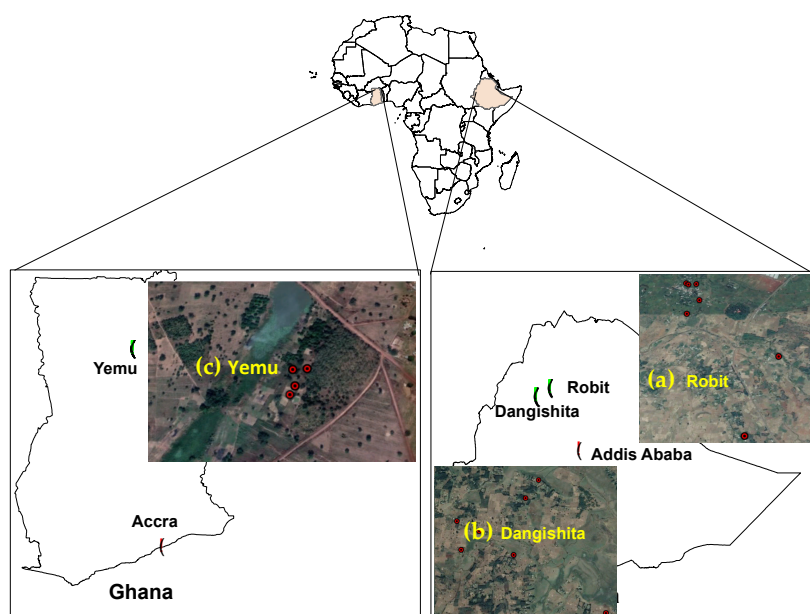


Figure 1. Location of experimental plots in Sub-Saharan Africa (SSA): Robit (a); Dangishita (b); and Yemu (c).

2.2. Experimental Design and Setup

The experiment was laid on a paired 't' design to compare the effects of CA (no-till, mulch, and rotation) with CT (farmer's tillage practices). Paired 't' is mathematically powerful [63] to compare two paired measurements, which have intrinsic relationships, and do not require a large sample size which allows good control of individual differences. In this experimental setup, CA is the treatment and CT is the control (Figure 2) in which participants were involved in both (CA and CT) practices. In CT practice, the farmers use traditional hand tools (like a pickaxe) to till their plots and dig small holes to plant or transplant the vegetables. Whereas in CA practice, the farmers put organic mulch (grass, crop residue) on their plots with no-till practice and dig small holes with traditional hand tools to plant or transplant the vegetables. Farmers used the sites to grow various crops using CT practice before the experiment. The experimental setup was established in 2015 for Ethiopia and in 2016 for Ghana on 100 m² plot; where half of this size was assigned to CA and another half to CT randomly. The drip irrigation system was placed for both CA and CT management practices. Farmers had various vegetables grown on the experimental plots across the sites and in different seasons.

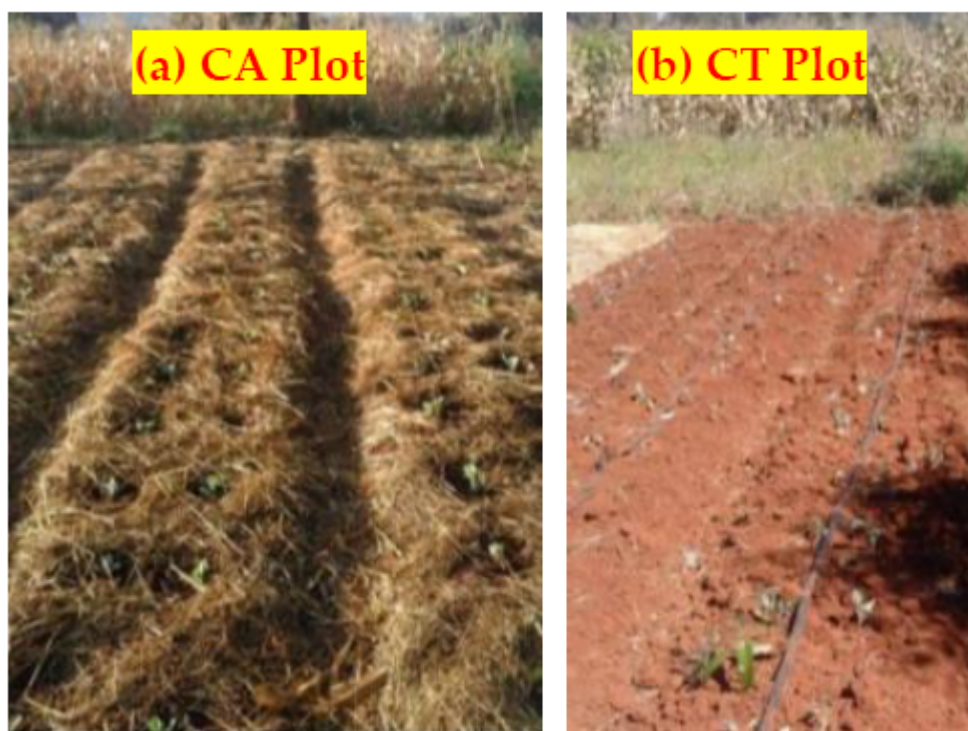


Figure 2. Experimental design and setup: conservation agriculture (CA) plot (a); and conventional tillage (CT) plot (b).

A series of discussions were made with local government and community leaders to locate the sites and select participants for the vegetable garden experiment. Participant farmers were selected based on their interest to participate in the experiment, availability of open plot close to their house (100 m² in size), and availability of nearby irrigation water source. All of the farmers participating in the experiment were provided with drip irrigation hardware and water storage tanks. Plots were selected close to the household. The plots were tilled, and beds were prepared based on the predetermined dimension and the drip system was installed (Figure 3). CA plots were covered (Figure 2a) with organic mulch (grass, and crop residue). The on-site demonstration was carried out for farmers regarding the thickness of mulch cover and drip irrigation system. The farmers assigned a very small piece of land for nursery purpose to grow vegetable seedlings. The farmers discuss first and decide on the type of vegetable they want to grow in each cropping season.



Figure 3. Preparation of beds and setup of drip system.

2.3. Data Monitoring

A data collection protocol has been developed for appropriate data analysis using paired ‘t’ statistics. Training was given to field technicians on the data protocol. Vegetable yield and irrigation water use under CA and CT practices were the two main variables monitored for paired ‘t’ statistical analysis. Farmers observe the soil moisture and use their judgment to determine irrigation frequency for various vegetables. A number of fixed size (500 L for Ethiopia and 200 L for Ghana) water storage tanks emptied, and the dates of water application were monitored. Vegetable yields were weighed during harvest in the presence of field technicians. Data were collected for three cropping cycles in Ethiopia and two cropping cycles in Ghana (Table 1).

Table 1. Vegetable types and their cropping sequence for the study sites.

Study Sites	Year	Growing Periods											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dangishita	2015												
	2016	■	■	■	■	■	■						■
	2017			■	■	■	■	■					
Robit	2015												■
	2016	■	■	■	■	■	■	■	■				■
	2017	■	■										■
Yemu	2016								■	■	■	■	■

Note: yellow = garlic, orange = onion, blue = tomato, green = cabbage, and black = sweet potato.

Field management activities such as fertilizer application, irrigation water use, and pesticide applications were monitored. Urea and Diammonium Phosphate (DAP) were applied for garlic, and sweet potato whereas only urea was applied for cabbage. Urea was applied at a rate of 100, 400, and 55 kg ha⁻¹ for garlic, cabbage, and sweet potato, respectively. Whereas DAP was applied at a rate of 200 and 300 kg ha⁻¹ for garlic and sweet potato, respectively. The farmers applied urea about 4, 6, and 2 weeks after the date of planting of garlic, cabbage, and sweet potato, respectively. Whereas the farmers applied DAP about 6 weeks, and 3 days after planting garlic and sweet potato, respectively. Malathion pesticide was applied at a rate of 0.5 L ha⁻¹ for tomato (4 weeks after plantation) whereas Dimeto 40% was applied for cabbage (2 weeks after plantation) at a rate of 20 L ha⁻¹. The farmers used their own practice, possibly assisted by government developmental agent, on the rate and timing of fertilizer and pesticide applications.

3. Results and Discussion

3.1. Direct Effects of Conservation Agriculture on Irrigation Water Use and Crop Yield

Irrigation water uses were monitored for various vegetables (garlic, onion, tomato, cabbage, and sweet potato) with farmers practice for water application. Substantial improvements were observed in irrigation water savings and crop yield under CA practice (Table 2). The average irrigation water use in CA was reduced by 18.4%, 45.6%, 19.5%, and 18% for garlic, onion, tomato, and cabbage respectively. Sweet potato was partly rainfed and then farmers applied an equal amount of irrigation water for CA and CT practices. Table 9 of Assefa et al. [29] explicitly shows the amount of rainfall during the cropping period of each vegetable at the same sites. The rainfall in Dangishita and Robit was mostly during the maturity period of crops. On the other hand, the average vegetable yield in CA was increased by 56%, 14%, 184%, 9%, and 56.8% for garlic, onion, tomato, cabbage, and sweet potato respectively.

Table 2. Average irrigation water uses and crop yield.

Irrigation Use (1000 m ³ ha ⁻¹)	Garlic	Onion	Tomato	Cabbage	Sweet Potato
CA	2.96	1.29	3.39	2.60	1.48
CT	3.63	2.38	4.21	3.17	1.48
Crop Yield (t ha ⁻¹)	Garlic	Onion	Tomato	Cabbage	Sweet Potato
CA	3.05	3.20	17.84	23.58	15.9
CT	1.96	2.81	6.29	21.54	10.14
N	9	5	4	4	5

Note: N = number of replicants.

3.2. Effects of Conservation Agriculture on Irrigation Water Productivity

Water productivity was used as a standardized measure to evaluate the overall impacts of CA with respect to CT practice. A one-tailed, paired *t*-test was used to examine the effects of CA on irrigation water productivity. It was meant to examine if the mean water productivity in CA is higher than that of CT practice. Farmers in Ethiopia have grown four different vegetables (garlic, onion, cabbage, and tomato) in four dry seasons, 2015 to 2017. Whereas farmers in Ghana have grown sweet potato in 2016. Some of the farmers were not included in the statistical analysis (Tables 2 and 3) due to animal invasion on their plots (i.e., most of the plots were not fenced) and the data could not be used to draw conclusions. Irrigation water productivity was found to increase significantly under CA when compared to CT for all vegetables (Table 3). The average irrigation water productivity in CA for garlic (1.1 kg m⁻³) and onion (2.59 kg m⁻³) was significantly ($\alpha = 0.05$) higher when compared with CT, 0.55 kg m⁻³ and 0.18 kg m⁻³ for garlic and onion, respectively (Figure 4). Irrigation water productivity was increased by about 100% and 120% for garlic and onion, respectively. Similarly, the average irrigation water productivity in CA for tomato (5.17 kg m⁻³) and cabbage (9.16 kg m⁻³) was significantly higher when compared with CT, 1.61 kg m⁻³ and 6.89 kg m⁻³ for tomato and cabbage, respectively (Figure 5). Irrigation water productivity was increased by about 222% and 33% for tomato and cabbage, respectively. Likewise, the average irrigation water productivity (Figure 6) in CA for sweet potato (9.95 kg m⁻³) is significantly higher (49% increase) when compared to CT (6.67 kg m⁻³).

Table 3. A one-tailed paired ‘t’ test for the average irrigation water productivity.

Items	Garlic (kg m ⁻³)	Onion (kg m ⁻³)	Tomato (kg m ⁻³)	Cabbage (kg m ⁻³)	Sweet Potato (kg m ⁻³)
CA	1.10	2.59	5.17	9.16	9.95
CT	0.55	1.06	1.61	6.89	6.67
N	9	5	4	4	4
p-value	0.002 *	0.015 *	0.09 **	0.005 *	0.004 *

Note: N = number of replicants, * $\alpha = 0.05$, ** $\alpha = 0.1$.

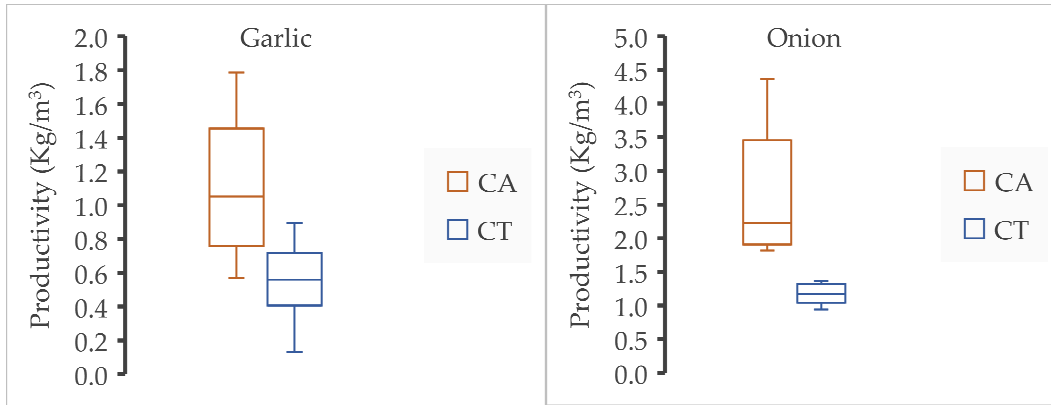


Figure 4. Irrigation water productivity for garlic and onion; Dangishita and Robit sites.

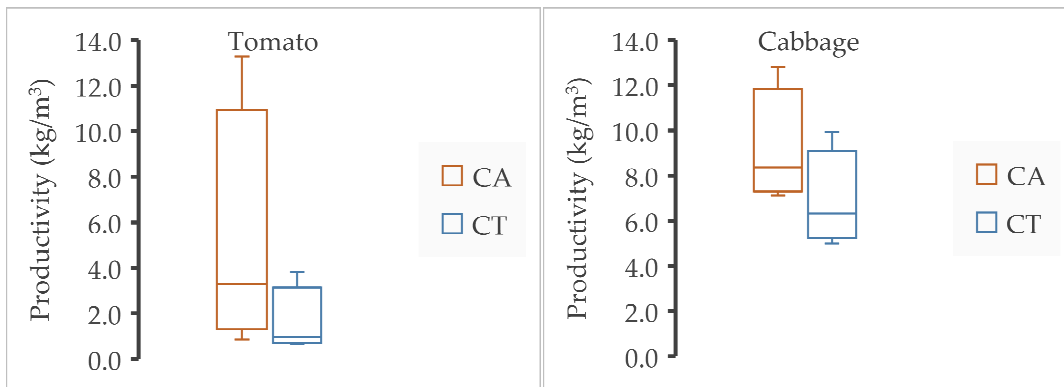


Figure 5. Irrigation water productivity for tomato and cabbage at Robit site.

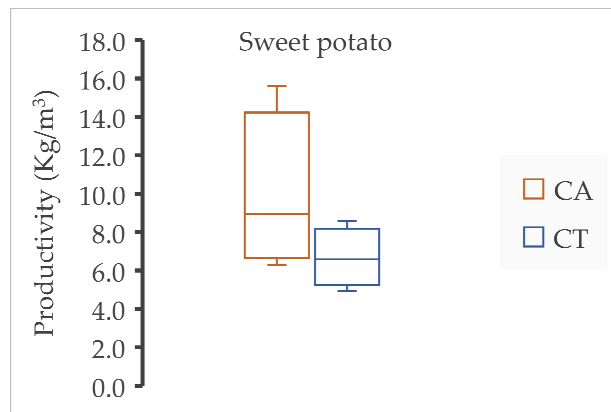


Figure 6. Irrigation water productivity for Sweet potato at Yemu site.

Tomato yield in Robit substantially varied between farmers in both CA and CT practices; the coefficient of variation was 0.98 in CA and 0.86 in CT. This variability could be due to the degree of farmers' devotion, frequent follow-up of the vegetable garden for weeding and on-time watering and providing a standard thickness of mulch. The national average for smallholder tomato production in Ethiopia is 8.9 t ha^{-1} [64]; which is less than tomato yield from CA plot (17.8 t ha^{-1}) but slightly higher than the yield from CT plot (6.3 t ha^{-1}). Irrigation water productivity in CA for tomato was substantially increased (Figure 5) compared to the other vegetables (garlic, onion, cabbage, and tomato). One of the main reasons is that the mulch served as a protection layer for the tomato from having direct contact with the soil and getting soil-borne diseases. The average cabbage yield in Robit (23.6 t ha^{-1} in CA and 21.5 t ha^{-1} in CT) was found to be higher than the national average (7.9 t ha^{-1}) for smallholder production [64]. Farmers in the study site applied nitrogen fertilizer (400 kg ha^{-1}) to cabbage more than the optimum amount suggested by Wolde and Tana [65] in Ethiopia (260 kg ha^{-1}). The average yield increment in CA (15.9 t ha^{-1}) for sweet potato in Yemu was statistically significant compared to CT (10.1 t ha^{-1}). The result is consistent with Dumbuya et al. [66] sweet potato yield findings for the tilled system (9.5 to 15.8 t ha^{-1}) in southern Ghana. On the other hand, garlic and onion yields in Dangishita and Robit sites were generally small, however, the yield increment in CA was statistically significant ($\alpha = 0.05$). The average garlic yield was 3.4 t ha^{-1} in CA and 2.2 t ha^{-1} in CT whereas the average onion yield was 3.2 t ha^{-1} in CA and 2.8 t ha^{-1} in CT. Garlic and onion production in Ethiopia is constrained due to various factors including nutrient and moisture stress, poor soil condition, weed invasion, and diseases [67]. The amount of nitrogen fertilizer applied for garlic, 100 kg ha^{-1} , was not enough based on Abadi [68] suggestion in Ethiopia (200 kg ha^{-1}) and no fertilizer was applied to onion, which could be the reason for lower garlic yield in Dangishita and Robit. In addition, the seed-borne disease was observed for onion in the experimental plots with no effective cure.

Significant improvement in irrigation water productivity and crop yield was observed under CA practice due to the improvement of soil structure (sticking soil particles together and increase soil aggregates) and quality (adding nutrients). As the organic mulch gets decomposed, soil organic matter is formed. Soil organic matter invites heroes of the soil world; worms, bacteria, and fungi. As the soil organic matter gets decomposed, it provides nitrogen and phosphorus to the vegetables (improving soil quality). The microorganisms use the organic matter as a food and produce chemicals which can stick the soil particles together and form an aggregate (improving soil structure). On the other hand, the addition of mulch reduces soil evaporation, surface runoff, and erosion. The combined effects of CA resulted in lower irrigation need (18 to 46% reduction) with higher crop yield (9 to 184% increase) for various vegetables across the sites when compared to CT.

3.3. Opportunities and Challenges

Several opportunities came into perspective when adapting CA with drip irrigation for expanding vegetable home gardens for smallholder farmers in SSA.

- Simplicity of the system; farmers involved in experimental plots appreciated the simplicity of home gardening practice with CA and drip irrigation.
- Providing a balanced diet; farmers spent a portion of the vegetable productions for household consumptions which helps the family members to get balanced diets.
- Potentially minimizing malnutrition; this can prove to be a strategic approach to minimize children's deaths and stunting caused by malnutrition, which is a serious problem in the region.
- Providing incentives; farmers took the surplus amount from the family, most of the production, to the market.
- Reducing labor; farmers experienced reduced labor when growing vegetables in CA with a drip irrigation system particularly for tillage, irrigation, and weeding.
- Increasing water productivity; CA with drip irrigation has proven potential to increase the cycles of vegetable production through increased water productivity.

Some challenges were also observed when adopting CA with drip irrigation for smallholder farmers in SSA.

- Competitive use of mulch; the mulch covers used were crop residues, dried grass, and other local organic materials which farmers also use it to feed their livestock.
- Water-lifting technique; the water-lifting technique used in Ethiopia, manual pulley system, was another challenge which required farmers to spend more time to extract water from groundwater wells to water storage tanks.

4. Conclusions

Vegetable home garden with CA and drip irrigation was tested in Ethiopia (Dangishita and Robit) and Ghana (Yemu) for its potential to improve irrigation water productivity and crop yield. Paired 't' experimental design was used on a 100 m² plot to examine the effects of CA and CT practices, both under drip irrigation system. Farmers in the study sites grew various vegetables; garlic, onion, cabbage, tomato and sweet potato. CA was found to increase irrigation water productivity and crop yield significantly at each site and has proven potential to sustainably intensify food production in the region. Irrigation water productivity increased by about 100%, 120%, 222%, 33%, and 49% for garlic, onion, tomato, cabbage, and sweet potato, respectively. This was due to the improvement of soil structure and quality, and water savings mainly from soil evaporation loss because of the CA practice. Irrigation water use efficiency and crop yield were significantly improved through the use of CA with the drip irrigation production system. Farmers used a portion of their vegetable production for household consumption, which could be considered as a strategic approach to address malnourishment challenges in the region. On the other hand, the competitive use of organic mulch was observed as a challenge for farmers to expand their production. Farmers could grow forage in the rainy season by intercropping with corn and use the forage as a mulch and food source for their farms and animals, respectively. The reduction of labor in CA was witnessed by farmers, particularly labor for tillage, irrigation, and weeding. Adaptability of the system creates an opportunity for smallholder farmers to maximize their production on a small plot of land and sustain their livelihood. In conclusion, CA with drip irrigation has proven potential to increase food supply and sustain the livelihood of smallholder farmers in Sub-Saharan Africa. It is suggested to test solar-driven pumps for irrigation which could potentially advance CA with drip irrigation production system. Also, intercropping forage in the rainfed corn production could be a potential solution to increase the availability of mulch in the dry season.

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